INDUSTRIAL AND COMMERCIAL POWER SYSTEM HARMONIC STUDIES

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Abstract -- This paper reviews the latest IEEE Std. 3002.8 “Recommended Practice for Conducting Harmonic Analysis Studies of Industrial and Commercial Power Systems”. The standard is based on IEEE Std. 399 (Brown Book) with many new enhancements and additions. The new standard systematically addresses requirements and recommendations for performing power system harmonic studies, including developing system models, modeling various harmonic sources and electrical equipment and devices, preparing required data for modeling and studies, validating model and data, selecting study cases, and analyzing results and outputs from the studies. Necessary features for computer tools that are used to perform harmonic-analysis are listed and discussed. The latest IEEE Std. 519-2014 “Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems” is referenced in the standard, as well as references related to interharmonics. One illustration example is provided at end of the paper to help readers further understand harmonic studies and expected results. The author of this paper is the co-chair of IEEE Std. 3002.8 working group.

Index Terms — Industrial and commercial power systems, Power system analysis and computing, Harmonics, Harmonic distortions, Harmonic limits, Harmonic modeling and study.

I. INTRODUCTION

Devices with nonlinear voltage-current characteristics generate harmonics. The main sources of harmonics in industrial and commercial power systems are static power converters used as rectifiers for various industrial applications such as adjustable speed drives (ASD), uninterruptible power system (UPS), chargers, switched-mode supplies, static frequency converter, cycloconverters, etc. Arc furnaces and saturated magnetic devices are also harmonic sources. A sample industrial power system with multiple harmonic sources is depicted in Fig. 1.

Since nonlinear devices represent an ever-increasing percentage of the total load in industrial and commercial electrical power distribution systems, harmonic studies become an important part of overall system design and operation. By modeling power system impedances as a function of frequency and harmonic sources as injecting currents or forced voltages, a harmonic study can be made to determine the level and effect of the harmonic distortions in the power system.

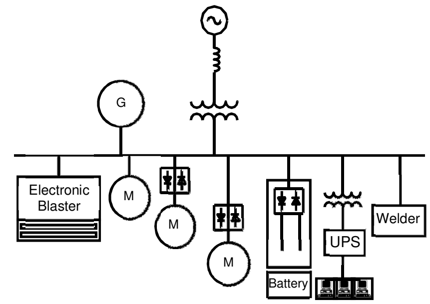


Fig. 1. Sample industrial power system with multiple harmonic sources

After twenty-one years, IEEE recommended practice for conducting harmonic study in industrial and commercial power systems has been updated. The previous standard was IEEE Standard 399 “IEEE Recommended Practice for Industrial and Commercial Power Systems Analysis (also known as Brown Book)” [1], published in 1997. Per IEEE decision, Chapter 10 of the Brown Book “Harmonic analysis studies” is converted into an independent dot standard of IEEE Standard 3002.8 “Recommended Practice for Conducting Harmonic Analysis Studies of Industrial and Commercial Power Systems” [2]. The new standard provides detailed practice on how to conduct harmonic studies and analysis of industrial and commercial power systems. It discusses basic concepts for harmonic study, the need for the study, required data for analysis, study methodologies, recognition of potential problems, corrective measures, and benefits of using a computer as a tool in a harmonic-analysis studies.

II. MAIN CHANGES IN NEW STANDARD

3002.8-2018 standard is based on previous IEEE Standard 399 “IEEE Recommended Practice for Industrial and Commercial Power Systems Analysis” (Brown Book), published in 1997.

Chapter 10 “Harmonic analysis studies” of the Brown Book has 48 pages, and 3002.8-2018 contains 76 pages.

Comparison of contents between Chapter 10 of the Brown Book and 3002.8-2018 are listed in TABLE I:

TABLE I
COMPARISON OF CONTENTS

IEEE Std. 399-1997 (Brown Book)	IEEE 3002.8-2018
n/a	Scope
n/a	Normative references
Introduction	Introduction
Background	Background

Purpose of harmonic study	Analysis objectives
General theory	Methodology and standards
System modeling	System simulation and modeling
n/a	Required data
n/a	Data collection and preparation
n/a	Model and data validation
n/a	Study scenarios
n/a	Solution parameters
n/a	Results and report
n/a	Features of analysis tools
Example solutions	Illustration examples
Remedial measures (filters)	(included in System simulation and modeling)
Harmonic standards	(included in Normative references)
References	(included in Bibliography)
Bibliography	Bibliography

As can be seen from Table I that 3002.8-2018 adds several new sections of required data for studies, recommendations to prepare and validate model and data, discussions for study cases, and illustrations of study results and report. It is the intention of the standard to provide complete guidelines for engineers to understand detailed procedures and necessary steps to prepare system models and data to perform harmonic studies.

In addition to the new sections, 3002.8-2018 also addresses a number of important issues including a discussion on interharmonics and its modeling for studies, the latest IEEE Standard 519 "IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems"[3] recommended harmonic limits at the interface of an industrial or commercial facility to the grid, and some useful features such as analyzer and visual presentations to study results in computer software which can greatly assist engineers in studies. Comparing to the Brown Book there is one sample study case, 3002.8-2018 provides three illustration cases which include the original case from the Brown Book and two new cases, the second case of 13-bus balanced industrial distribution case from IEEE PES Task Force on Harmonics Modeling and Simulation, and the third case is a composite industrial power system.

III. OBJECTIVE AND METHODOLOGY

The new standard discusses objectives to perform harmonic studies, benefits for the studies, and methodology (approach) to conduct the studies in different phases of a system.

A. Objectives

The standard lists following situations that may necessitate a harmonic study:

1. To comply with IEEE Std 519, which defines the current distortion limits a user should meet at the Point of Common Coupling (PCC) with the utility
2. To evaluate impact on the system due to utility voltage harmonic distortion specified in IEEE Std 519
3. To investigate root causes of a system with history of harmonic-related problems, such as failure of power-factor compensation capacitors, overheating of cables, transformers, motors, etc., or misoperation of protective relays or control devices
4. To plan and simulate a system expansion where significant nonlinear loads are added or where a significant amount of capacitance is added
5. To design a new facility or power system where the load flow, power factor compensation, and harmonic analyses are considered as one integrated study

B. Benefits

Reasons and benefits to conduct harmonic-analysis studies on industrial and commercial power systems include:

1. Benchmark existing system and collect data to calibrate the model by measuring the existing system with a well-defined test plan
2. Identify location, type, and magnitude of harmonic sources in the system
3. Simulate impacts of these harmonic sources on system voltages and currents
4. Study harmonic penetrations to the system
5. Calculate voltage and current harmonic distortions on each individual frequency and Total Harmonic Distortion (THD)
6. Check if there exists any violations in harmonic voltage and current distortion levels
7. Calculate other harmonic indices and compare them to the standard or code limitations
8. Investigate if the system has parallel or series resonance conditions
9. Design harmonic filters and test harmonic filters
10. Test transformer phase shift and analyze its effects on harmonic current cancellation and harmonic distortion deduction
11. Test other harmonic mitigation designs and performance

C. Methodology

Based on differing phases of a power system, the methodology of conducting harmonic study has different focus.

1. Design phase

During system design phase, the following factors are to be considered in the study:

a) Model harmonic sources from nonlinear loads and powered electronics devices, simulate their impacts, and assess harmonic voltage and current distortion levels
b) Calculate harmonic distortion indices for both voltage and current
c) Compare distortion levels and harmonic indices with the standard and code limits to see if there are any violations
d) Identify system parallel or series resonance frequencies
e) Check if there are any harmonic source frequencies at or near the system parallel

resonance points

f) If there are harmonic source frequencies at or near the system parallel resonance points, assess the overvoltage conditions at these frequency points

g) If there are harmonic source frequencies at or near the system series resonance points, assess the overcurrent conditions

h) If necessary, design and test harmonic mitigation methods such as:
   - Install harmonic filters to reduce the harmonic distortion levels and shift resonance frequencies to less harmful regions
   - Use transformer phase shift to cancel harmonics and obtain overall harmonic distortion reduction

i) Simulate the final system for overall harmonic voltage and current distortions after harmonic mitigations are implemented

2. Operation phase

For systems in operation phase, harmonic-analysis studies should be done to simulate various operating conditions and configurations to verify if there are any excessive harmonic distortions and harmful parallel resonances under all possible operating conditions.

3. Expansion phase

If an existing system is to be expanded, harmonic-analysis studies should be performed to model and simulate system changes and prevent harmonic distortion deterioration and new parallel resonance and overvoltage situations which could be introduced by new harmonic sources added to the system and system impedance changes due to new configurations.

IV. HARMONIC SOURCE MODELING

Harmonic sources are the reason why harmonic studies need to be done. Depending on their types, harmonic sources can be presented as characters harmonics or interharmonics. From system modeling point of view, harmonics generally are represented as injected currents to the system.

A. Types of Harmonic Current Sources

Most harmonic sources present themselves to the rest of system as current sources. Based on non-linear device characteristics, harmonic current sources can be modeled differently.

1. Characteristic harmonics

Harmonics generated by pulse converters are well-known. The magnitude of the harmonic current is given by [1]:

$$I_h = \frac{I_1}{h} \quad (1)$$

where

I_1 is the fundament current

h is the harmonic order given by $h = mp \pm 1$

and

m is an integer

p is the number of pulse

A sample of harmonic current spectrum from a 6-pulse ASD at 480 V is measured and listed in the Table II. A more popular presentation of harmonic content is using a spectrum for harmonic magnitude which is shown in Fig. 2 for the same harmonic source in TABLE II

TABLE II
HARMONIC SOURCE DATA FOR ASD

Harmonic order	Magnitude (%)	Relative angle
1	100.00	0.00
5	18.24	–55.68
7	11.90	–84.11
11	5.73	–143.56
13	4.01	–175.58
17	1.93	111.39
19	1.39	68.30
23	0.94	–24.61
25	0.86	–67.64
29	0.71	–145.46
31	0.62	176.83
35	0.44	97.40
37	0.38	54.36

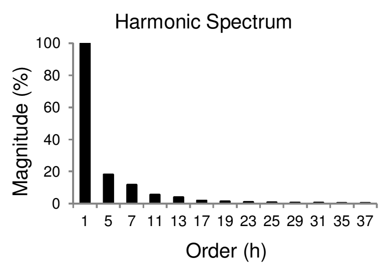


Fig. 2. Harmonic magnitude spectrum

2. Interharmonics

Some devices and equipment in power systems can generate currents that contain components that are non-integer multipliers to the fundamental frequency. These components are called interharmonics. Devices and situations that can result in interharmonics in industrial and commercial power systems are cycloconverters, ASDs, arc furnaces, and loads that do not pulsate synchronously with the fundamental power system frequency, etc.

Interharmonics generated from these devices and situations can be expressed in Eq. (2):

$$f_i = (mp_1 \pm 1)f_n \pm np_2 f_z \quad (2)$$

where

f_n is the system fundamental frequency

f_z is the modulation frequency that is converter/ASD output, or load fluctuation frequency

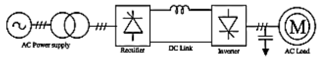
p_1 is the converter/ASD rectifier number of pulse

p_2 is the converter/ASD inverter number of pulse

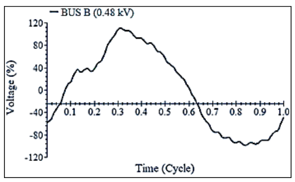
m = 0, 1, 2, 3…

n = 1, 2, 3…

The phase sequence of interharmonics requires special attention to determine, because it is important in harmonic power flow studies. Details on interharmonics, their origin, phase sequence, and special issues in harmonic-analysis are found in reference [5]. Fig. 3 shows a sample voltage waveform from studies resulting from interharmonic current sources.



(a) ASD configuration



(b) Waveform including interharmonics

Fig. 3 Interharmonics from an ASD

B. Harmonic Source Modeling

Harmonic currents from nonlinear devices can be acquired by one of the following options:

1. Obtain the harmonic spectrum of the source from the equipment manufacturer (This is particularly important in cases where new technology or non-standard equipment is applied)
2. Calculate the generated harmonics by analytical methods where possible
3. Use computer simulation software that simulates the operation of the power electronics circuit to generate harmonic spectra and waveforms
4. Apply typical values based on similar applications or published data

It should be noted that on-site harmonic measurements may not yield the worst-case harmonic spectrum, depending on the equipment operating modes. Usually, the worst operating condition needs to be determined, and the design should be based on the "worst-generated" harmonics case. It needs to be recognized that even with the "worst-generated" harmonic case, the harmonic flows within different elements of the network can be different, depending on system configuration. This necessitates that the "worst-generated" case at the "worst-operating" case(s) must be analyzed.

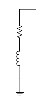
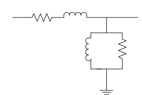
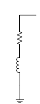
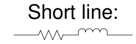
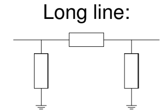
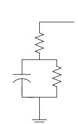
When multiple harmonic sources exist in the same system, phase angles between the harmonics of the same order can change study results. Determination of phase angles of harmonics can be quite complex but should not be ignored

For unbalanced three-phase systems, it is desirable to determine the harmonics generated in all three phases.

V. NETWORK MODELING

Modeling each power system component and device must be properly done in harmonic studies. TABLE III gives a summary for modeling of the most common power system components. Other system components should also be modeled with necessary frequency adjustments.

TABLE III
POWER SYSTEM COMPONENT MODELS FOR HARMONIC-ANALYSIS

Component	Equivalent circuit model	Model parameters
Rotating machine		$R_h = R\sqrt{h}$ $X_h = hX_2$, or $X_h = \frac{(X''_d + X''_q)}{2}$ R is machine resistance derived from the machine power loss at fundamental frequency X_2, X''_d, and X''_q are machine negative sequence reactance, d-axis subtransient, and q-axis subtransient reactance, respectively
Transformer	 Shunt can be ignored if not a significant harmonic source	$R_h = R_T\sqrt{h}$ $X_h = hX_T$ R_T is derived from transformer power loss at fundamental frequency X_T is transformer short-circuit reactance
Passive load		$R = \frac{V^2}{P}$, $X = \frac{V^2}{Q}$ $R_h = R\sqrt{h}$, $X_h = hX$ R and X are equivalent load resistance and reactance P and Q are active and reactive load on the bus
Line and cable	Short line:  Long line: 	$R = R_{dc}\begin{cases} 0.035M^2 + 0.938 & M < 2.4 \\ 0.35M + 0.3 & M \geq 2.4 \end{cases}$ $M = 0.05012\sqrt{\frac{f\mu_r}{R_{dc}}}$ f = frequency (Hz) R_{dc} = dc resistance (Ω/km) μ_r = relative permeability of the cylindrical wire l = length (m) $z = r + jx_L$ (Ω/m) $y = g + jb_C$ (S/m) $Z_c = \sqrt{\frac{z}{y}}$ $Z = Z_c sinh(\gamma_e l)$ $\frac{Y}{2} = \frac{1}{Z_c} tanh\left(\frac{\gamma_e l}{2}\right)$
Shunt capacitor		R_{loss} = equivalent loss resistance (Ω) $R_{discharge}$ = equivalent discharge resistance (Ω) X_c = capacitor impedance (Ω)

Both characteristic harmonic and interharmonic calculations will involve modeling of sequence networks.

Therefore, each component should have sequence models determined, namely positive, negative and zero sequence impedance representations.

VI. DATA REQUIREMENT AND PREPARATION

To help engineers understand data requirement for system modeling and study, standard recommends requirement data for harmonic-analysis and suggested sources for the data.

A. Required Data for Analysis

Data in TABLE IV are required for a typical industrial and commercial power system harmonic-analysis studies:

TABLE IV
REQUIRED DATA FOR HARMONIC-ANALYSIS

Component	Data
System	Single-line diagram of the power system; System configurations; Maximum expected operating voltages at nonlinear loads
Bus	Bus nominal voltage, harmonic distortion limits for both total harmonics and each individual harmonic
Utility connecting point	Three-phase and single-phase short-circuit MVA and X/R ratio or positive, negative, and zero sequence resistance and reactance; Utility harmonic voltage spectrum (if utility is a harmonic source); Utility harmonic impedance at different frequencies
Generator	Rated MVA/kVA, rated voltage, sequence impedance, operating mode, winding connection and grounding type; If generator is a harmonic source, then a harmonic spectrum
Motor	Rated MVA/kVA/HP, rated voltage, sequence impedance, winding connection and ground type, and loading
Transmission line Cable	Length, sequence impedance and admittance, frequency characteristics of impedance
Bus duct Current limiting reactor Other circuit element	Sequence impedance, and frequency characteristics of impedance.
Transformers	MVA/kVA rating, rated voltages, sequence impedance and X/R ratio, three-phase connection and grounding types of power. If the transformer harmonics due to in-rush or saturation are to be considered, then harmonic spectrum
Shunt capacitors Shunt reactors	The three-phase connections, kvar, and kV ratings, sequence impedance or admittance
Loads	Bus connection, rated MVA/kVA, rated voltage, initial loading, phase connection and grounding type, frequency characteristics of the load
Converter	Nameplate ratings, number of phases, pulses, and connections; Converter's harmonic characteristics or harmonic spectrum including harmonic type (voltage or current), harmonic magnitudes, and phase angles
Arc furnace installations	Harmonic type (voltage or current) and harmonic contents
Harmonic filter	Type and structure, resistance, reactance, and capacitance for all elements, maximum voltage rating for capacitors, and maximum currents rating for inductor
Special buses (PCC, etc.)	Harmonic limits for total harmonic distortion as well as for individual harmonic

B. Data Collection and Preparation

System modeling and data collection are vital to harmonic-analysis. TABLE V shows recommended data sources for typical system components and equipment.

TABLE V
SUGGESTED DATA SOURCE

Data Type	Data Sources
Power grid	Utility
Rotating machine	Machine manufacturer-provided data sheet and nameplate, plus any data from available factory acceptance test, site acceptance test, and/or commissioning test
Load	Load name plate plus any testing data
Line and cable	Manufacturer provided data sheet plus any testing data
Other power system component	Manufacturer-provided data sheet and nameplate, plus any testing data
Transformer	Nameplate plus any testing data
Nonlinear device voltage-current characteristics	Manufacturer provided data sheet plus any special test data
Harmonic filter	Manufacturer data sheet plus any testing data
Voltage and current harmonic spectrum	Manufacturer plus any field testing data

VII. SIMULATION STUDY

There are two basic modeling and simulation methods available for harmonic studies.

A. Harmonic Power Flow Method

This method models harmonic generation from nonlinear power system devices by injecting harmonic currents into the network. Harmonic current sources are expressed in a series of harmonics. The electrical system is modeled as a network based on impedance at the given harmonic. A nodal voltage equation is formulated to solve nodal voltages as shown in Eq. (3).

$$\begin{bmatrix} Y_{11}(h) & -Y_{12}(h) & \cdots -Y_{1n}(h) \\ -Y_{12}(h) & Y_{22}(h) & \cdots -Y_{2n}(h) \\ \vdots & \vdots & \ddots \quad \vdots \\ -Y_{1n}(h) & -Y_{2n}(h) & \cdots \cdots Y_{nn}(h) \end{bmatrix} \begin{bmatrix} V_1(h) \\ V_2(h) \\ \vdots \\ V_n(h) \end{bmatrix} = \begin{bmatrix} I_1(h) \\ I_2(h) \\ \vdots \\ I_n(h) \end{bmatrix} \quad (3)$$

where

$Y_{ij}(h)$ is Y-Bus matrix element corresponding to branch admittance between nodal i and nodal j for harmonic h

$V_i(h)$ is nodal voltage at nodal i at harmonic h

$I_j(h)$ is nodal current at nodal j at harmonic h

Note that both structure and values of the Y-Bus matrix vary with harmonic h due to sequence (positive, negative, or zero) that h is representing and actual frequency determined by h. At each h, a new Y-Bus must be constructed.

From solved harmonic voltages harmonic currents in each branch will be computed from Eq. (4):

$$I_{ij}(h) = \left(V_i(h) - V_j(h)\right) \times V_{ij}(h) \quad (4)$$

where

$I_{ij}(h)$is branch current flowing from nodal i to nodal j for harmonic h

A more detailed description of power flow type harmonic-analysis method can be found in chapter 7 “Tutorial on harmonics modeling and simulation” by IEEE Power Engineering Society. [4]

B. Hybrid Method

Harmonic-analysis can also be done by a directly modeling method which implements output characteristics of nonlinear devices. Each nonlinear device is represented by its voltage-current characteristic curve. The solution starts from a chosen operating point, for example an estimated or rated operating condition. With the initial harmonic injection current assumed, a power flow type of method is applied to solve for network harmonics. The solved device terminal voltages are then used to adjust new harmonic currents per the device voltage-current characteristic curves. After needed iterations, a final solution can be reached to provide accurate harmonic currents for nonlinear devices. [6]

The other simulation methods for harmonic-analysis involves full time-domain simulation programs, such as an EMTP type of calculation which models nonlinear devices and all other components in three-phase. Nonlinearities of devices are modeled with a very small integration time step so that all details can be included. The solutions from the EMTP method are the true waveforms for voltage and current in the system. Fourier analysis can then be applied to decompose the waveforms and obtain harmonic contents for the voltages and currents of interest.

VIII. STUDY SCENARIOS AND SOLUTION PARAMETERS

Studies should cover operations in both normal and abnormal conditions, especially the worst cases, in order to better understand system situations from a harmonic perspective. This is achieved by defining and selecting appropriate study scenarios. Solution parameters are also used to specify additional requirements and options for studies.

A. Study Scenarios

The standard recommends some common scenarios for harmonic studies which are given in TABLE VI.

TABLE VI
HARMONIC STUDY SCENARIOS

Scenario	Objective
1	For all studies, include system configuration, data revision, harmonic filter locations, types, and parameters; for harmonic power flow studies, specify system load, power generation and regulated voltage, harmonic source data, and other parameters; for harmonic frequency scan studies, specify range for scanning frequency and step of frequency increment
2	Specify points of interest for bus voltage harmonic distortion, branch current harmonic distortion, and bus driving point impedance
3	Cover all possible system configurations, operating conditions, as well as all harmonic sources; also investigate parallel oscillation conditions under all possible system configurations and operating conditions
4	Add additional study scenarios to the base scenario if necessary
5	Save study scenarios and solutions for future retrieval or modification

B. Solution Parameters

Solution parameters are used to ensure a calculation study is executed for a specific condition. These parameters include, but are not limited to those are listed in TABLE VII.

TABLE VII
HARMONIC STUDY SOLUTION PARAMETERS

#	Parameters
1	Solution method and precision for fundamental load flow calculation
2	Initial bus voltage magnitude and phase angle
3	Options for reporting, plotting, and displaying results
4	Modeling method; i.e., short-line or long-line model for transmission lines and cables
5	Frequency step and range for frequency scan
6	Warning and alarm boundaries and thresholds for current and voltage harmonic distortions, and parallel resonance

IX. STUDY PROCEDURES AND RESULTS

The standard recommends a procedure for harmonic studies, starting from data preparation, to model construction, to calculation, and to potential mitigations. Industry standardized harmonic distortions are referenced and used for study report to show the level of harmonic affection in the studied system.

A. Study Procedures

TABLE VIII summarizes steps normally followed for a harmonic study in industrial and commercial environments.

TABLE VIII
HARMONIC STUDY PROCEDURES

Steps	Tasks
1	Prepare system one-line diagram; include capacitor banks and long lines and cables within the industrial system or the utility system near PCC
2	Gather equipment data and ratings
3	Obtain locations of nonlinear loads and sources of harmonic currents
4	Obtain from utility company the relevant data and harmonic limits at the PCC
5	Obtain Minimum and maximum fault current levels and power grid frequency dependent impedances
6	Obtain Permissible limits on harmonics including distortion factors and I-T factor at important locations
7	Carry out harmonic-analysis for the base system configuration by calculating the driving point impedance loci at specified locations especially at all shunt capacitor locations
8	Compute individual and total harmonic voltage and current distortion factors and I-T values (if required) at PCC
9	Examine and analyze results
10	Compare the composite loading requirements of shunt capacitor banks with manufacturer limits or the maximum rating permitted by IEEE Std 18 [7]: • Continuous operating voltage ≤ 110% of the rated voltage • rms crest voltage ≤ 1.2 times the rated rms voltage • kvar ≤ 135% of the rated kvar • Current ≤ 180% of the rated rms currents
11	Relocate the capacitors or change the bank ratings if they are found to exceed their ratings; apply a detuning reactor if a resonance condition is found
12	Add filters if the harmonic distortion factors and I-T values at the PCC exceed the limit imposed by the utility

B. Common Harmonic Distortion Indices

Commonly used harmonic distortion indices are introduced in the standard and recommended for studies. All of these indices can be readily computed after the harmonic power flow calculation. These indices are listed below. Note that U designates either voltage or current.

1. Total Harmonic Distortion

$$THD = 100 \times \frac{\sqrt{\sum_{n=2}^{\infty} U_n^2}}{U_1} \tag{5}$$

where
n is the harmonic order and usually the summation is made up to the 50th harmonic order

2. Individual Harmonic Distortion

$$IHD = 100 \times \frac{U_n}{U_1} \tag{6}$$

where
n is the harmonic order and usually the value is taken up to the 50th harmonic order

3. rms value

$$U_{rms} = \sqrt{\sum_{n=1}^{\infty} U_n^2} \tag{7}$$

where
n is the harmonic order and usually the summation is made up to the 50th harmonic order

4. Telephone interference magnitude

$$UT = \sqrt{\sum_{n=1}^{\infty} (K_n \times P_n \times U_n)^2} \tag{8}$$

where
n is the harmonic order
K_n and P_n are the weighting factors related to hearing sensitivity [3]
UT is used for Telephone Interference Factor TIF calculation

5. Telephone Interference Factor

$$TIF = \frac{UT}{U_{rms}} \tag{9}$$

C. Harmonic Distortion Limits

The standard adapts IEEE Std 519 for current and voltage harmonic distortion limits as shown in TABLE IX-1, IX-2, IX-3 and TABLE X. These limits are specified at the point of common coupling (PCC) which is normally at the gird side of main transformer connecting to the industrial or commercial facility.

TABLE IX-1
HARMONIC CURRENT DISTORTION LIMIT FOR VOLTAGE RANGE 120 V TO 69 KV

I_{sc}/I_L	3 ≤ h < 11	11 ≤ h < 17	17 ≤ h < 23	23 ≤ h < 35	35 ≤ h ≤ 50	TDD
< 20	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

TABLE IX-2
HARMONIC CURRENT DISTORTION LIMIT FOR VOLTAGE RANGE 69 kV TO 161 KV

I_{sc}/I_L	3 ≤ h < 11	11 ≤ h < 17	17 ≤ h < 23	23 ≤ h < 35	35 ≤ h ≤ 50	TDD
< 20	2.0	1.0	0.75	0.3	0.15	2.5
20 < 50	3.5	1.75	1.25	0.5	0.25	4.0
50 < 100	5.0	2.25	2.0	0.75	0.35	6.0
100 < 1000	6.0	2.75	2.5	1.0	0.5	7.5
> 1000	7.5	3.5	3.0	1.25	0.7	10.0

TABLE IX-3
HARMONIC CURRENT DISTORTION LIMIT FOR VOLTAGE RANGE GREATER THAN 69 KV

I_{sc}/I_L	3 ≤ h < 11	11 ≤ h < 17	17 ≤ h < 23	23 ≤ h < 35	35 ≤ h ≤ 50	TDD
< 25	1.0	0.5	0.38	0.15	0.1	1.5
25 < 50	2.0	1.0	0.75	0.3	0.15	2.5
≥ 50	3.0	1.5	1.15	0.45	0.22	3.75

where
ISC/IL is the ratio of short-circuit current in percent available at PCC to the maximum fundamental load current

TABLE X
HARMONIC VOLTAGE DISTORTION LIMIT

Bus voltage at PCC	IHD (%)	THD (%)
V ≤ 1.0 kV	5.0	8.0
1 kV < V ≤ 69 kV	3.0	5.0
69 kV < V ≤ 161 kV	1.5	2.5
161.001 kV < V	1.0	1.5[a]

D. *Bus Impedance*

There are two types of bus impedance. The driving point impedance is defined as voltage at a node i, due to current injected at the same node as in Eq. (10):

$$Z_{ii} = \frac{V_i}{I_i} \tag{10}$$

and the transfer impedance is defined as the voltage measured at one bus due to current injected at another bus as in Eq. (11):

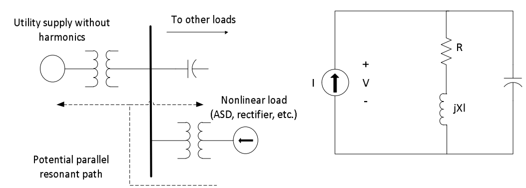
$$Z_{ij} = \frac{V_i}{I_j} \tag{11}$$

Where
Z_{ii} is the driving point impedance to bus i
Z_{ij} is the transfer impedance to bus i
V_i is the voltage measured at bus i
I_i is the current injected at bus i
I_j is the current injected at bus j

Bus impedances are used to study the system characteristics for series and parallel resonances..

E. *Harmonic Resonances*

Industrial and commercial power systems are often at risk of harmonic resonance, particularly parallel resonance. A typical parallel resonant circuit encountered in power systems is shown in Fig. 4.



(a) Parallel resonant configuration (b) Equivalent circuit
Fig. 4 Typical industrial power system parallel resonance configuration and equivalent circuit

Impedance at the top node of Fig. 3 (b) can be computed as:

$$\bar{Z} = \frac{-jX_C(R+jX_L)}{R+j(X_L-X_C)} \tag{12}$$

The magnitude of Z is a function of frequency as shown in Fig. 5:

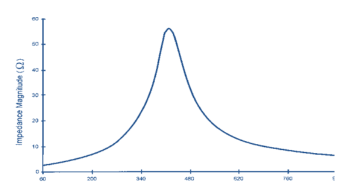


Fig. 5 Impedance magnitude vs. frequency for parallel circuits

The maximum value of Z appears at a resonance condition of $X_L = X_C$ from which the resonance frequency is defined:

$$\omega_0 = \frac{1}{\sqrt{LC}} \tag{13a}$$

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{13b}$$

Considering voltage at the top node of Fig. 2 (b) is given by:

$$\bar{V} = \bar{I}\bar{Z} \quad (14)$$

if at or closer to the resonant frequency harmonic current injection I is not zero, then the nodal voltage V can present excessive harmonic overvoltage causing damage to equipment.

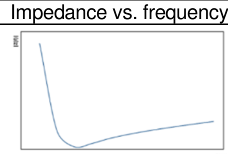
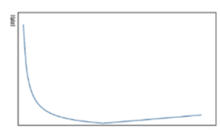
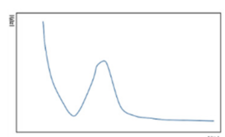
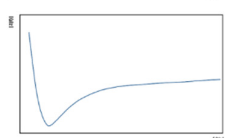
Harmonic resonance conditions are scanned and identified by harmonic frequency scan study which calculates and plots bus driving point impedance at selected buses similar to Fig. 4, and computes harmonic voltage at these buses by multiplying the impedance with harmonic current injection at corresponding frequency.

X. FILTER AND FILTER SIZING

Harmonic filtering using passive filters is one of the most convenient and practical methods for harmonic distortion as well as parallel resonance mitigation.

Filters most commonly used for harmonic mitigation are illustrated in Table XI along with their impedance magnitude vs frequency characteristics.

Table XI
FILTERS COMMONLY USED FOR HARMONIC MITIGATION

Type	Structure	Impedance vs. frequency
Single-tuned filter		
High-pass filter (second order)		
Undamped high-pass filter (third order)		
High-pass C-type filter (third order)		

A single-tuned filter is used to suppress a specific harmonic at or near the tuned frequency. High-pass filters can be of first, second, or third order. The second-order filter is often used to suppress higher frequencies. A C-type high-pass filter is becoming popular due to its exhibiting smaller losses at the fundamental frequency.

Generally, filters are tuned at one of the dominant harmonics starting from the lowest order. Ideally, the filters should be tuned to the exact harmonic order; however, the practical considerations may require tuning it slightly below the nominal frequency.

The two main components of passive filters are capacitors and reactors. Be aware that capacitor voltage can increase (above the bus voltage) due to impedance cancellation with reactor roughly by the factor in Eq. (15):

$$c = \frac{h^2}{h^2-1} \quad (15)$$

where
h is the harmonic order

For the conventional single-tuned filter this factor is calculated in TABLE XII.

TABLE XII
FUNDAMENTAL VOLTAGE ACROSS A SINGLE-TUNED FILTER CAPACITOR

Harmonic order h	3rd	5th	7th	11th	13th
Capacitor voltage c in	1.125	1.049	1.021	1.008	1.005

Once the harmonic study is completed and the filter selection has been made, the capacitor rating with respect to voltage, current, and kvar should be checked. All these ratings need to be satisfied independently according to IEEE Std 18 [7].

Other remedial measures for harmonic mitigation include moving the disturbing loads to higher voltage levels, changing capacitor sizes, adding tuning reactors to capacitor banks, and installing active filtering.

XI. ILLUSTRATION EXAMPLE

One of the examples in the standard is from IEEE Task Force paper on Harmonics Modeling and Simulation [8] with some data slightly modified. The system consists of 13 buses and is representative of a medium-sized industrial plant, shown in Fig. 6.

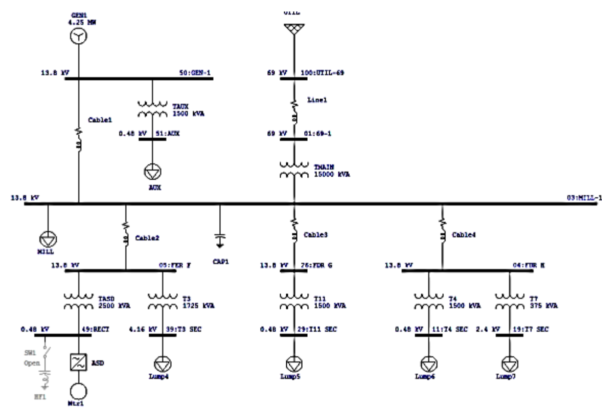


Fig. 6 One-line diagram of 13-bus illustration case

The plant is fed from a utility supply and an onsite generator. Loads are distributed at 13.8 kV and 480 volts levels. A 1500 HP motor driven by an ASD generates and injects harmonic currents into the system. Evaluation of harmonic voltage and current distortion inside the plant and at PCC bus are needed.

System data including utility, generator, bus, transformer, cable, and load are found from the reference. The harmonic current spectrum from a 6-pulse ASD at 480 V are measured and listed in TABLE XIII.

TABLE XIII
HARMONIC SOURCE DATA FOR ASD

Harmonic order	Current (%)	Relative angle
1	100.00	0.00
5	18.24	–55.68
7	11.90	–84.11
11	5.73	–143.56
13	4.01	–175.58
17	1.93	111.39
19	1.39	68.30
23	0.94	–24.61
25	0.86	–67.64
29	0.71	–145.46
31	0.62	176.83
35	0.44	97.40
37	0.38	54.36

Based on the harmonic source data, an harmonic power flow study is performed. Bus fundamental and harmonic voltages computed through the system are summarized in Table XIV. The highest voltage harmonic distortion appears at a 480 V bus 49: RECT which is the terminal bus of ASD.

Table XIV
PLANT HARMONIC VOTLAGE DISTORTION SUMMARY

Bus	V_1	V_5	V_7	THD (%)
100:UTIL-69	39645.70	40.37	104.23	0.28
01:69-1	39538.00	52.36	135.14	0.37
03:MILL-1	7712.77	53.51	138.13	1.93
50:GEN1	7726.55	51.72	133.51	1.87
51;AUX	262.74	1.72	4.40	1.81
05:FDR F	7709.24	54.07	138.35	1.94
49:RECT	269.89	12.79	12.83	8.02
39:T3 SEC	2240.05	14.83	37.21	1.80
26:FDR G	7709.07	53.48	138.04	1.93
06:FDR H	7703.35	53.43	137.91	1.93
11:T4 SEC	260.40	1.78	4.59	1.90
19:T7 SEC	1302.74	8.58	21.78	1.81
29:T11 SEC	256.29	1.71	4.36	1.84

Total and individual harmonic voltage distortions for each bus need to be carefully checked and compared with harmonic limits. If any violations are found, remedial measures need to be taken to reduce harmonic distortion below the limits.

XII. CONCLUSIONS

The new IEEE Standard 3002.8-2018 provides detailed recommendations on the practice of conducting harmonic studies and analysis of industrial and commercial power systems. It discusses basic concepts for harmonic study, the need for the study, required data for analysis, study methodologies, awareness of potential problems, corrective measures, and benefits of using a computer as a tool in a harmonic-analysis studies. Comparing to the old IEEE Standard 399, 3002.8-2018 adds several new sections to guide users regarding required data for studies, recommends practical ways to prepare and validate model and data. It also adds discussions on common study cases and typical study results. 3002.8-2018 further addresses a number of important issues including interharmonics and the latest IEEE 519 recommended harmonic limits at PCC, and some useful features in computer software for performing harmonic studies. The new standard provides three cases as illustration of harmonic studies. The new standard also offers very detailed guidelines for engineers who need to conduct harmonic studies.

VI. REFERENCES

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[2] *IEEE Recommended Practice for Conducting Harmonic Studies and Analysis of Industrial and Commercial Power Systems*, IEEE Standard 3002.8, 2018.

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[4] M. Halpin, P. Ribeiro, and J.J. Dai, Chapter 7, “Frequency-Domain Harmonic-analysis Methods”, IEEE Power Engineering Society, *Tutorial on harmonics modeling and simulation*, IEEE catalog no. 98TP125-0, 1998.

[5] IEEE Task Force on Harmonics Modeling and Simulation, “Interharmonics: theory and modeling,” *IEEE Transactions on Power Delivery*, vol. 22, no. 4, pp. 2335–2347, Oct. 2007.

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[7] *IEEE Standard for Shunt Power Capacitors*, IEEE Standard 18, 2012.

[8] IEEE Power Engineering Society Transmission and Distribution Committee Task Force on Harmonics Modeling and Simulation, “Test systems for harmonic modeling and simulation,” *IEEE Transactions on Power Delivery*, vol. 14, no. 2, pp. 579–587, Apr. 1999.

XIII. VITA

JJ Dai (SIEEE) received his BS, MS, PhD all in electrical engineering. He was a senior VP with ETAP for twenty-one years. He joined Eaton Corporation in 2013, served as engineering service director with Eaton APAC for five years, and currently is Global Account Manager with Eaton Oil & Gas. He has been actively involved in IEEE standard committees and IAS subcommittees. He is the co-chair of IEEE 3002.8 standard working committee for IEEE Recommended Practice for Conducting Harmonic Studies and Analysis of Industrial and Commercial Power Systems. He is a registered Professional Engineer in the State of California, USA. He can be reached at jjdai@eaton.com.