Sources and Mitigation of Harmonics in Industrial Electrical Power Systems: State of the Art

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***Abstract* – Power systems are designed to operate at frequencies of 50 Hz or 60Hz. However, certain types of loads produce currents and voltages with frequencies that are integer multiples of the 50 or 60 Hz fundamental frequency. These higher frequencies represent a form of electrical network pollutions known as "power system harmonics". This paper presents an extensive literature review in the petrochemical sector for the power system harmonics such as harmonics fundamentals, harmonics harmful effects on various electrical equipment, harmonic distortion limits and harmonic mitigation techniques. This paper is intended as a guide for those interested in this problem or intending to perform further researches in this area.**

***Index Terms*- Harmonics, Mitigation, Variable Speed Drives, Total Harmonic distortion, Point of Common Coupling.**

I. Nomenclature

VSD	Variable speed drive
VFD	Variable frequency drive
SMPS	Switched mode power supply
UPS	Uninterruptable power supply
SCR	Silicon controlled rectifier
PCC	Point of common coupling
THD	Total harmonic distortion
CT	Current transformer
VT	Voltage transformer
FFT	Fast fourier transform
STD	Standard
IGBT	Insulated gate bi-polar transistor
CAD	Computer aided design
PWM	Pulse width modulation
VSI	Voltage source inverter
FEED	Front end engineering design
LNG	Liquefaction of natural gas
SLD	Single line diagram
ESP	Electrical submersible pump
TIF	Telephone influence factor
WTHD	Weighted THD
APF	Active power filter
ETAP	Electrical transient analyzer program
TINA Pro	Design and circuit simulation software

II. Introduction

Power system harmonics are not a new phenomenon. Concern over harmonic distortion has been introduced throughout the history of electric power systems. Steinmetz published a book in 1916 that devoted considerable attention to the study of harmonics in three-phase power systems. His main concern was third harmonic currents caused by saturated iron in transformers and machines, and he was the first to propose delta connections for blocking third harmonic currents. Later, with the innovation of rural electrification and telephone service, power and telephone circuits were often placed on common rights-of-way; accordingly harmonic currents produced by transformer magnetizing currents caused inductive interference with open-wire telephone systems. The interference was so severe at times that voice communication was impossible. This problem was studied and treated by filtering and by placing design limits on transformer magnetizing currents. Today, the most common sources of harmonics are power electronic devices such as VSD, SMPS, UPS, and Static VAR Compensators. These loads use diodes, (SCRs), power transistors, and other electronic switches which chop the sinusoidal waveforms to control power or to convert 50/60Hz AC wave to DC wave and accordingly drew non-sinusoidal currents from the supply network. The work of J.B.J. Fourier (1768-1830) have been extensively useful for analyzing these non-sinusoidal waveforms, as it allows any periodic function to be described in a series of sinusoidal and co-sinusoidal functions, In 1920s and 1930s the AC/ DC converters were developed using mercury arc rectifiers, The invention of (SCR's) or thyristors in the 1950s, led to a tremendous development in the AC/ DC converters, which are nonlinear loads.

An explanatory introduction to current and voltage harmonics fundamentals, definitions of harmonics factors such as crest factor and Total harmonic distortion (THD) are extensively explained in Ref. [1-2], Then these references show how the harmonics are measured and the filtering solutions to mitigate the harmonic distortion within a power system. The harmonic resonance phenomenon is explained in detail and the inter-harmonics are clearly discussed as well.

Harmonics harmful effects on different power system elements like generators, transformers, motors, cables, capacitors, and metering devices are presented in Ref. [2-5]. They show the different techniques of harmonic filtering such as passive filters, active filters, and hybrid filters. Then harmonic resonance phenomenon is explained showing its nature, causes, types, measurements, and the available methods to avoid this phenomenon. Finally they present harmonic filters implementation procedures supported by computer aided design programs such as MATLAB.

Industrial facilities are by far the major producers of harmonic currents. Most industrial processes involve one form or another of power conversion to run processes that use large direct current (DC) motors or variable frequency drives. Others feed large electric furnaces, electric welders, or battery chargers, which are formidable sources of harmonic currents. Additionally, the use of energy-saving devices, such as electronic ballasts in commercial lighting fixtures and uninterruptible power supplies makes the harmonic problem even larger.

The international standards/ Practices [6-7] provide the methodology of harmonics analysis and the acceptable limits for the harmonic content within an electrical network. Besides, they intend to establish goals for the design of electrical systems that include both linear and nonlinear loads. The voltage and current waveforms that may exist throughout the system are described.

III. Problem Formulation

Analysis and mitigation of power system harmonics in the industrial electrical power systems should be performed on the following steps:

- Investigation and assessment of the plant nature, activities, and the type of electrical loads within this plant.
- Defining the possible Harmonic sources and their effects on the power system elements.
- Performing the required harmonic measurements and further harmonic studies.
- Introducing the optimum solutions to mitigate the harmonic levels (If required) with the relevant optimum sizing and location.
- Ensuring the electrical system compliance with the international harmonic limits.

IV. Literature Review

A review of the literature on power system harmonics sources, problems, measurements and calculations up to compliance with the international standards has been extensively researched over the past several decades and presented in the following categories:

A. Basics and Fundamentals of Harmonics:

Ref. [8] presents a complete analysis of the harmonic sources found in any power system, the three phase bridge is considered the most common source of harmonics in power systems because it is found in most AC/ DC converters, This three phase bridge is simply composed of a rectifier, DC link, and an inverter. For a six pulse bridge, there are six pulses or ripples in the DC side voltage per one period of the AC fundamental voltage. This six pulse bridge will produce harmonics of the following orders:

$$N = 6K \pm 1 \quad (1)$$

Where,

- N: The harmonic order
- K: an integer

Accordingly the Six pulse bridge will produce the 5th harmonic, 7^{th}, 11^{th}, 13^{th}, and so on. The reference also explains the effect of increasing the number of pulses on the reduction of harmonic content generated from the bridge. For example; the twelve pulse bridge will produce harmonics of the order:

$$N = 12K \pm 1 \quad (2)$$

Accordingly the twelve pulse bridge will generate the 11th harmonic, 13^{th}, 23^{rd}, 25^{th} and so on (the 5^{th} and 7^{th} harmonics are eliminated)

As the number of pulses increases, the harmonic content will be reduced but on the other hand, the drive cost and complexity will be increased. Finally, there should be a compromise between the required harmonic distortion and the cost of the bridge.

Ref. [9] describes the measurements and calculations techniques of power system harmonics. The harmonic measurement is a compromise between desirable and possible, in an ideal case, it would be possible to use calibrated and sensitive current and voltage sensors to measure the harmonic content but the normally available is using the existing CT's and VT's only. The harmonic calculation is also a compromise between the available data to the design engineer and the purpose of the harmonic calculation. The harmonic measurement is a sequential process which depends on the following parameters:

1. The electrical transducers such as CT's and VT's, used as measurement probes in the power system. The optimum transducers are sensitive to harmonics and well calibrated for this task specifically, but to avoid causing a plant shut down, existing CT's and VT's can be used.
2. The type of the data acquisition and data storage devices used for the harmonic measurements. Measuring devices receives samples from the system voltages and currents, and then it performs some analytical techniques on these values such as fast fourier transform (FFT) to get the harmonic content in the system voltage and current.

Harmonic measurements/ studies are required in the following cases:

a. Ensuring system compatibility with the international standards as IEEE STD 519-1992 [7] in order to meet the utility company requirements.
b. Solving a problem arising from a harmonics related issue (e.g. nuisance tripping of protection devices, telecommunication systems interference, overheating in transformers, motors, cables…etc).
c. Expansion of an existing electrical system by adding new harmonic sources (e.g. VFD's). According to IEEE

STD 399 [6], when the harmonic loads are about 30 % or larger from the system total plant loads, the harmonic impacts needs to be examined.

3. The analytical techniques used to analyze the measured data. There are two domains to analyze the harmonic contents, the frequency domain and the time domain. The frequency domain is used when the purpose of the study is checking the compatibility with the international standards. The time domain is used when a better understanding of the system wave shape and characteristics is required.
4. The presentation of the analyzed data.

Ref. [10] explains the problems caused by harmonic sources; the author categorizes the harmonic problems according to the frequency range of harmonics as follow:

1. The high frequency harmonics (from 5 KHz to 50 KHz). In this frequency range, the most common problems are the telecommunication systems interference, high "dv/dt" problems and notching problems. Notching or commutation notches are distortions in the system waveforms caused by short circuits occurring when a rectifier bridge is commutated. For example, a six pulse bridge gives six notches per cycle. Notching phenomena greatly affects the electrical devices operating by the "zero crossing principle" like many recent protection relays. In addition, the high "dv/dt" associated with the beginning and end of the commutation notches affects the electrical equipment insulation like generator's insulation.
2. The Fourier harmonics (from 150 Hz to 1500 Hz). These harmonics are the most important harmonics to be assessed, because their frequencies are near to the power system frequency (50 or 60 Hz). For many power systems applications, it is necessary to carry out the harmonics calculations between the 3rd and the 27th harmonics. These Fourier harmonics have many harmful effects on the power systems that can be summarized as follows:
   a. Overheating in generators, transformers, motors and cables.
   b. Parallel and series resonances resulting in over current and over voltage problems.
   c. Excessive shaft voltages and relevant bearing currents in motors, causing bearing damage for many induction motors fed from distorted supplies.
   d. Nuisance and mal-operation of metering devices and protective relays.
3. The low frequency harmonics below fundamental, (also called inter-harmonics or sub-harmonics). These harmonics are generated by large converters and they are not integer harmonics of the fundamental frequency.

In Ref. [11], the inter-harmonics are explained in detail. The term inter-harmonics covers a wide range of frequencies generated by converters that are not integer harmonics of the fundamental frequency. In majority of cases, the inter-harmonics appear where there are two AC systems running at different frequencies and joined together through some sort of DC link stations. The problem arises when the two systems are not perfectly decoupled through the DC link.

Ref. [12] provides an in-depth discussion on harmonic distortion in the industrial power systems especially, the petrochemical industry. It begins with a discussion on harmonics caused by saturable magnetic devices such as generators and transformers. Generation and control of harmonic voltages and currents produced in these devices are also covered. Then, a discussion on the generation and control of harmonic voltages and currents produced by power electronic devices such as (VSD's) and (UPS's) are deeply discussed. A case study of a petrochemical plant suffering from a harmonic problem and a harmonic mitigation technique are presented. Firstly, it explains the first category of harmonic sources which is the saturable magnetic devices such as power generators and transformers. Harmonics are due primarily created due to the iron core saturation. Due to the design of these equipment, the magnetizing current can be highly distorted and rich in third harmonic component. The third harmonics caused by iron saturation have been established since the adventure of magnetic circuits. Power engineers have dealt with and mitigated the problems of third harmonics through transformer connections and generator designs. Secondly, the author explains the second category of harmonic sources which is power electronics devices. Power engineers have spent years perfecting the generation of a sinusoidal voltage waveform for delivering power from the generating stations to the end users. With the dramatic increase in power electronic devices, more and more nonlinear loads are being placed on the power system. The petrochemical industry is no exception. Power electronic devices create harmonics by drawing power only during part of the voltage cycle. Some of the earlier electronic devices were simple power rectifiers converting power from AC to DC. These loads were created using half-wave or full-wave rectifiers. The power electronic devices have become more complex with the use of sophisticated power electronic switching devices such as thyristors and the IGBT. The latter allows many switching cycles within the normal 50 or 60 Hz power cycle. Some of the nowadays power electronic systems in the petrochemical industry include:

- UPS
- VSD
- large rectifiers
- Static VAR compensators

The third part of [12] discusses the harmonic problems and its effects on power system operation, summarized as follows:

- Over-Heating in motors and generators
- De-rating of power transformers
- Power cable problems
- Power Capacitor failures
- Unreliable operation of protection Relays

Ref. [13] shows that harmonic distortion is not a new phenomenon, concerning over harmonic distortion emerged during the early history of ac power systems. Widespread applications of power electronic-based loads continue to increase concerns over harmonic distortion. Harmonic problems have sparked research that has led to the nowadays' understanding of the power quality problems. The current drawn by electronic loads can be made virtually distortion-free (i.e., perfectly sinusoidal), but the cost of doing this is significant and is the subject of ongoing debate between equipment manufacturers and electric utility companies in standard-making activities. Two main questions often arise during these debates:

1. What are the acceptable levels of current distortion produced by nonlinear loads?
2. Who should be responsible for controlling harmonics, the end users or the utility companies?

The IEEE STD 519-1992 provides an excellent ground work to address both concerns.

Ref. [14] emphasizes that one of the main aspects of power quality is the harmonic related problems in power systems. A proper learning of harmonics is essential for power engineers to deal with these problems. This Ref. reviews the efforts made in teaching power system harmonics in undergraduate and graduate levels. Hardware and software tools have been developed in order to improve the teaching and learning processes. General aspects of these tools are presented as well as their educational methodologies. Conclusions, improvement ideas and future work lines are also introduced. A state of the art has been made in teaching power system harmonics in undergraduate and graduate levels. Although harmonic related problems have a great importance among power quality subjects, few studies have been found regarding teaching harmonics. Most of the reviewed works did not make a survey in order to evaluate the course or the tool proposed to enhance the teaching and learning processes. Software simulation tools are more appropriate than hardware tools for developing of the teaching and learning processes. Within the future work lines, there is a need for more comprehensive tools related to teaching harmonics. The reference indicates that most of the tools reviewed lack some detailed aspects of harmonics subject.

In Ref. [15], firstly power system harmonics sources are presented. Secondly, the impact and harmful effects of the harmonics on the power system are analyzed. Then the commonly used solution measure is proposed. Finally some applicable thoughts on the harmonic sources technological design are raised to prevent harmonic generation on power system. This reference highlights that the harmonic pollution has become a one of the major obstacles preventing electric power technology development. Therefore, it is necessary to strengthen protection measures, by reforming the harmonic source and installing the mitigation equipment to suppress the harmonics.

B. Harmonics Effects and Problems in Industrial and Petrochemical Facilities:

Ref. [16] highlights that the AC-supply voltage waveforms on offshore oil platforms can be heavily distorted during drilling operations. The harmonic and commutation distortion is caused by the drilling rectifiers which drive large DC motors. The authors examine a method of analyzing these disturbances, especially the commutation spikes that appear on the high-voltage bus bars (the point of common coupling) and are spread throughout the platform supplies. The analytical method uses proprietary computer aided design (CAD) software and equivalent-circuits to analyze the waveforms using a time-domain approach. The tool developed is thus used to show directly how the drilling and platform parameters will affect the current and voltage wave shapes. The effects of firing angle, rectifier rating, and platform short-circuit levels and cable capacitances among others are discussed. It is also shown that variable-speed drives have a similar effect. The consequence of sharing generation between platforms is illustrated and the use of damper circuits to reduce the commutation spikes as well. When drilling operations are carried out on offshore platforms, the AC-supply voltages are distorted at all voltage levels. The distortion takes two forms; first conventional harmonic distortion and second disturbances caused by the commutation process. A discussion of the possible problem caused by these commutation spikes has been deeply given in this work, including disturbances to computers, all types of controllers and possible longer term deterioration of insulation, especially in cables. It has been shown that it is possible to model these commutation disturbances using widely available CAD software. The various parameters in the circuit such as bridges, generator impedances and cables can be represented by their equivalent circuits. Using a time domain analysis package it is possible to calculate the exact wave shapes which will be expected in practice. The main difficulty is in getting realistic data of platform parameters. In particular, the value of damping at the oscillatory frequency will be important. The paper has also shown how different system parameters will affect the spikes and how future development could further solve the problem. The behavior with different values of short-circuit level is described and the variation of wave shape with firing angle and the number of converters on a given bus bar as well. Future developments are highlighted by examples of joining up platforms and the use of variable frequency drives.

Ref. [17] compares between two possible methods of evaluating power quality difficulties in petroleum terminals. It focuses on voltage and current harmonics caused by the application of (PWM) inverters, and addresses voltage dips and transients as well. Many users have questions about the application of (ASDs) and their impact on power quality relative to the IEEE STD 519-1992. This paper examines those questions and provides relevant analysis. The authors have selected a petroleum terminal application as a basis for evaluating power quality issues relative to ASDs. There are several power disturbances which can adversely affect the quality of power within a petroleum terminal. They are voltage dips, voltage spikes, and current and voltage harmonics. Petroleum terminal equipment and production may be directly affected by any or all of these conditions. This paper identifies and defines the condition as it may occur, quantify the condition, determine its relative impact on the overall system, and provide analysis. The intent is to use a petroleum terminal as a model to which other similar systems may be equivalently evaluated and resolved. When applying ASDs in petroleum terminals, special design considerations must be given to power quality issues. Power disturbances may adversely affect operating equipment which results in loss of production. This paper has described several of these disturbances including line dips, line spikes, and harmonics with provided analysis. Both Manual and computerized software solutions have been introduced. The manual calculation method, which follows the recommended IEEE STD 519-1992 may not be adequate to model complete petroleum terminal power systems due to the system complexity. The computerized software can model the complete petroleum terminal power system with great accuracy. The authors hope that their future work provide similar analysis on more complex power systems in other applications for further understanding of the issues presented in their paper. Perhaps a comparison can be made between actual field measurements and either the manual calculations or software modeling.

In Ref. [18], the medium voltage (ASDs) are assessed in detail. They have become more commonly used in industrial applications due to their ability to save owners money and improve product quality. In recent years, ASDs of all ratings have become more common in the petroleum industry because of their decreased cost, improved reliability, and demonstrated savings. The authors inform users how to select the correct size and install medium voltage ASDs. They address many of the problems that can be encountered when an ASD is installed in a power system. They cover ASDs for induction motors running at speeds no higher than 110% of their normal synchronous speed.

Ref. [19] indicates that energy management and efficient use of electricity are being promoted by most utilities in Canada and the U.S. In some cases, cash incentives are being offered toward conducting feasibility studies and project implementation when the energy paybacks are attractive. Results of a comprehensive study completed in July 1995 for a large Canadian utility, covering users' and manufacturers' experiences with medium-voltage (ASD's) for induction motors are presented. Thirty out of forty users, primarily from the petrochemical industry in the U.S. and Canada, participated in completing a detailed questionnaire and reported on 66 medium-voltage drives ranging from 800 to 10,000 hp. Information was gathered on the performance and reliability of the total drive system, including the motor, drive, driven equipment, isolation transformer, line filters, and selection criteria. Also, four manufacturers of medium-voltage drives provided information on their ASD system, technology, features, customer requirements, and future trends. This paper presents the analysis of the data gathered from both the users and the manufacturers. Based on the study findings, suggestions and recommendations are made to ASD manufacturers, users, and utilities.

Ref. [20] emphasizes that designing of medium voltage adjustable speed drive systems 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. Several loss mechanisms operate in converter-fed motors, and various steps can be taken in the selection of the converter and design of the motor to mitigate the losses. Temperature rise should be assessed during the factory acceptance tests to ensure that the motor will operate within the permitted temperature range. This is done either by calculation or testing. 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. Prevention of sparking requires special care in the selection and design of the frequency converter and motor. Bearing currents and shaft voltages are caused by the common mode voltage that arises between parasitic capacitances in the motor, an effect typical of converter-fed motors. A number of methods are available to mitigate this phenomenon. How to select the correct size and install medium voltage ASDs is demonstrated in this reference. A procedure is presented on how to validate the entire installation through computer simulation after the ASD has been selected.

Ref. [21] shows that extensive power system studies are required to confirm that the proposed electrical systems for new build industrial and petrochemical plants satisfy stringent design requirements. It outlines the load-flow, short-circuit, transient-stability and harmonic studies typically undertaken as part of the (FEED) of such a system. These are illustrated using as an example an LNG plant. Performed studies had verified the rating of the main equipment in the system SLD and ensured that circuit breaker ratings are adequate. Harmonic studies comprise of two steps; analyzing the harmonic sensitivity of the electrical network, followed by the harmonic penetration studies which assess the voltage and current distortion within the network. The IEEE STD 519-1992 detail commonly applied individual and total harmonic distortion limits. Networks with high distortion levels may be required to install harmonic distortion mitigation equipment. The predominant harmonic current sources within the electrical system of an LNG Plant will be the large variable speed drives for the LNG compressors. With increasing VFD compressor loads, the voltage at which to supply these drives is also increased.

Ref. [22], presents the challenges encountered when adding a new ethylene plant, a polyethylene plant, a cogeneration plant, and associated utilities to a major petrochemical facility located in Joffre, AB, Canada. It covers load estimation, power quality, reliability, common electrical specifications, and project coordination with several major engineering, procurement, and construction firms. It also highlights the unique design and utility interconnection challenges of building Canada's largest cogeneration plant (rated at 420 MW) within an existing petrochemical plant. The challenges include transmission system capacity and connection, fault levels, stability, and voltage regulation. Recommendations based on the learning experienced during the implementation of this project, to assist the reader faced with a similar major plant expansion are cited. A power quality study was carried out to determine the level of harmonics within the plant, ensure compliance with the utility requirements at the point of common coupling (PCC) at 138 kV, and meet the IEEE STD 519-1992 for harmonic guidelines. The study also identified whether harmonic resonance existed or not. The following assumptions have been made to carry out harmonic study.

1. The plant input data and system configuration are based on the load-flow study and short circuit study.
2. The mega volt ampere short circuit level is calculated at all buses without motor contribution.
3. The utility harmonic impedance profile is modeled based on the harmonic spectrum provided by the utility.
4. All ASDs are assumed running at rated load and rated speed for maximum harmonic generation.
5. The current spectrum for medium-voltage ASDs is based on measurements taken during factory acceptance tests rather than the typical published values.
6. The electric heaters are assumed not to produce any harmonics.
7. Typical harmonic spectrum is used for all existing DC drives.
8. The harmonic spectrums for all low-voltage ASDs are obtained from the manufacturers.
9. All linear loads at 600 V and 4160 V are combined where ASDs are connected.
10. Cable impedance at 13.8 kV and 138 kV is included.
11. The electrical demand for the existing plants is based on the utility power billing for the previous 12 months.

Ref. [23] indicates that the application of a large number of adjustable speed drives operating Electric Submersible Pumps (ESP's) on offshore platforms, connected to a limited electrical power system on a tanker feeding power to the platforms via subsea power cables, presents technical problems because of the involvement of high levels of harmonic distortions that, by experience, can impact the overall system reliability. Also the paper discussed the undersea cable effects on harmonics as it is well understood that any shielded cable system is electrically represented in a single phase circuit as a series of pie circuits. The shunt capacitance in each pie circuit represents the charging current of the cable. Effectively the undersea cable responds to the harmonics generated on the platforms in three ways according to the computer model as follows:

a. The low frequency harmonics tend to grow as they transverse through the cable. This can be further explained knowing that the 60 Hz voltage across a capacitor bank at the end of an inductive transmission line is larger than the voltage at the source.
b. The higher frequency harmonics are attenuated by the undersea cable because the capacitors become practically short circuited at these frequencies. Effectively, the harmonics stop amplifying and begin attenuating at the frequency when the impedance of the capacitance becomes somewhat less than the impedance of the series inductance if one pie circuit is isolated for this analysis.
c. The capacitance in the undersea cable creates a system parallel resonance at some frequency depending on the system inductance such as the number of generators on line. In this project the overall effective capacitance of the cable was minimized by adding extra insulation thickness which also provides a safety margin to the system.

Ref. [24], Indicates that the electric utilities, electric manufacturers and consumers have become more concerned about power quality due to the prevalent application of nonlinear loads such as electronic devices, saturable equipment and arcing devices. The growing use of power electronic applications has increased the fraction of nonlinear loads and hence the fraction of non-sinusoidal currents and voltages in utility networks. These applications include power converters, switch-mode power supplies, (UPS), and (ASD). The unwanted effects of power system harmonics are well documented. As the fraction of nonlinear load has increased, so has the anxiety over the effect of these loads and whether they should be limited. Several international organizations have issued limits on power harmonics. The limits are based on the effects of these loads and the best judgment of the members of the standards organizations. Electric utility companies, which usually have the responsibility of maintaining low voltage distortion, may not know the locations of the distorting loads. If sufficient measurements are taken, the utility may estimate the most likely locations and possibly find a solution to the problem. In this reference, authors introduce a preliminary survey of harmonic levels within the Saudi Arabian power network with industrial facilities. The major industries are petrochemical related and a number of arc furnaces. The voltage and current harmonic levels are within the IEEE STD 519-1992. The results indicate a growing level of harmonics as more and more petrochemical industries are connected to the network.

Ref. [25] focuses on the fact that the concern about power quality is continuously increasing, due to the industry automation and use of nonlinear devices that have been introduced to the power system. These nonlinear control devices or loads may cause harmonics or distortions to the current waveform. Such distortions will cause malfunction to the sensitive devices such as metering instruments, on-line process analyzers, and measuring devices thus false readings may be displayed. These false readings are going to affect the operation of the plant and may cause shut down and large monetary losses. The paper outlines the subject of harmonics and conducts and demonstrates harmonic study on a petrochemical company power system in Saudi Arabia. The study ensures that the harmonic flows between different buses are within standards for industrial plants, and emphasizes that the plant can be safely operated from the harmonics effects point view. Also, it determines the THD values, and conducts mitigation if high THD, TIF values obtained are beyond of recommended practices recommended by the IEEE STD 519-1992.

In Ref. [26], the procedure for calculating optimum controller parameters of the Active Power Filters (APFs), which are implemented into a multi-bus industrial power system for harmonic voltage mitigation, is presented. The node voltage detection control strategy is applied and the optimum controller parameters are found by solving the multiple (APF) harmonic problem. Thus, the best places for several (APFs) may be proposed, taking into account also a real control strategy as well as (APF) controller parameters.

Ref. [27] indicates that offshore oil rigs use large DC drives, usually fed from AC utility services through AC/DC converters, thus distorting current and voltage waveforms. Passive filters have been very effective solution for the harmonic mitigation as well as reactive VAR compensation. However, improper choice of filter components may lead to severe voltage and current stress to power system components or even sometimes may further deteriorate the power quality. The paper describes an effective design procedure of passive filter to mitigate power system harmonics of a typical offshore oil rig. It concludes 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. Moreover, there was no chance for parallel resonances.

C. Harmonics Effects on Induction Motors:

In Ref. [28], the behavior of a 7.5 kW high efficiency cage induction motor fed by distorted supply has been investigated. Experimental data were collected by developing a testing facility consisting of a three phase harmonic generator, a double chamber calorimeter, and a PC based data acquisition system. Motor additional losses due to the presence of harmonics were estimated using the calorimetric method. It has been shown that a distorted voltage containing low order harmonics causes more losses in the motor as compared with the high order harmonics. Accordingly, weighted THD (WTHD) has been defined to specify the limits for additional losses in a motor supplied by distorted voltages. The variation of test motor parameters with harmonic order as well as the variation of additional losses with WTHD has led to de-rating of the test induction motor. The effect of supply voltage distortions has been investigated on several induction motors with different power ratings has been examined. It has been demonstrated that with a service factor of 1.15, most induction motors are capable to handle distorted voltages as defined by standards.

D. Harmonics Effects on Distribution Networks:

Ref. [29] shows that the Electric utilities have been committed to supply their customers with reliable power, taking into account that the customer satisfaction is the cutting edge in the competitive environment. However, the number of nonlinear loads is increasing due to the development of electronics in equipment. Consequently, utilities are faced with the risk that the permissible levels defined in the standards could be violated on a number of their networks. That brings the quality of supply at the top of utility strategies in a more structured way than in the past. The Ref. presents some aspects of the power quality program in Alexandria-Egypt, program that was started since 2000. The purpose of this program is to review the overall scheme of voltage quality through extensive monitoring. Such monitoring system yields a massive database of service quality data. The paper also presents 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 that are calculated using data collected from the program. The information in this research has crucial importance in supporting issues about quality service regulations for customer's satisfaction.

Ref. [30] indicates that the harmonic distortion in the power system is increasing with wide use of nonlinear loads such as wave rectifiers, and solid-state controlled devices. Thus, it is important to analyze and evaluate the various harmonic problems in the power system and introduce the appropriate solution techniques. Firstly, they analyze the propagation of harmonic current and voltage in power system networks and appreciate their consequences on both utility system components and end user equipment. Throughout wave analysis of the harmonic wave forms and the concepts of cancellation and combination, effective techniques have been introduced via the application of phase shifting transformers. Besides, other alternatives to mitigate harmonic effects on the system components utilizing harmonic filters are given. The merits of the introduced techniques were highlighted through a study case using Electrical Transient Analysis Program (ETAP) computer package.

Ref. [31] states that the assessment of the harmonics found in the electrical distribution system of several buildings in the three department of energy in Oak Ridge plants in Tennessee has yielded several conclusions useful in the design of electrical distribution systems. A preliminary survey to determine where significant amounts of harmonic currents or voltages existed in the distribution system was performed at several buildings by comparing readings taken with true root-mean-square (RMS) multi meters and averaging multi meters (non-true RMS meters). From these measurements and subsequent calculations, facilities that appeared to have significant levels of harmonics present were analyzed with a harmonics power analyzer that could record waveforms and give the spectrum and magnitude of harmonics. Sample waveforms are illustrated and drawn for nonlinear loads including fluorescent lighting (both magnetic and electronic ballasts), variable frequency drives, switch mode power supplies, and uninterruptible power supplies. A discussion of how various harmonic waveforms come about as a result of these nonlinear loads is also outlined.

In Ref. [32], it is clearly shown that the two major problems in the electrical industry today are sagging and swelling of line voltage and harmonic currents. Voltage sagging and swelling may result in equipment malfunction and shut down. Harmonics also affect the electrical equipment to fail and deteriorate the waveform of the current. To mitigate the voltage sags and swells, uninterrupted power supply was used. But uninterrupted power supply is an example of nonlinear load which creates harmonics in the power system. Active power filters were used to eliminate the harmonics in the system. This study aims to create three models of active power filters that compensate the harmonics, mitigate the voltage sags and swells, and also correct the power factor. The models were simulated to know which of the three active power filter models gives the best performance. The simulation tools that were used in this study were MATLAB/SIMULINK and TINA PRO softwares. Based on their results, the active power filter models compensate the harmonics, mitigate the voltage sags and swells, and correct the power factor of the system.

E. Harmonics Mitigation and Modeling Techniques:

Ref. [33] represents that nowadays, power electronics are widely used in industry for supplying loads with amplitude and frequency controlled voltage. These systems comprise mainly rectifiers and inverters which, as nonlinear loads, produce currents with high harmonic content. In order to fulfill the legislation concerning voltage harmonic distortion, it is necessary to put in place corrective actions. Among these corrective actions, active filters are one of the most effective solutions. For the design of these filters, simulation has been proved to be a very useful tool. In this paper, the simulation using MATLAB/ SIMULINK of an active filter for the reduction of the harmonic distortion is analyzed. Two examples are presented; a steel plant and an underground traction system. The main requirement of any electric power system is the supply of electricity with a determined power quality and reliability to the minimum possible cost. Due to the increased quality of life, it has taken place a spectacular increase of the number and installed power of nonlinear loads, especially of electronic devices used mainly in the control of systems and power hardware. Depending on the nature of these loads, the distortion created can be very high and affect the voltage supplied by the distribution network. In this case, it is highly possible that other loads served from the same network will be affected. For regulating this situation, a complete legislation exists at national and supranational levels concerning voltage harmonic distortion. To comply with legislation, corrective actions have to be taken to reduce harmonic distortion to established regulated levels. Among the possible corrective actions, as mentioned before, active filters are one of the most effective. Before taking any corrective action, it is necessary to evaluate the distortion introduced by the installation into the distribution network and the expected reduction when the active filter is in use. In this stage, simulation has been proved to be a useful tool. It allows quantifying the harmonic distortion created by a system and, when a corrective action is introduced, simulation will show the reduction in the distortion. Besides, simulation can be used as a tool for the design of the active filter. As a summary conclusion, the use of simulation tools of MATLAB/ SIMULINK, allows to reproduce the behavior of the power systems in different situations, analyze how the system answers in these situations and choose 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 have been obtained. Moreover, the reduction of the distortion by the used active filter has been simulated for both systems.

From the authors' point of view, Ref. [34] is considered an excellent reference for comparing between modern active filters and traditional passive filters. Unlike traditional passive filters, modern active filters have the following multiple functions; 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. Significant cost reductions in both power semiconductor devices and signal processing devices have inspired manufactures to put active filters on the market. This Ref. 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. Active filters based on leading-edge power electronics technology can be classified into pure active filters and hybrid active filters. The reader may ask the following simple question in his/her mind, "Which is preferred, a pure active filter or a hybrid active filter?" Fortunately or unfortunately, engineering has no versatile techniques in terms of cost and performance, and it is based on a compromise or a trade-off between cost and performance. Therefore, a comprehensive answer of the author to the question depends strongly on the function(s) of active filters intended for installation. A pure active filter provides multiple functions such as harmonic filtering, damping, isolation and termination, load balancing, reactive-power control for power-factor correction and voltage regulation, voltage-flicker reduction, and/or their combinations. A cluster of the above functions can be represented by "power conditioning" Hence, the pure active filter is well suited to "power conditioning" of nonlinear loads such as electric AC arc furnaces, and utility/industrial distribution feeders. On the other hand, a hybrid active filter consists of an active filter and a single-tuned filter that are directly connected in series without transformer. This hybrid filter is exclusively devoted to "harmonic filtering" of three-phase diode rectifiers, because it has no capability of reactive-power control from a practical point of view although it has from a theoretical point of view. Some manufactures have already put active filters for power conditioning on the market. However, they should strive for cost reductions, as well as better filtering performance and higher efficiency, to compete well with traditional passive filters. In addition to the harmonic guidelines or recommendations, sincere efforts by the manufactures would accelerate installation of active filters in the vicinity of nonlinear loads. This in turn would bring greater cost reductions to the active filters due to the economy of large-scale production. Constituting such a positive feedback loop would encourage wide acceptance of the active filters, resulting in solving harmonic pollution and improving power quality.

Ref. [35] introduces a practical case study of harmonic problem which is the resonance phenomena and introduces the optimum solutions to mitigate this problem. For the aluminum company at Nag-hammady in Egypt, resonances are detected for all expected operational conditions. Harmonic filters are designed, and suggested to be installed, and resonances due to expected switching of those filters are found. Finally methods of harmonic resonance prevention technique in that company network are applied and their effectiveness has been proved. It is shown that the application of such techniques will assure continual service for that important company, together with saving of equipment and rectifiers damaged yearly by those harmonic resonances. The severest harmful effect of harmonics on power system is the harmonic resonances, arising from the presence of harmonic currents of high frequencies and network reactances at those harmonic frequencies. Harmonic resonances cause damages in networks, rectifier bridges, devices, protection relays, controllers, measuring instruments and harmonic filters. Because of those harmonic resonances, huge economic deficiencies are suffered by industrial firms, power systems facilities and utilities. Moreover, harmonic resonances can occur at any time and at unexpected periods as they can occur by any manipulation in the external connected systems or by routine switching or separations of shunt or series capacitors or of static VAR compensators. This is why studies of harmonic resonances become essential and very important and this is why harmonic resonances are the main objective of this reference. The authors 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, is the first goal of their research. Harmonic filters are designed for the aluminum company at Nag-hammady firm and harmonic resonant and anti-resonant frequencies are detected for various operational conditions, together with the influences of the passive filters, once they will be installed. Damping effect of the new developed active filters is suggested for eliminating the harmonic resonances in order to avoid damages, service interruptions and to save the economical deficiencies in that important national firm in Nag-Hammady, Egypt.

Ref. [36], presents 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. With the use of variable speed drives incorporating sinusoidal rectifiers there exists the possibility that the PWM-modulated voltage of the sinusoidal front end or network rectifier, could be modulated to inject harmonic current into the network. This would allow compensation of harmonic voltage distortion caused by other nonlinear loads already connected to the same busbar. The use of a commercially available variable speed drive and modifying its rectifier to be a sinusoidal rectifier is described. This modification derives the line current references and performs further analysis on it to compensate for the 5th and 7th harmonic current distortion. The method by which the harmonic current references are determined and the method by which they are controlled are presented in detail. The concept of using mains voltage distortion at the point of common coupling as feedback is justified.

Ref. [37] indicates that problems associated with harmonic distortion are well understood for many power system applications. However, finding the right solution is challenging. Special considerations for applying capacitors on a power system with harmonics have been discussed. Issues such as applying a single medium voltage capacitor or filter versus multiple low voltage banks are evaluated. Finally, opportunities for improving energy efficiency using harmonic technologies are explored. The general discussion of their work deals with standard considerations when dealing with typical harmonic producing loads in commercial and industrial power systems. Regarding harmonic problems, the bottom line is expressed as:" Harmonics are not a problem unless they are a problem". Just because you have harmonic currents flowing in your system and you are measuring voltage distortion, you don’t necessarily have a problem. Very often, harmonics issues are raised because the levels have exceeded the IEEE STD 519-1992 recommended limits somewhere in a power system. It is fact that is most equipment can withstand harmonic distortion levels well above these conservative recommended limits. Harmonics are interesting and can be problematic but often are blamed for problems with no real proof. Take the time to learn about harmonics and how power systems and equipment are actually affected and you’ll save yourself a lot of trouble and certainly a lot of money! How do you know you have a problem? The only way to know is to identify symptoms of harmonics. Very often, if you recognize specific symptoms of harmonics, the problem has already created issues on your power system. The trick is to recognize potential symptoms and identify potential harmonic issues before they occur or to implement correction into the system design. Sometimes modeling and simple calculations will help identify the issues before they become a problem. Symptoms of harmonic problems can be divided into four major areas: equipment failure and mal-operation, economic considerations, application of power factor correction capacitors, and other issues. The following symptoms are examples of equipment failure and mal-operation associated with harmonics on a power system:

a. Voltage notching
b. Erratic electronic equipment operation

c. Computer and/or PLC lockups
d. Overheating (motors, cables, transformers, neutrals)
e. Motor vibrations
f. Audible noise in transformers and rotating machines
g. Nuisance circuit breaker operation
h. Voltage regulator malfunctioning
i. Generator regulator malfunctioning
j. Timing or digital clock errors
k. Electrical fires

The following are economic considerations that should be evaluated with regard to harmonics:

a. Losses/inefficiency (motors)
b. kW losses in cables and transformers
c. Low total power factor
d. Generator sizing considerations
e. UPS sizing consideration
l. Capacity concerns (transformers, cables)
f. Utility imposed penalties

Applying power factor correction capacitors requires special considerations with regard to harmonics such as:

a. Capacitor failures
b. Fuse or breaker (feeding capacitors) nuisance tripping
c. Calculated or measured harmonic resonance conditions (series or parallel resonance)

Other significant issues are typically raised with regard to harmonics. Interestingly, these issues are often not real problems but rather hype created by a lack of understanding of harmonics. Many harmonics problems are because of specification issues, rather than real problems, such as the following:

1. Metering – do you really have a problem or did you just install a new meter that can show you the waveform and it "looks like" you should have a problem?
2. Marketing based upon a product specification – do you even have a problem or is somebody scaring you into believing that a problem exists so you buy their product?
3. Specifications writers "who shall follow IEEE- 519…" While IEEE STD 519-1992 is a recommended practice (note that the key word is "Recommended"), some thought must be given to the practical side of the standard. In addition, applying the IEEE STD 519-1992 limits at other locations in the power system (other PCC) is often costly or problematic. Each one of these symptoms or issues could be discussed in its own technical paper but suffice it to say that the magnitude of the "cost" of these symptoms is typically proportional to the complexity and cost of the solution.

In Ref. [38], various harmonic sources, their effects on common power system and well known equipment are presented comprehensively. Some methods are introduced to suppress low order harmonics. Their results are obtained and discussed. In general, the method of increased pulse numbering, passive filtering, active filtering, and alternative methods are discussed. A comparative study is performed based on their ease of application, economic aspects, and effectiveness. The study is expected to yield recommendatory suggestions for specific usages and their merits and difficulties.

Ref. [39], proposes a hybrid active filter for damping of harmonic resonance in industrial power systems. The hybrid filter consists of a small-rated active filter and a 5th-tuned passive filter. The active filter is characterized by detecting the 5th harmonic current flowing into the passive filter. It is controlled in such a way to behave as a negative or positive resistor by adjusting a feedback gain from a negative to positive value, and vice versa. The negative resistor presented by the active filter cancels a positive resistor inherent in the passive filter, so that the hybrid filter acts as an ideal passive filter with infinite quality factor. This significantly improves damping of the harmonic resonance, compared with the passive filter used alone. Moreover, the active filter acts as a positive resistor to prevent an excessive harmonic current from flowing into the passive filter. Experimental results obtained from a 20 kW laboratory model verify the viability and effectiveness of the hybrid active filter proposed in this reference.

F. Acceptable Harmonics Limits and Compliance with the IEEE 519-1992 Standards:

The IEEE 519-1992 [7] provides useful recommended practices for harmonics control in the electrical networks, accordingly it is widely used in the industrial sector and many consultants use the limits indicated in it as contractual limits within their specifications. There exist some other specifications like the IEC 61000-3-2 [40] which specifies the current harmonic limits for low voltage equipment that has an input current less than 16 Amp, but these standards are not commonly used in the industrial sector because they are focusing on individual harmonic sources like VFD's and do not set limits on the overall distribution network. In 2008, the IEC 61000-3-6 [41] specification was published and it performs an assessment of the harmonic emission limits for distorting loads in medium voltage and high voltage power systems but up till now, this specification is not widely used in the industrial sector because it is newly created.

Ref. [41] mentions that in 1973 two events occurred that changed the way that utilization equipment is applied on industrial power systems. The first was the oil embargo that increased the cost of energy; and the second was the coming of age of adjustable speed drives using static power converters. To minimize electrical energy costs, which are made up of demand and kilowatt-hour charges, users began to apply capacitors to their systems to lower the demand charges from utility companies. With the increased use of static power converters that require harmonic currents from the power system, the stage was set for trouble. The static power converter committee of the industry applications society recognized the potential problem and started work on a standard that would give guidelines to users and engineer-architects in the application of static power converter drives and other uses on electric power systems that containing capacitors. The result was IEEE STD 519-1981, IEEE guide for harmonic control and reactive compensation of static power converters.

Ref. [42] presents typical case studies reported in this paper addressing the application of the IEEE STD 519-1992 guidelines to mitigate harmonics. The study discusses possible techniques to mitigate harmonics generated by nonlinear loads, especially (VFDs) that are also known as (ASDs). The paper shows how one can apply IEEE STD 519-1992 within an industrial or commercial environment to minimize the effect of harmonics on the electrical system in a given plant. It is shown that the IEEE STD 519-1992 methodology can be applied at the point where a nonlinear load (ASDs in particular) connects to the AC power system. This would lead to solving harmonic problems within a facility in addition to making sure the IEEE STD 519-1992 are being met at the point of utility metering. Test results showing the performance of a new passive filter configuration, which reduces the harmonic currents being injected back into the power system network to meet IEEE STD 519-1992 at the input terminals of the ASD, are also presented.

Ref. [43] emphasizes that the IEEE STD 519-1992 engineering recommendations is possibly one of the most well-known and widely used documents in the power quality area. The objective of the recommendation is, however, many times misunderstood and consequently erroneously interpreted and applied. This panel reviews and discusses common misinterpretations and distortions in the application of harmonic distortion recommendations with particular reference to IEEE STD 519-1992. The panelists will attempt to clarify several different issues and misconceptions related to parameters, point of application, and nature of the recommendations. The issues will be presented and discussed in a contrasting approach. Suggestions are then made for improving the implementation of these engineering recommendations.

Ref. [44] states that the IEEE STD 519 was first introduced in 1981 to provide direction on dealing with harmonics introduced by static power converters and other nonlinear loads so that power quality problems could be averted. It is being applied by consulting engineers and enforced by utilities more frequently in recent years as the use of variable frequency drives and other nonlinear loads has grown. Two of the most difficult aspects of applying IEEE STD 519 are

i. Determining an appropriate point of common coupling (PCC).
ii. Establishing a precise average demand current during the design stage.

This is because the standard does not provide a concise definition of the PCC and the recommended definition of demand current is a value that can only be determined by measurements taken after installation. The paper represents the authors' best interpretation of IEEE STD 519. It attempts to provide clarity in the determination of the PCC and offers a means by which IEEE STD 519 can be applied at the design stage when the precise demand current is unknown.

Ref. [45], highlights that Saskpower's electric system, like that of many utilities in North America, is increasingly experiencing harmonic distortion problems. SaskPower has adopted harmonic limit standards along the guidelines proposed in the IEEE 519-1981 standard and revised in the IEEE 519-1992. These limits are discussed and a detailed method is given to evaluate a customer's installation. Two example cases are presented including the evaluation of a gas pipeline compressor station installation and an oil field installation.

References [47-49] indicate that the IEEE STD 519-1992 is a useful document for understanding harmonics and applying harmonic limits in power systems. Despite many years of good use, there is still some confusion about how to apply certain aspects of the standard such as the definition and location of the point of common coupling PCC. There is considerable debate about precisely how some elements of IEEE STD 519-1992 should be interpreted. Also the various topologies of the variable speed drives are addressed from the compliance with the harmonic limits point of view.

V. CONCLUSION

Power system harmonics, nowadays, cause many problems like equipment failures, mal-operations and plant shutdowns accordingly mitigation of these harmonics is considered an important target especially for the industrial applications where any small downtime period may lead to great economic losses. This paper presents an extensive literature review in the petrochemical sector for the power system harmonics such as the harmonics fundamentals, effects, mitigation techniques and distortion allowable limits. It is clear, from the existing literature, that harmonics sources, analysis, effects, and mitigation still need further research.

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