HARMONICS PART 2

ADVANCED TOPICS

In our continued discussion about harmonics, we shall take a more in-depth look at the following topics:

- IEEE STANDARD 519-1992 – PRACTICES AND REQUIREMENTS FOR HARMONIC CONTROL
- CALCULATION OF I_{rms} FOR HARMONIC CURRENTS
- POWER FACTOR AND HARMONICS
- TRANSFORMER K-FACTOR
- RMS CURRENT IN SHARED NEUTRALS
- HARMONIC FILTERS

IEEE STANDARD 519-1992 – PRACTICES AND REQUIREMENTS FOR HARMONIC CONTROL

IEEE Standard 519-1992 provides recommended practices for electric power systems that are subjected to non-linear loads. The standard includes information on harmonic generation, system response characteristics, the effects of harmonics, harmonic control, and recommended practices for individual customers and utilities.

The generation of harmonics in a power system can be attributed to the use of rectifiers, arc furnaces, static var compensators, inverters, electronic phase controllers, cycloconverters, switched mode power converters, and pulse width modulated drives, as defined in IEEE Standard 519-1992. All of these devices may cause harmonics in the voltage and/or current waveshape provided by the utility. In the case of devices containing solid state components to achieve switching, voltage harmonics can be attributed to voltage notching due to commutation periods while current harmonics can be attributed to discontinuous conduction due to the switching of the solid state components.

The system response characteristics to harmonic loads on a distribution system determine the effect of these loads. The flow of harmonic currents in a distribution network is dependent on the system short-circuit capacity, the placement and size of capacitor banks, the characteristics of the loads on the system, and finally, the balanced/unbalanced conditions of the system.

Normally in a distribution network, harmonic currents tend to flow between the harmonic load and the lowest system impedance. In most cases, this will be the utility source or point of generation. When capacitor banks and load characteristics are taken into effect, parallel and/or series resonant conditions may appear in the distribution system, causing oscillations and further producing an increase in voltage distortion. Because of this fact, a thorough investigation of the characteristics of the installed capacitor banks and loads must be done to avoid resonances.

Specifically, IEEE Standard 519-1992 provides recommended practices for harmonic control for both the utility and individual customer. Because of the wide range of harmonic-producing loads described above, three harmonic indices have been recommended for the individual customer to provide a meaningful insight of harmonic effects[1] . These indices include:

(1) Depth of notches, total notch area, and distortion (RSS) of bus voltage distorted by commutation notches (low-voltage systems),

(2) Individual and total voltage distortion, and

(3) Individual and total current distortion.

The harmonic voltage distortion on a distribution network is a function of the total injected harmonic current and the system impedance at each of the harmonic frequencies. Because of this relation, current distortion limits have been developed to curtail voltage distortion produced by individual customers. The objectives of developing current distortion limits are to:

(1) Limit the harmonic injection from individual customers so that they will not cause unacceptable voltage distortion levels for normal system characteristics, and

(2) Limit the overall harmonic distortion of the system voltage supplied by the utility.

Note that the total injected harmonic current is dependent on the number of individual customers injecting harmonic current and the size of each customer. Thus, the harmonic current limits developed are dependent upon customer size. The size of the customer is determined by its Short-Circuit Ratio (SCR) at the Point of Common Coupling (PCC) with the customer-utility interface. The SCR for a customer may be defined as:

$$SCR = \frac{I_{SC}}{I_L}$$

where:

I_{SC} = utility system short-circuit current capacity at the PCC, and

I_L = customers maximum demand load current (fundamental frequency component at the PCC).

Note that the SCR is an indication of the "stiffness" of the bus at the PCC. Thus, customers which represent a relatively large portion of the utility's total system load will have a more stringent current distortion limit than smaller customers.

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[1] "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems," The Institute of Electrical and Electronic Engineers, Inc., 345 East 47th St., New York, NY, IEEE Std. 519-1992

The basis for current distortion limits is to limit the maximum individual frequency voltage harmonics to tolerable levels. The voltage harmonic limits and corresponding SCRs are shown below in Table 1.

SCR AT PCC	MAXIMUM INDIVIDUAL FREQUENCY VOLTAGE HARMONIC (%)	RELATED ASSUMPTION
10	2.5 – 3.0	Dedicated system
20	2.0 – 2.5	1-2 large customers
50	1.0 – 1.5	A few relatively large customers
100	0.5 – 1.0	5-20 medium size customers
1,000	0.05 – 0.10	Many small customers

Table 1. Basis for IEEE 519-1992 Harmonic Current Limits

Table 2 shows the current distortion limits for general distribution systems (120V through 69kV) for corresponding SCRs at the PCC. The index used to determine the maximum allowable current distortion allowable for a specific SCR is the Total Demand Distortion (TDD). The TDD is defined as the harmonic current distortion in percent of maximum demand load current.

I_{SC}/I_L	<11	11<=h<17	17<=h<23	23<=h<35	h>=35	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 2. IEEE 519-1992 Current Distortion Limits for General Distribution Systems (120V through 69kV)

CALCULATION OF I_{rms} FOR HARMONIC CURRENTS

The “root mean square” summation of current, otherwise known as I_{rms}, is aggregation of all of the harmonics, including the fundamental, which may be present in the current waveform. Mathematically, the I_{rms} calculation can be expressed as:

$$I_{rms} = \sqrt{I_1^2 + I_2^2 + I_3^2 + \ldots + I_n^2}$$

where: I_1 = 1st order (fundamental, or 60 Hz) current magnitude,
n = harmonic order

The distortion root mean square, or $I_{rms(distortion)}$, is identical to the calculation for I_{rms} except that the fundamental is left out of the summation. Mathematically, the calculation for $I_{rms(distortion)}$ can be expressed as:

$$I_{rms(distortion)} = \sqrt{I_2^2 + I_3^2 + \ldots + I_n^2}$$

The total harmonic distortion (THD) of a current waveform containing harmonics can be calculated by dividing the $I_{rms(distortion)}$ value by the fundamental magnitude. Mathematically, this can be expressed as:

$$THD_{\%\,fundamental} = \left(\frac{I_{rms(distortion)}}{I_1} \right) \text{x } 100$$

If we apply the above equations to current waveforms with and without harmonic content, it can clearly be shown that a current waveform containing harmonics has a higher I_{rms}, $I_{rms(distortion)}$, and $THD_{\%fundamental}$, than a current waveform free of harmonics. This is demonstrated in Table 1 below.

	CURRENT WAVEFORM WITHOUT HARMONICS	**CURRENT WAVEFORM WITHOUT HARMONICS**
I_1, amps (fundamental)	10	10
I_3, amps	0	3
I_5, amps	0	2
I_7, amps	0	1
I_{rms}, amps	10	10.68
$I_{rms(distortion)}$, amps	0	3.74
$THD_{\%fundamental}$, %	0	37.4

As the amount of harmonic content in the current waveform increases, the I_{rms} and $THD_{\%fundamental}$ increase. Subsequently, the increase of I_{rms} due to harmonics results in an increase in power losses across line impedances which can be calculated as follows:

$$P_{loss} = I_{rms}^2 \text{ x } R$$

For instance, let's assume that the currents described in Table 1 are applied to a line impedance of 0.25 ohms resistive. Substituting the I_{rms} values for current waveforms without and with harmonics into the P_{loss} equation above gives us:

Without Harmonics: $P_{loss} = I_{rms}^2 \text{ x } R = 10^2 \text{ x } 0.25 = 25.0W$

Without Harmonics: $P_{loss} = I_{rms}^2 \text{ x } R = 10.68^2 \text{ x } 0.25 = 28.5W$

Thus, a current waveform with 37.4% $THD_{\%\,fundamental}$ results in a 3.5% increase in I_{rms}^2 x R power losses.

POWER FACTOR AND HARMONICS

Power factor is a measure of how efficiently a load utilizes the current from an AC power system. There are some utility rate schedules that offer incentives to large customers to increase their facility power factor to near-unity as this increases the overall power supply efficiency. In most facilities, the largest contributors to a relatively low power factor are reactive loads such as induction motors (e.g., compressor motors, pump motors, and fan motors). But harmonic currents can also have an adverse impact on power factor.

For a sinusoidal voltage and current situation, the apparent power (S) is the vector sum of real (P) and reactive (Q) power. This is expressed by the following equation:

$$S = P + Q$$

The true power factor, in this case, is the ratio of the magnitudes of real power to apparent power:

$$PF_{TRUE} = P / S \ (kw / kVA)$$

If all the power required by a load is non-reactive, then the true power factor is unity. Reactive power consumers such as induction motors will reduce the true power factor below unity. The installation of shunt capacitors can correct power factor to near-unity levels. Displacement power factor is defined as the cosine of the phase angle difference between voltage and current:

$$PF_{DISP} = \cos\,(Angle_V - Angle_1)$$

For the sinusoidal voltage and current situation, true power factor is equal to the displacement power factor. Such is not the case for non-sinusoidal voltages and currents. Distortion power factor is expressed by the following equation:

$$PF_{DIST} = \left(1/\sqrt{1+(THD_v)^2}\right) \text{ x } \left(1/\sqrt{1+(THD_1)^2}\right)$$

where THD_V = Voltage Total Harmonic Distortion,
and THD_I = Current Total Harmonic Distortion.

Except for extreme cases where THD_V exceeds 10%, distortion power factor can be expressed as:

$$PF_{DIST} = \left(1/\sqrt{1+(THD_1)^2}\right)$$

True power factor in the non-sinusoidal case, is equal to the product of displacement power factor times distortion power factor. Therefore, true power factor is expressed by the following equation:

$$PF_{TRUE} = PF_{DISP} \text{ x } PF_{DIST} = \cos(Angle_V - Angle_1) \text{ x } \left(1/\sqrt{1+(THD_1)^2}\right)$$

As implied by the above equation, increasing the current harmonic distortion will result in lowering the overall true power factor as seen by the power supply.

TRANSFORMER K-FACTOR [2]

Transformer K-factor is an index used to de-rate transformers to compensate for the increased stress to windings imposed by harmonic currents present in a distribution system. For a measured or calculated or measured peak harmonic current I_h at a specific harmonic order h the K factor is expressed by the following equation:

$$K = \sum_{h\infty 1}^{\infty} h^2 I_h^2$$

A standard transformer has a K-factor of 1. K-rated transformers are constructed to withstand the additional heat that needs to be dissipated within their winding and conductor impedances due to harmonic currents. Basically, their design is the same as a standard transformer (K-1) that has been increased in size to accommodate the current at the fundamental frequency of 60 Hz plus additional currents at the specified harmonic. Additionally, the neutral of the K-rated transformer may be sized at 200% of the current rating of the phase connections. Typical K-rated transformer categories and their applications are:

K-4: HID lighting, induction heaters, welders, UPS with optional input filtering, PLC and solid sate controls.
K-13: Multiple receptacle circuits in health care facilities, UPS without optional input filtering, production or assembly line equipment, school and classroom facilities.
K-20: SCR adjustable speed drives, circuits with exclusive data processing equipment, critical care facilities and hospital operating rooms.

It should be noted that K-rated transformers do not mitigate harmonics on a distribution system; they simply accommodate the additional non-linear load present on the system.

RMS CURRENT IN SHARED NEUTRALS

The currents in a shared neutral conductor of a 3-phase, 4-wire wye distribution system will cancel under a balanced sinusoidal phase current situation. Non-linear load currents present in the distribution system, however, may not have this canceling effect. Triplen harmonic currents (i.e., currents at the 3rd harmonic, 6th harmonic, 9th harmonic, etc.) are especially problematic. It can be shown mathematically that the worst-case RMS shared neutral current is 1.73 times the largest phase current, or:

$$I_{Nrms} = \sqrt{3} \text{ x } I_{\o rms}$$

To accommodate for non-linear loads, neutral conductors are therefore typically sized 200% larger than the phase conductors. Again, this measure is to accommodate harmonics within the distribution system and is not a mitigation means.

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[2] American National Standards Institute, Inc., 'Recommended Practice for Establishing Transormer Capability when Supplying Nonsinusoidal Load Currents,' The Institute of Electrical and Electronic Engineers, Inc., 345 East 47th Street, New York, NY, ANSI/IEEE C57.110-1986.

HARMONIC FILTERS

To effectively attenuate harmonic current injection into the system a method is required to effectively filter out the unwanted currents at specific frequencies. There are many types of filters available today that effectively reduce harmonics at the point source. There are, for example, single-phase passive filters in either the series-connected parallel filter configuration or the parallel-connected series filter configuration. These filters, sometimes called “harmonic traps”, use lumped reactor and capacitor components to filter out 3rd harmonic currents back fed from switched electronic power supplies to the AC power distribution system. Other single-phase designs incorporate active MOSFET components that can be built into electronic power supplies.

For 3-phase loads such as adjustable speed drives, there are drive-applied harmonic filters available. Harmonic filtering is also available as an option in certain dry-type transformers.

Care must be taken when adding these filters to a distribution system, especially where power factor correction capacitors have been installed, to avoid a resonant condition that may amplify voltage transients whenever they appear on the system.

CLOSING REMARKS

Electronics are here to stay – they are a part of the information age and also aid in increasing the energy efficiency of facilities. One of the unfortunate consequences in increasing electronic load in a facility is the increase of harmonic currents. We have seen how increased harmonics in an electrical distribution system have a negative impact on equipment, conductor insulation, and power factor. As discussed in this article, there are techniques available to either accommodate or reduce the dispersal of harmonics.

As this article gives a general description of harmonic control methods, it is highly recommended that facility engineers seek the advice of licensed electrical consulting engineers in the actual application of these methods for particular problems related to harmonics.