



GUIDANCE NOTES ON

CONTROL OF HARMONICS IN ELECTRICAL POWER SYSTEMS

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Foreword

Harmonics (or distortion in wave form) has always existed in electrical power systems. It is harmless as long as its level is not substantial. However, with the recent rapid advancement of power electronics technology, so-called nonlinear loads, such as variable frequency drives for motor power/speed control, are increasingly finding their way to shipboard or offshore applications. Harmonics induced by these nonlinear loads are a potential risk if they are not predicted and controlled.

The *ABS Guidance Notes for Control of Harmonics in Electrical Power Systems* has been developed in order to raise awareness among electrical system designers of the potential risks associated with the harmonics in electrical power systems onboard ships or offshore installations. These Guidance Notes encompass topics from the fundamental physics of harmonics to available means of mitigation to practical testing methods. These Guidance Notes are intended to aid designers to plan an appropriate means of harmonics mitigation early in the design stage of the electrical power distribution systems to make the system robust and predictable.

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SECTION 1 Introduction

1 Background

Over recent years, there has been a significant increase in the installation and use of power electronic equipment onboard ships and on offshore installations. The operation of this equipment has in many cases significantly degraded the ship or offshore installation electrical power quality to such an extent that measures have to be implemented in order to minimize the resultant adverse effects on the electrical plant and equipment.

The quality and security of voltage supplies are important to the safety of any vessel and its crew and to the protection of the marine environment. Any failure or malfunction of equipment such as propulsion or navigation systems can result in an accident at sea or close inshore with serious consequences. Many power quality issues are transient, for example, the starting of a large electric thruster motor resulting in a momentary dip before the generator regulators correct the situation and reinstate the correct level of voltage and frequency.

However, as the title suggests, the specific power quality issue to be addressed in these Guidance Notes is that of the harmonic distortion of voltage supplies caused by the operation of electronic devices which draw nonlinear (i.e., non-sinusoidal in nature) currents from the voltage supplies. These same items of “nonlinear” equipment can also be affected by harmonic currents and the subsequent voltage distortion they produce, as can the majority of “linear” equipment (particularly generators, AC motors and transformers). As harmonic distortion is “steady state” and continuous, the issue of electrical power quality associated with harmonics is an important concern to the marine safety aspects and in addition, to any adverse effects harmonic distortion has on the performance and reliability of the majority of marine and offshore systems and equipment.

Examples of the serious impact of harmonics and associated power quality effects on marine and offshore supply voltage waveforms, in these instances, due to electrical variable speed drives (the main producer of harmonic currents on marine and offshore installations) are illustrated in Section 1, Figures 1, 2, 3 and 4.

FIGURE 1
Input Waveforms (440 V) to 6-Pulse DC SCR Drive

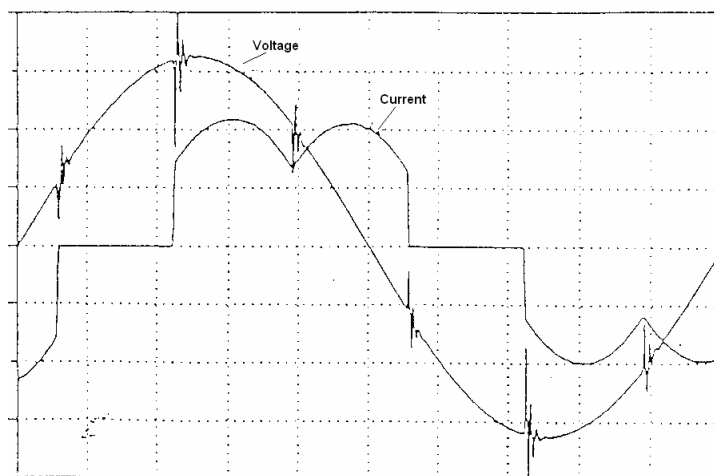


FIGURE 2
Line-to-line Voltage (440 V) at Input to a 6-Pulse DC SCR Drive

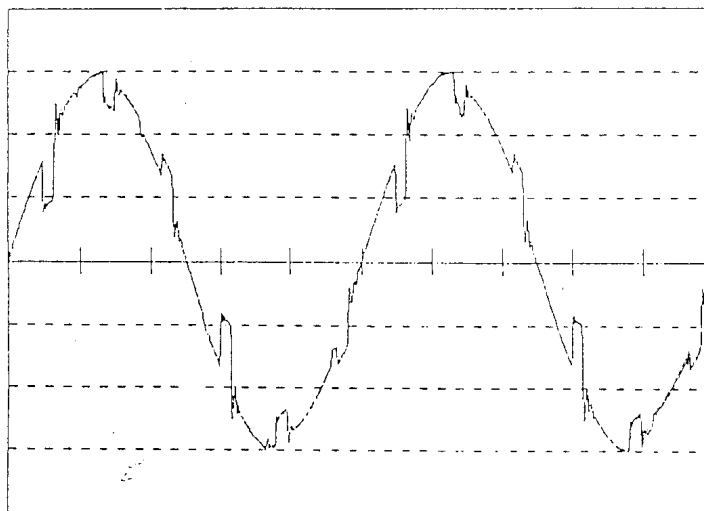


FIGURE 3
415 V Line-to-line Volts on Ship with Four 1100 kW/1500 HP AC SCR
Converter-fed Thruster Motors

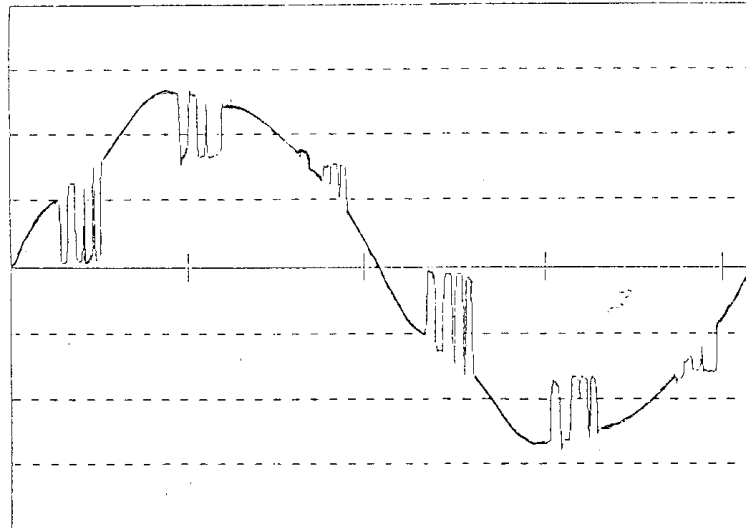
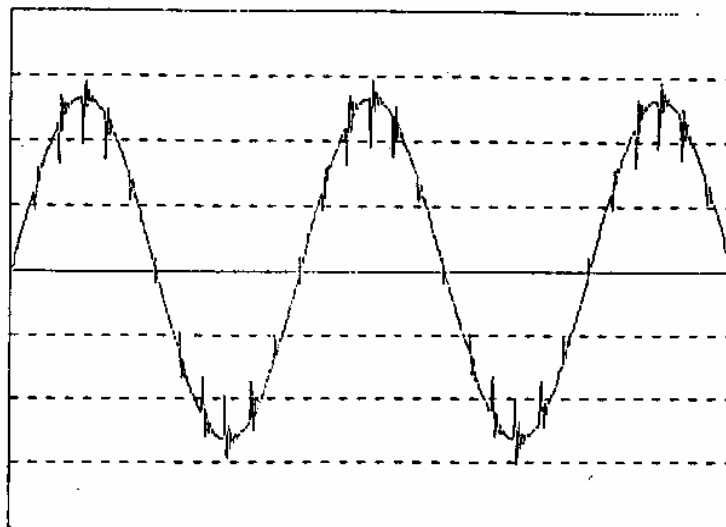


FIGURE 4
Primary Voltage (11 kV) of Transformer Supplying a 2 MW (2680 HP)
Variable Frequency Drive



The American Bureau of Shipping (ABS) is concerned with the effects of harmonic voltage distortion and the possible resultant consequences should some critical item of equipment malfunction or fail. This concern is largely a result of the increasing demand for high power nonlinear equipment, such as AC and DC variable speed drives, used for main propulsion, thrusters and other duties. Therefore, ABS has imposed limitations on the magnitude of harmonic voltage distortion permitted on classed vessels.

The aim of these Guidance Notes, which solely address the harmonics issue, is to provide information as to what harmonics are and how they interact with the supply impedances, what effects they have on the different types of equipment, what items of equipment typically produce harmonic currents and how harmonic currents can be attenuated or mitigated such that any adverse effects are significantly reduced.

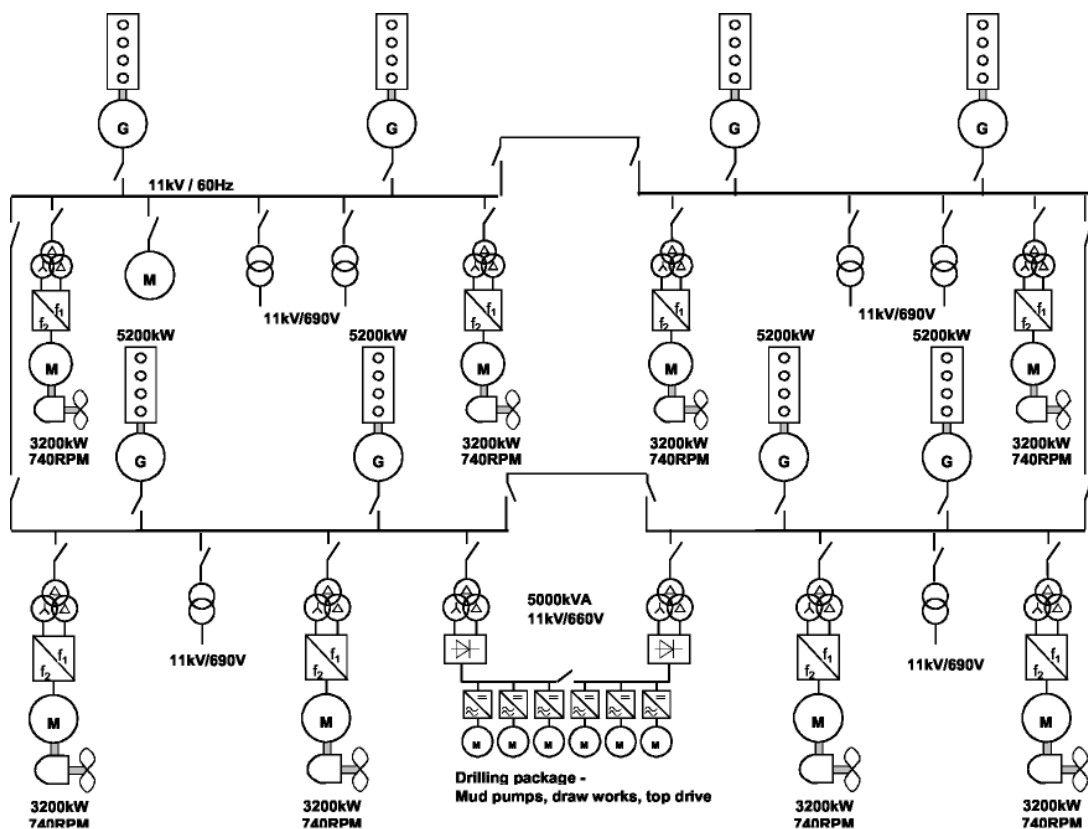
As indicated in the title, these Guidance Notes are designed to be practical “guidance notes”, not a reference book on harmonics. It is aimed at the “non-expert”, hence the use of a minimum of complex math. There are a number of high-quality harmonics and power quality reference books available, although very few dealing with harmonics and power quality issues specifically from the marine viewpoint. The Appendix recommends some of these books should the reader wish further information.

These Guidance Notes will indicate that there are a number of sources of harmonic currents. “Linear” equipment, such as generators, AC motors and transformers, is also known to produce harmonics, albeit in limited quantities compared to large “nonlinear loads”. However, in the context of the marine and offshore installations, it is the electric variable speed drive (a combination of an electric motor and electronic power converter) whether AC or DC based, which, due to its increased popularity in a host of applications, is the main source of harmonic currents and subsequent voltage distortion. Therefore, the electric variable speed drives and harmonic mitigation of this type of equipment will be a primary focus of these Guidance Notes.

However, single-phase electrical and electronic equipment, including fluorescent lighting, variable speed drives and computer-based equipment all produce harmonic currents and therefore will distort the voltage supplies. On large passenger vessels, 4-wire systems [three-phase and neutral (grounded or insulated)] are now being installed, resulting in potentially high levels of neutral currents due to arithmetic addition of triplen harmonics in that conductor, up to almost twice the phase current values. Therefore, lower voltage single-phase equipment down to 110 V is also of significant importance in many vessels in terms of harmonics and associated effects.

Section 1, Figure 5, below, illustrates the popularity and the reliance some classes of vessel now have with regard to electrical variable speed drives (in this instance a self-propelled drilling rig).

FIGURE 5
Typical Power System Single Line Diagram for DPS-3 Drilling Rig



2 The Use of Electric Drives in Marine Applications

For the first half of the 20th century, the majority of vessels were steam turbine or diesel engine driven. DC generators were common and therefore, ships utilized DC motors to power a host of applications, including cargo winches, windlasses, pumps, fans and other auxiliary driven equipment. Speed control was easily achieved using resistance-based control systems for both armature voltage control (for speed variation up to base speed) and field control (above base speed). As no “voltage conversion” was taking place (e.g., AC to DC) no harmonic currents were produced by this type of equipment.

From the early 1960s, AC generators were installed in new vessels as the benefits of AC voltage supplies became common. With the introduction of AC power, however, the ease in which electric motor speed control was previously achieved was significantly diminished for all but some specialized applications. For duties where speed control was considered necessary (for example, windlass or mooring winch applications), special systems including the “Ward-Leonard” AC motor-DC generator system were developed. The Ward-Leonard set supplied a DC motor which powered the driven load. The voltage, and hence speed and torque, of the DC drive motor was controlled by the excitation of the Ward Leonard DC generator driven by a fixed-speed AC motor and the “field controller” should speeds above base speed be needed. No “voltage conversion” (AC to DC, in this case) was necessary. Therefore, harmonic distortion was not an issue that had to be considered.

Around the mid-to-late 1960s, the first generation of solid state SCR (“silicon controlled rectifier” or “thyristor”) based variable speed drive systems were introduced for the control of DC motors. The power conversion process from AC voltage to DC voltage draws “nonlinear” (non-sinusoidal) currents from the supply, resulting in harmonic voltage distortion as the harmonic currents produced interact with supply impedances. It has to be noted that the theory of harmonics with respect to electrical networks has been known since the start of the 20th Century, but until relatively recently, there was no effective or accurate monitoring equipment available to measure it.

Common applications for DC SCR drives on AC vessels from the mid-to-late 1960s included windlasses, mooring winches and some cargo winches, while the majority of engine room auxiliaries; pumps, fans, compressors and other equipment were driven by fixed-speed AC motors with bypass systems, valve throttling or damper control used to vary flow. It was common on these vessels fitted with DC SCR cargo handling systems to experience light “flicker”, caused by a combination of “line notching”, “interharmonics” and harmonic currents interacting with the generator(s), cabling and other supply impedances when cargo was being worked.

From the mid 1960s, DC SCR drives were used extensively on drilling rigs for main propulsion, mud pumps, draw-works, anchor windlasses and other duties. As can be seen in Section 1, Figure 5, DC SCR drives have now largely been replaced by AC drives.

In the late 1970s and early 1980s, AC variable frequency drives (“VFDs” or “inverters”) were developed in various forms, “quasi square wave drives” and “current source drives”, being two common examples. However, it was only in the late 1980s that AC drive technology (most notably in the form of “pulse width modulation” (“PWM”) drives) started to appear on ships in any numbers, although they were installed on offshore oil production installations from the mid 1980s for a few duties, especially including down-hole pumps, where the initial benefit was as “soft-starters” for the pumps. Shortly thereafter, the speed control feature was utilized as oil reservoirs became depleted and flow rate had to be controlled.

Offshore, on applications where robust, variable speed control was needed, DC SCR drives were most common. DC SCR drives went largely unchallenged until the early-to-mid 1990s. However, from that time on, as the physical size, performance, reduction in maintenance of AC motors compared to DC motors, cost, and reliability of AC drives continued to improve, their popularity increased making AC drives comparable to DC SCR drives. As can be seen from Section 1, Figure 5, AC PWM drives have completely replaced DC drives in the majority of drilling rig applications.

With the exception of large main propulsion drives (above 5-8 MW/6700-10700 HP), where “load commutated inverters” and “cyclo-converters” are still more common, AC PWM drives are popular (for example, for small main propulsion systems, thrusters, cargo pumps and other LV and HV applications). The increased installed drive capacity on vessels, whether based on AC or DC converters, has led to a significant increase in harmonic voltage distortion levels on a large number of vessels. Although in many cases harmonic mitigation has been used, these may not be sufficient to attain the levels of attenuation necessary to guarantee compliance with the harmonic limits imposed by classification societies. In a relatively large number of cases, the harmonic voltage distortion has reached surprising levels, well in excess of the classification societies’ limitations.

AC PWM drives with “active front ends” (sinusoidal input rectifiers), which offer relatively low harmonic current levels compared to present “standard” AC converter drives, have been available for a number of years. There are a number of significant commercial and technological issues still to be completely resolved, including cost, physical size, increased levels of electro-magnetic interference (EMI), input bridge carrier frequency suppression which needs large passive reactor-capacitor-reactor (L-C-L) filters, the production of high order harmonics (usually above the 40th or 50th) and compatibility with generator-derived supplies regarding suitably low values of source impedance. However, despite these issues, their use in marine applications is increasing. There are a number of harmonic mitigation solutions which, when used with “standard” 6-pulse AC drives, offer similar levels of performance at less cost, reduced complexity, higher efficiency, less EMI and higher reliability.

DC SCR drives are still operating in older vessels and in new, specialist survey vessels, for example, where low noise and vibration levels are important. The power ratings of DC drives systems, however, are largely limited to a few MWs due to restrictions on the brush-gear and mass of the DC motor armature.

It should be noted that the present power restrictions with AC PWM converters is due to lack of suitable power semiconductors in terms of current and voltage ratings. It is estimated that ratings up to 50 MW for AC PWM drives may be available within a few years based on new types of power devices.

3 Main Propulsion Drives

Electric drives for propulsion have been used onboard ship for the majority of the 20th Century, albeit in very small numbers. Indeed, small inland vessels with DC electric motors for propulsion operated in the United Kingdom and Russia as early as 1893.

Large seagoing vessels first appeared with full electric propulsion in the 1920s with the introduction of the Panama Pacific Line ships, *Virginia* and *California*, each powered by two synchronous motors each rated at 6750 HP. In Europe around the same time, four synchronous motors with a total of 116MW (155,500HP) propelled the French passenger liner, *Normandie*. During the Second World War, DC propulsion motors were used extensively on US-built T2 tankers. Cruise liners in the 1960s, including *Canberra*, were fitted with 30 MW (40,000 HP) synchronous propulsion motors. In the mid 1980s, *Queen Elizabeth II* was converted from steam turbine to electric propulsion by installing two 40 MW synchronous motors and converters. A large proportion of modern cruise liners also utilize full electric propulsion, either via conventional shaft arrangements or via podded propulsors.

The application of electric propulsion has increased in the last five years, largely due to the introduction of new classes of vessels and the expansion of new builds, including Ropax ferries, offshore supply vessels, survey ships, “floating production storage and offloading” vessels (FPSOs), shuttle tankers, cable-ships and cruise liners, where electric propulsion provides significant benefits, including increased cargo carrying capabilities, lower running costs, less maintenance, reduced manpower, greater redundancy, lower emissions and improved maneuverability (with podded or azimuth type propulsors – see Section 1, Figure 6.).

As of the year 2000, over 2% of vessels over 500 gross tons were fitted with electrically-driven propulsion. The percentage of new vessels being built with electric propulsion continues to increase annually.

Section 1, Figure 7, shows a typical application of an electrically-propelled vessel, in this instance a dynamically-positioned shuttle tanker using AC drives; 12 MW cycloconverters for main propulsion and PWM drives for thrusters, fixed and podded, in addition to main cargo pumps.

The decision as to whether to install electric propulsion in a vessel is complex and is usually dependent on the type of vessel and the operating profile envisaged. Naval warship design, however, is currently also being significantly changed with the adoption of fully-integrated electric propulsion systems, which will accrue significant strategic additional benefits from new generations of electric weapon platforms that will utilize the increased onboard power generating capacity necessary for the main electric propulsion systems.

FIGURE 6
Electrically-driven Podded Propulsor

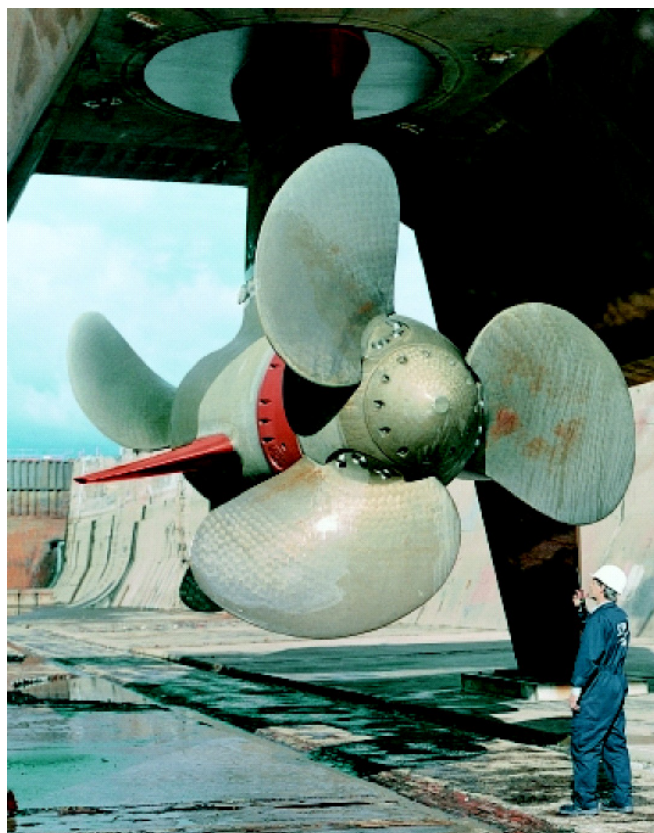
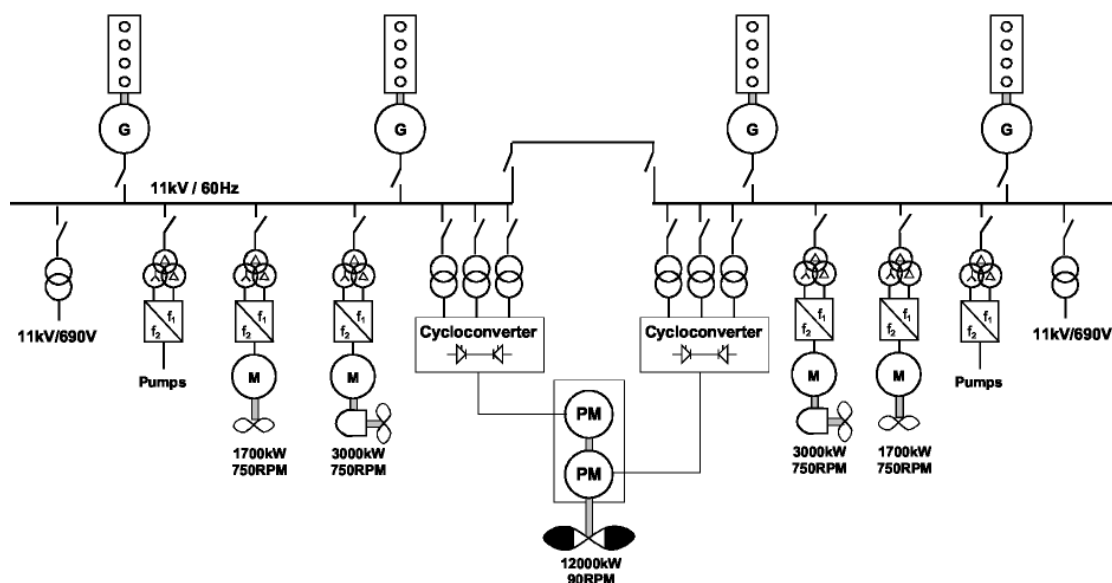


FIGURE 7
Dynamically-positioned Shuttle Tanker Equipped with AC Electric Variable Speed Main Propulsion and Thrusters



4 The Future?

The use of electric variable speed drives, particularly AC converters, for main propulsion and a host of other applications within the marine and offshore sectors will continue to increase.

The continual advances in power semiconductors, electromagnetics, control systems, software engineering and other related technologies will lead to the development of higher performance, more compact, more cost effective and more efficient types of electric drives and motors.

The majority of the emerging AC drive converter types, including “matrix converters”, “resonant converters” and “pulse frequency modulated” (PFM) converters will all have low harmonic profiles compared to the majority of generic drive technologies available at present.

However, it may be some years before these emerging AC drive converter developments permeate through from mainly military (naval) development programs and are available to commercial organizations. Their financial viability for any applications other than specialized naval warship duties may also have to be carefully assessed. In the meantime, the issue of harmonic distortion and the effects on plant and equipment has to be addressed to ensure the safety of the ship or offshore installation, the protection of the crew, and where appropriate, the passengers and the marine environment.

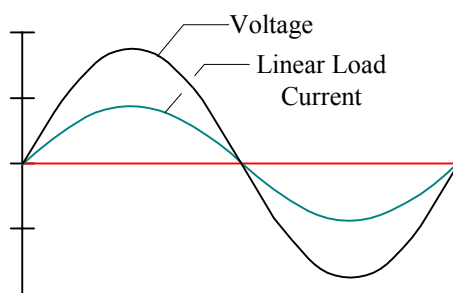
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SECTION 2 The Production of Harmonics

1 Production of Harmonics

In a power system, any item of equipment which draws current from the supply which is proportional to the applied voltage is termed a “linear” load. Examples of linear loads include resistance heaters and incandescent lamps. The current and voltage waveforms associated with linear loads are shown in Section 2, Figure 1.

FIGURE 1
Voltage and Current Waveforms for Linear Load



The term “nonlinear” is used to describe loads which draw current from the supply that is dissimilar in shape to the applied voltage. Examples include discharge lighting, computers and variable speed drives.

In order to explain pictorially how nonlinear current distorts the voltage supply waveform it is necessary to refer Section 2, Figures 2 and 3.

Section 2, Figure 2a illustrates a simple single-phase full wave rectifier supplying a load containing both inductance and resistance. The impedance of the AC supply is represented by the inductance L_{ac} . Section 2, Figure 2b illustrates the DC load current (I_{dc}) and AC input current (I_{ac}), respectively.

FIGURE 2a
Single Phase Full Wave Rectifier

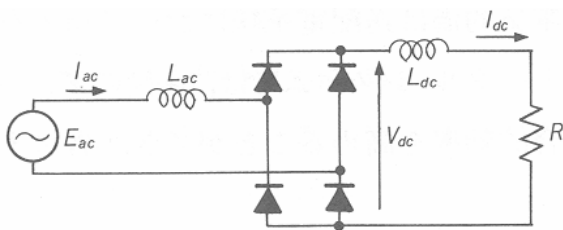
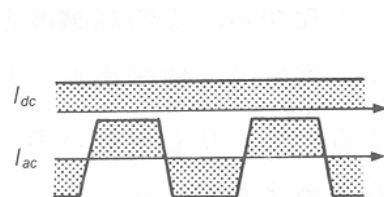


FIGURE 2b
Load and AC Supply Currents



Section 2, Figure 3a shows a simple single line diagram comprising source voltage (u) and source impedance (L_N). The harmonic current (i_N) passing through the source impedance produces a voltage drop (U_L) according the following formula:

$$U_L = L_N \cdot \frac{di_N}{dt} \dots\dots\dots (2.1)$$

Section 2, Figure 3b illustrates the nonlinear current (i_N) and voltage drop (U_L) waveforms.

FIGURE 3a
Simple Single Line
Diagram

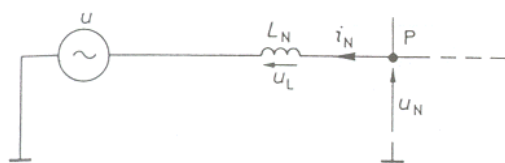
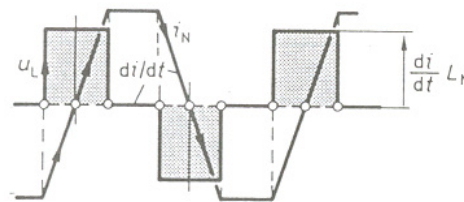


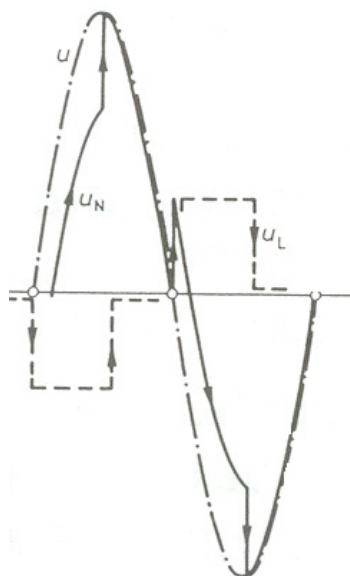
FIGURE 3b
Load Current and Volt Drop
Waveforms



The voltage drop across the source impedance (U_L) is subtracted from the induced voltage (u), resulting in the distortion of the supply voltage waveform, as illustrated in Section 2, Figure 4.

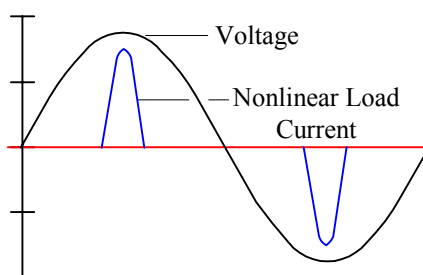
Note: The example below has been exaggerated in order to illustrate the principle graphically of how nonlinear current distorts the supply voltage.

FIGURE 4
How Voltage Distortion is Produced (Simplified)



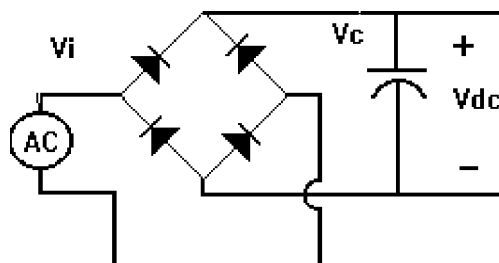
The majority of nonlinear loads is equipment that utilizes power semiconductor devices for power conversion (e.g., rectifiers). They include, for example, computer switched mode power systems (SMPS) for converting AC to DC. Section 2, Figure 5 illustrates a typical current waveform of a computer switched mode power supplier unit.

FIGURE 5
Typical Computer Nonlinear Load



In order to appreciate why the current waveform shown in Section 2, Figure 5 is of a “pulsed” nature, it is beneficial to consider the design of switched mode power supplies, an example of which is illustrated in Section 2, Figure 6.

FIGURE 6
Single-phase Switched Mode Power Supply



This type of power supply uses capacitors to smooth the rectified DC voltage and current prior to it being supplied to other internal subsystems and components. The semiconductor diode rectifiers are unidirectional devices (i.e., they conduct in one direction only). The additional function of the capacitor is to store energy which is drawn by the load as necessary. When the input voltage (V_i) is higher in value than the capacitor voltage (V_c), the appropriate diode will conduct and non-sinusoidal, “pulsed” current will be drawn from the supply. This non-sinusoidal current contains “harmonic currents” in addition to the sinusoidal fundamental (50 Hz or 60 Hz) current, as illustrated in Section 2, Figure 7.

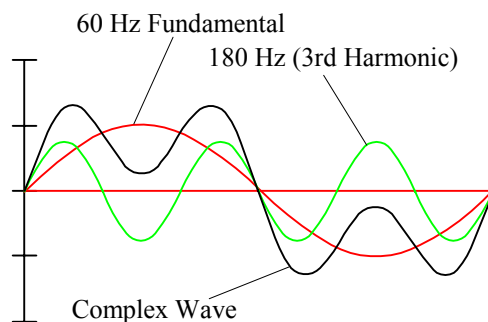
Note: As can be seen below, the harmonic spectrum contains only “odd” harmonics (1, 3, 5, 7...). This is due to the “full wave rectification” used in the SMPS. If the SMPS were to use “half wave” rectification “even” order (2, 4, 6, 8...) harmonics would also be present.

FIGURE 7
Harmonic Spectrum of Currents Drawn by
Computer Switched Mode Power Supply



Harmonic voltages and currents are integer multiples of the fundamental frequency. On 60 Hz supplies, for instance, the 5th harmonic is 300 Hz; the 7th harmonic is 420 Hz, and so forth. When all harmonic voltages and currents are added to the fundamental, a waveform known as a “complex wave” is formed. An example of complex wave consisting of the fundamental (1st harmonic) and 3rd harmonic is illustrated in Section 2, Figure 8.

FIGURE 8
Construction of Complex Wave



Section 2, Figure 8 is an example of a symmetrical waveform in which the positive portion of the wave is identical to the negative portion. It should be noted that symmetrical waveforms only contain odd harmonics, whereas asymmetrical waveforms (where both positive and negative portions are different) contain even and odd harmonics and possibly DC components. An example of an asymmetrical waveform would be that produced by a half wave rectifier.

2 Characteristic Harmonic Currents

Power conversion using full wave rectifiers generates idealized characteristic harmonic currents given by the formula:

$$h = np \pm 1 \dots\dots\dots (2.2)$$

where

h = order of harmonics

n = an integer 1, 2, 3...

p = number of current pulses per cycle

It should be noted that in the “ideal” harmonic theory, the following hypotheses are assumed for all rectifiers:

- The impedance of the AC supply network is zero.
- The DC component of the rectifier configuration is uniform.
- An AC line or commutating reactor is not used in front of the rectifier.
- The AC supply network is symmetrical (i.e., balanced).
- The AC supply is sinusoidal, free from harmonics.
- There are no “overlap” or delay angles for the devices.

Note: Any divergence from any of the above hypotheses will introduce “non-characteristic” harmonics, including possibly DC, into the harmonic series. In practical terms, it has to be noted that supply networks or connected equipment are never “idealized” (i.e., based on the above hypotheses) and, therefore, any actual harmonic currents measured will not be exactly as calculated using the above simplified formula.

In addition, in idealized harmonic theory, the magnitude of the harmonic current is stated as the reciprocal of the harmonic number:

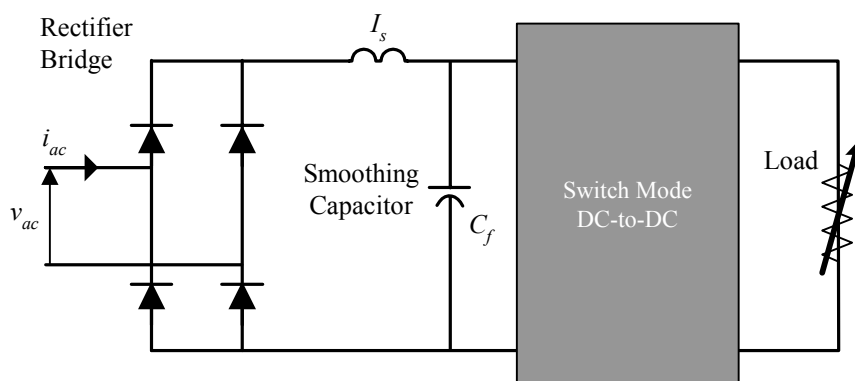
$$I = \frac{1}{h} \dots\dots\dots (2.3)$$

Therefore, in theory, the 5th harmonic current and 7th harmonic current, for example, should represent 20% and 14% of the total rms current, respectively. However, again, this is never transferred into practical reality as the magnitudes of the various harmonic currents are determined by the per-phase inductance of the AC supply connected, the rectifier and the impedance of the rectifier as “seen” by the AC supply.

In rectifiers without added inductance (e.g., AC line reactors) it is not uncommon to measure 5th harmonic current up to ~80% on single-phase rectifiers and 65% on three-phase rectifiers.

Section 2, Figure 9 illustrates a typical single-phase computer switched mode power supply with full wave bridge rectifier.

FIGURE 9
Computer Power Supply with Single-phase Full Wave Bridge Rectifier



For the single full wave diode bridge rectifier above, the characteristic harmonic currents based on two rectified current pulses per cycle (i.e., one per half cycle per phase), as shown in Section 2, Figure 10, converted into DC load will be:

$$h = np \pm 1$$

$$h = n \cdot 2 \pm 1$$

$$h = 3, 5, 7, 9, 11, 13, 15 \dots$$

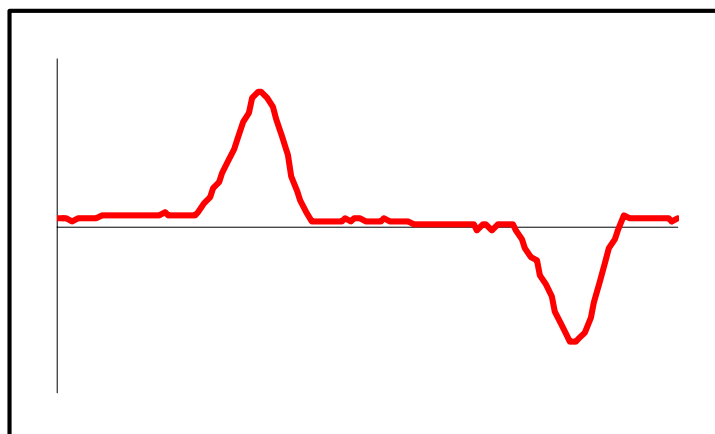
where

h = harmonic number

n = integer, 1, 2, 3...

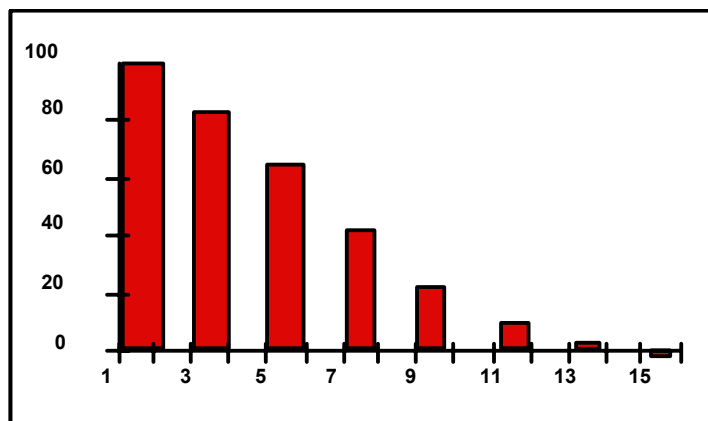
p = pulses, (2)

FIGURE 10
Computer Switch Mode Power Supply Input Current Waveform



The harmonic series calculated for a single-phase full wave rectifier is shown in Section 2, Figure 11.

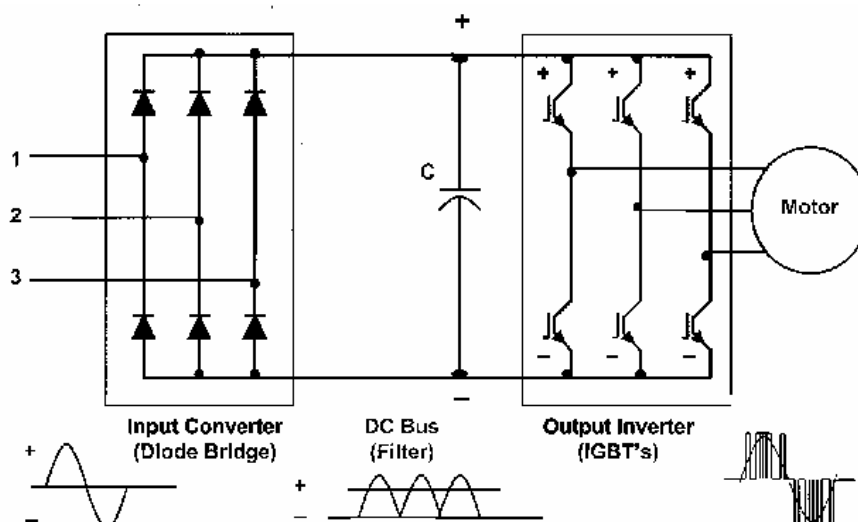
FIGURE 11
Typical Waveform from Computer Switched Power Supply



Note: It should be noted that in four-wire distribution systems (three-phase and neutral), the currents in the three phases return via the neutral conductor, the 120-degree phase shift between respective phase currents causes the currents to cancel out in the neutral, under balanced loading conditions. However, when nonlinear loads are present, any “triplen” (3rd, 9th...) harmonics in the phase currents do not cancel out but add cumulatively in the neutral conductor, which can carry up to 173% of phase current at a frequency of predominately 180 Hz (3rd harmonic). This issue will be discussed in more detail in Section 4, “Sources of Harmonics”.

Section 2, Figure 12 shows a typical 6-pulse PWM AC drive, where the rectifier bridge supplies the DC link section of the drive.

FIGURE 12
Typical 6-Pulse PWM AC Drive



For a three-phase full wave diode rectifier bridge [also known as a “6-pulse bridge”, as it rectifies six current pulses (one per half cycle per phase) into the load side of the bridge], the characteristic harmonic currents will therefore be:

$$h = np \pm 1$$

$$h = n \cdot 6 \pm 1$$

$$h = 5, 7, 11, 13, 17, 19, \dots$$

where

h = harmonic number

n = integer, 1, 2, 3...

p = pulses, (6)

Similarly, the characteristic harmonic currents for a 12-pulse rectifier will be:

$$h = n \cdot 12 \pm 1$$

$$h = 11, 13, 23, 24, 35, 37, \dots$$

Section 2, Figures 13 and 14, respectively, show the input phase current waveforms and harmonic current spectrum measured on a typical 6-pulse AC PWM drive.

FIGURE 13
6-Pulse AC PWM Drive Input Current Waveforms for One Phase

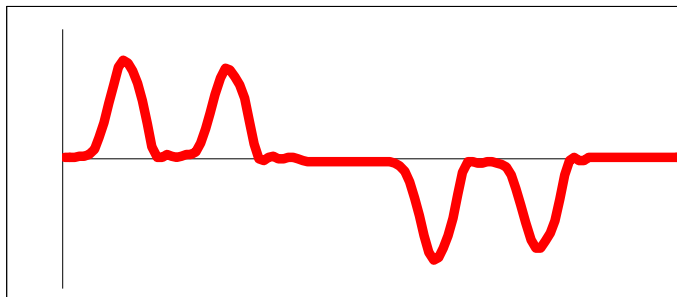
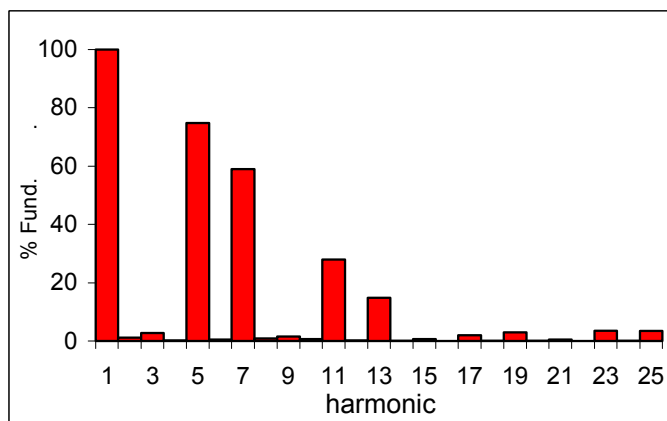


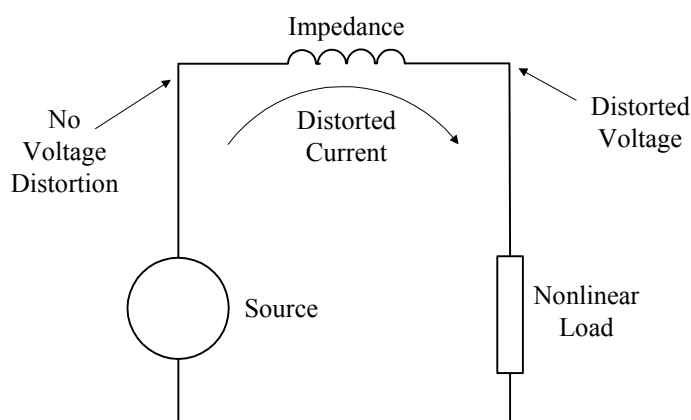
FIGURE 14
Typical Harmonic Spectrum for 6-Pulse AC PWM Drive



3 Effect of Harmonic Currents on Impedance(s)

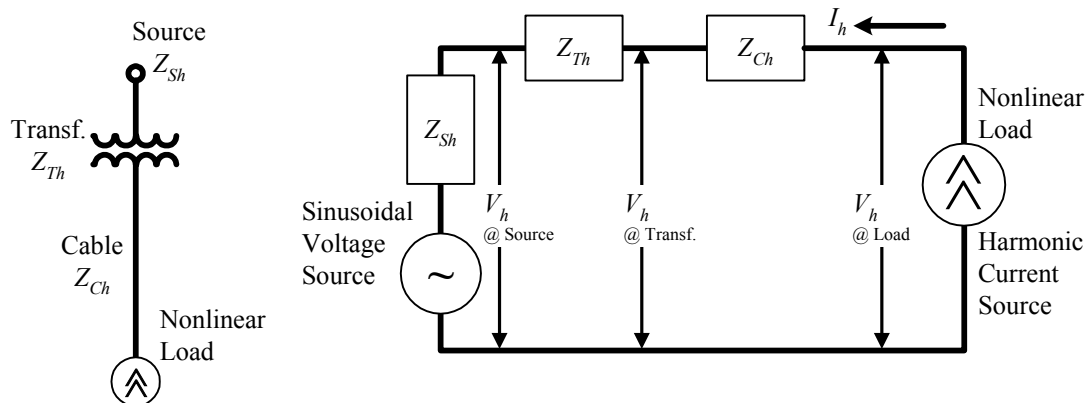
Section 2, Figure 15 shows in a simplified form that when a nonlinear load draws distorted (non-sinusoidal) current from the supply, that distorted current passes through all of the impedance between the load and power source. The associated harmonic currents passing through the system impedance cause voltage drops for each harmonic frequency based on Ohm's Law ($V_h = I_h \times Z_h$). The vector sum of all the individual voltage drops results in total voltage distortion, the magnitude of which depends on the system impedance and the levels of harmonic currents at each harmonic frequency.

FIGURE 15
Distorted Currents Induce Voltage Distortion



Section 2, Figure 16 shows in detail the effect individual harmonic currents have on the impedances within the power system and the associated voltage drops for each. Note that the “total harmonic voltage distortion”, V_{thd} (based on the vector sum of all individual harmonics), is reduced as more impedance is introduced between the nonlinear load and the source.

FIGURE 16
How Individual Harmonic Voltage Drops Develop Across System Impedances



$$V = I_h \times Z_h \text{ (Ohm's Law)}$$

$$\text{At the load: } V_h = I_h \times (Z_{Ch} + Z_{Th} + Z_{Sh})$$

$$\text{At the trans.: } V_h = I_h \times (Z_{Th} + Z_{Sh})$$

$$\text{At the source: } V_h = I_h \times (Z_{Sh})$$

where

$$Z = \text{impedance at frequency of harmonic (e.g., 250 Hz)}$$

$$V_h = \text{harmonic voltage at } h\text{-th harmonic (e.g., 5th)}$$

$$I_h = \text{harmonic current at } h\text{-th harmonic (e.g., 5th)}$$

$$V_{thd} = \text{total harmonic voltage distortion}$$

4 Calculation of Voltage Distortion

Any periodic (repetitive) complex waveform is composed of a sinusoidal component at the fundamental frequency and a number of harmonic components which are integral multipliers of the fundamental frequency. The instantaneous value of voltage for non-sinusoidal waveform or complex wave can be expressed as:

$$v = V_0 + V_1 \sin(\omega t + \phi_1) + V_2 \sin(2\omega t + \phi_2) + V_3 \sin(3\omega t + \phi_3) + \dots V_n \sin(n\omega t + \phi_n) \dots \dots \dots (2.4)$$

where

$$v = \text{instantaneous value at any time } t$$

$$V_0 = \text{direct (or mean) value (DC component)}$$

$$V_1 = \text{rms value of the fundamental component}$$

$$V_2 = \text{rms value of the second harmonic component}$$

$$V_3 = \text{rms value of the third harmonic component}$$

$$V_n = \text{rms value of the } n\text{th harmonic component}$$

$$\phi = \text{relative angular frequency}$$

$$\omega = 2\pi f$$

$$f = \text{frequency of fundamental component (1/f defining the time over which the complex wave repeats itself)}$$

It is usually more convenient, however, to interpret a complex wave by means of "Fourier Series" and associated analysis methods. Joseph Fourier, a 19th century French physicist introduced a theory that any periodic function in a interval of time could be expressed by the sum of the fundamental and a series of higher order harmonic frequencies which are integral multipliers of the fundamental component.

Ignoring any DC components in the above formula, where V_1 and I_1 represent the fundamental voltage and current, respectively, the instantaneous rms voltage, V_h , can be represented as a Fourier Series:

$$v(t) = \sum_{h=1}^{\infty} v_h(t) = \sum_{h=1}^{\infty} \sqrt{2} V_h \sin(h\omega_0 t + \phi_h) \dots\dots\dots (2.5)$$

The rms value of voltage can be expressed as:

$$V_{rms} = \sqrt{\frac{1}{T} \int_0^T v^2(t) dt} = \sqrt{\sum_{h=1}^{\infty} V_h^2} = \sqrt{V_1^2 + V_2^2 + V_3^2 \dots\dots + V_n^2} \dots\dots\dots (2.6)$$

$$I_{rms} = \sqrt{\frac{1}{T} \int_0^T i^2(t) dt} = \sqrt{\sum_{h=1}^{\infty} I_h^2} = \sqrt{I_1^2 + I_2^2 + I_3^2 \dots\dots + I_n^2} \dots\dots\dots (2.7)$$

The rms voltage or current “total harmonic distortion”, V_{thd} and I_{thd} , respectively can be expressed as:

$$V_{thd} = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1} \times 100\% = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 \dots\dots + V_n^2}}{V_1} \times 100\% \dots\dots\dots (2.8)$$

$$I_{thd} = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \times 100\% = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 \dots\dots + I_n^2}}{I_1} \times 100\% \dots\dots\dots (2.9)$$

Other simple but practical harmonic formulae include:

$$\text{Total rms current: } I_{rms} = \sqrt{I_{fund}^2 + I_{harm}^2} \dots\dots\dots (2.10)$$

$$\text{or } I_{rms} = I_{fund} \sqrt{1 + \left(\frac{I_{thd}}{100}\right)^2} \dots\dots\dots (2.11)$$

$$\text{Fundamental current: } I_{fund} = \frac{I_{rms}}{\sqrt{1 + I_{thd}^2}} \dots\dots\dots (2.12)$$

$$\text{Total fundamental current distortion: } I_{thd(fund)} = \sqrt{\left(\frac{I_{rms}}{I_{fund}}\right)^2 - 1} \dots\dots\dots (2.13)$$

$$\text{Total Demand Distortion (TDD)} = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_{load}} = I_{TDD} = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 \dots\dots + I_n^2}}{I_{load}} \dots\dots\dots (2.14)$$

where

I_{load} = maximum demand load current (fundamental) at the PCC

TDD = ‘total demand distortion’ of current (expressed as measured total harmonic current distortion, per unit of load current. For example, a 30% total current distortion measured against a 50% load would result in a TDD of 15%).

Note: In the above Equations 2.10 to 2.13, the voltage (V) can be substituted for the current (I).

5 Harmonic Sequence Components

Each harmonic has an order (number), a frequency which is an integer multiple of the fundamental frequency and a “sequence”. The sequence refers in vector rotation with respect to the fundamental. Section 2, Table 1 details the harmonic sequence components for an idealized 6-pulse rectifier.

TABLE 1
Harmonic Sequence Components for 6-Pulse Rectifier

Harmonic	1	5	7	11	13	17	19	23	25....
Sequence	+	-	+	-	+	-	+	-	+
Rotation	F	B	F	B	F	B	F	B	F

Harmonics such as the 7th, 13th, 19th and 25th, and so on, which rotate in a forward direction (i.e., in the same sequence as fundamental) are termed “positive sequence harmonics” whereas the 5th, 11th, 17th, 23rd, and so on, which rotate in the opposite direction to the fundamental are termed “negative sequence harmonics”.

Triplen harmonics (3rd, 9th...), as produced in single-phase full wave rectifiers, for example, do not rotate. They are in phase with each other and are therefore termed “zero sequence harmonics”.

The impact of sequence harmonics on rotating machines will be discussed in Section 3, “Effects of Harmonics”.

6 Line Notching

Although not strictly “harmonics”, “line notching” is a phenomenon normally associated with the SCR (thyristor) based “phase-controlled” rectifiers such as those utilized in AC and DC variable speed drives and UPS systems, also sources of harmonics. Diode bridges can also exhibit “commutation notches”, but to a lesser extent than those associated with SCR bridges. The effects of “line notching” can have a serious impact on the supply system and other equipment.

Section 2, Figure 17 depicts a simple three-phase full wave SCR bridge network supplying a DC load.

Section 2, Figure 18 illustrates theoretical notching at the terminals of the SCR input bridge and therefore assumes no additional inductance in the circuit. The voltage notches occur when the continuous line current commutates (i.e., transfers) from one phase to another. During the “commutation period”, the two phases are short-circuited (i.e., connected together) for very short durations through the converter bridge and the AC source impedance. The result is that the voltage, as illustrated, reduces to almost zero as the current increases, limited only by the circuit impedance.

FIGURE 17
Simple Three-phase SCR Bridge for Phase Control

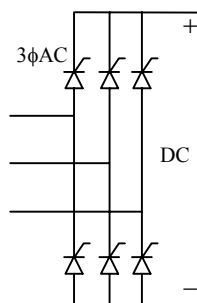
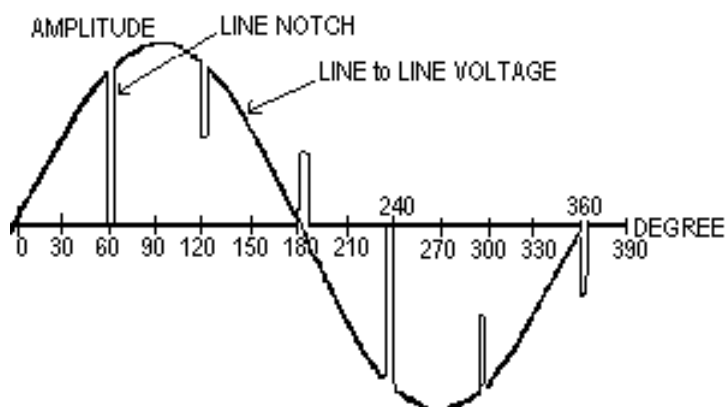


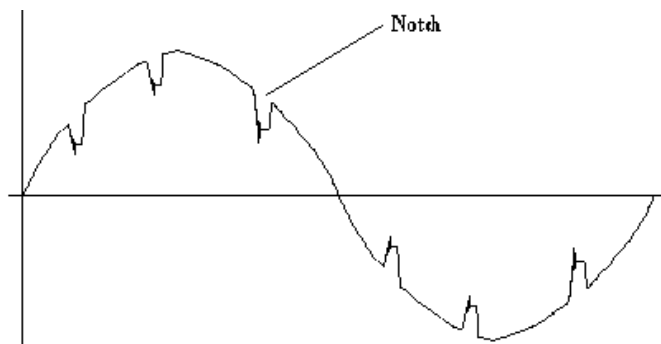
FIGURE 18
Exaggerated Example of “Line Notching”



In practical terms, the notches can be present anywhere in the respective half cycles, as the phase angle of SCRs varies according to the needed output voltage (or current for current source AC drives). The disturbances associated with line notching tend to progressively reduce nearer to a “stiff” source impedance (i.e., an impedance of relatively low value with relatively high short circuit capacity) due to the additional impedances downstream in the circuit, including that associated with cabling.

With reference to Section 2, Figure 19, the area of the notch (depth and width) is dependent on the volt-milliseconds absorbed in the circuits in the line from the source generator or transformer to the SCR bridge input terminals. It is common practice to add “commutation reactors” or isolation transformers in the AC line of the SCR bridge to minimize the notch, but regardless of how much inductance is added at the bridge terminals, the notch area tends to remain constant as the addition of AC line inductance will reduce the notch depth *but will increase the notch width*. It should be noted that the only real practical way to reduce the notch area is to provide part of the necessary commutation energy from a capacitor bank.

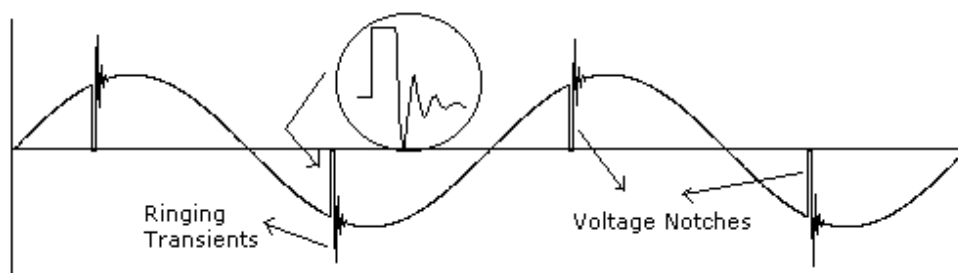
FIGURE 19
Voltage Notching due to SCR Bridge Commutation



In severe cases, especially where no additional AC line reactance is present, the voltage can be reduced to zero creating additional “zero crossovers” (i.e., the points where the voltage would normally change polarity). Section 1, Figures 2 and 3 illustrates the significant effects of line notching. The oscillograph in Section 1, Figure 3 refers to a vessel where up to four AC SCR input bridge drives were operating.

Although secondary to line notching, an important phenomenon associated with SCR phase control is “ringing”. “Ringing” is the term given high frequency oscillations due to the rapid switching of the SCRs, as illustrated in Section 2, Figure 20. It is the result of high frequency “resonance” occurring in the rectifier circuit due to inherent inductance and capacitance in the equipment circuitry.

FIGURE 20
SCR Line Notching and Associated “Ringing”



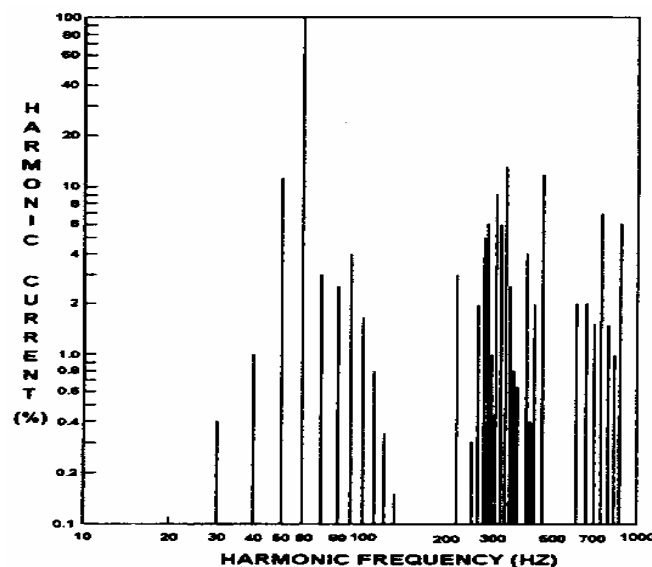
It should be noted that line notching and associated ringing do not usually influence the V_{thd} , as the harmonics associated with them are of high frequency, usually above the highest measured (i.e., 50th). However, line notching and ringing can have significant effects on voltage quality, as shown in Section 1, Figure 4. The effects of line notching on generators and other equipment will be discussed in Section 3.

7 Interharmonics

Interharmonics are defined in IEC Standard 1000-2-1 as: “Between the harmonics of the power frequency voltage and current, further frequencies can be observed which are not an integer of the fundamental. They appear as discrete frequencies or as a wide-band spectrum”.

Interharmonics can therefore be considered as the “inter-modulation” of the fundamental and harmonic components of the system with any other frequency components. These can be observed increasingly with nonlinear loads, including large AC frequency converters drives (especially under unbalanced conditions and/or levels of pre-existing voltage distortion), cycloconverters (see Section 2, Figure 21) and static slip recovery drives.

FIGURE 21
Cycloconverter Current Spectrum – Includes Interharmonics



Both harmonics and interharmonics can be defined in a quasi-steady state in terms of their spectral components over a range of frequencies as detailed below:

Harmonics: $f = h \cdot f_1$ where h is an integer > 0

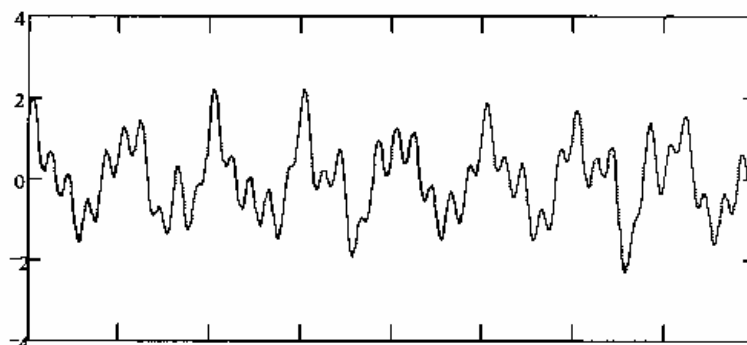
DC: $f = 0 \text{ Hz}$ ($f = h \cdot f_1$, where $h = 0$)

Interharmonics: f is not equal to $h \cdot f_1$, where h is an integer > 0

Subharmonics: $f > 0$ and $f < f_1$, where f_1 is the fundamental frequency

Waveforms which contain both harmonics and interharmonics of constant amplitude but differing frequencies are rarely periodic (i.e., repetitive), as Section 2, Figure 22 illustrates. The effect of interharmonics on equipment will be discussed in later Sections. See 3/5.1, 3/6, 4/3.3, 6/2.4 and 10/11.1.

FIGURE 22
Waveform Containing both Harmonics and Interharmonics



Due to the modulation of steady state harmonic voltages, the supply voltage will vary in amplitude and rms value according to:

$$v(t) = \sin(2\pi f_1 t) + a \sin(2\pi f_i t) \dots \dots \dots (2.15)$$

where

f_1 = fundamental frequency

a = amplitude (per unit) of the interharmonics voltage
 (amplitude of the fundamental voltage = 1.0 per unit *)

f_i = interharmonics frequency

* The per unit system is based on the formula below. Using this method, quantities are expressed as ratios, similar to the use of percentage values.

$$\text{per unit} = \frac{\text{actual quantity}}{\text{base quantity}}$$

Note: Maximum voltage change in the voltage amplitude is equal to the amplitude of the interharmonics voltage, while the change in the voltage rms value is dependent on both the amplitude and the interharmonics frequency.

The rms voltage value can be given by:

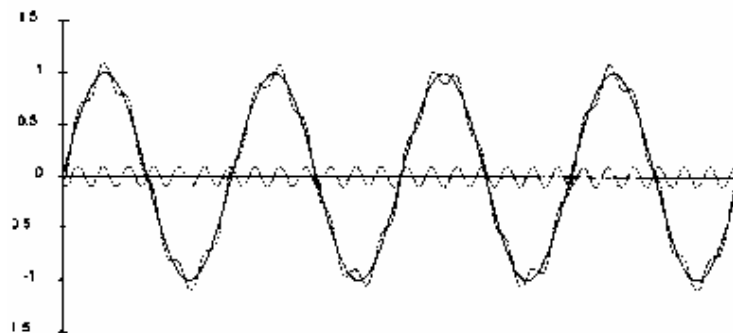
$$V = \sqrt{\frac{1}{T} \int_0^T v(t)^2 dt} \dots \dots \dots (2.16)$$

where the period of integration $T = 1/f_1$.

The maximum percentage rms voltage deviation over several periods of the fundamental due to interharmonics can be calculated by combining Equations 2.15 and 2.16.

In equipment which utilize capacitors on the DC side (for example, AC PWM drives), current is only drawn from the supply when the AC voltage is greater than the DC side capacitor voltage, and as such, it is the AC peak voltage which normally recharges the capacitor(s). The resultant integer harmonics in the voltage supply do not effect the AC peak voltage as these integer harmonics are synchronized with the fundamental frequency. However, interharmonics are not synchronized with the fundamental and therefore affect the peak amplitude of the AC supply voltage (see Section 2, Figure 23) causing deviations of peak voltage which can adversely effect the connected equipment, both those utilizing capacitors and also several types of lighting.

FIGURE 23
Peak Voltage Deviations due to Interharmonics Voltage



The distorted voltage waveform depicted in Section 2, Figure 23 can be calculated as:

$$V(t) = V_1 \sin(2\pi f_1 t) + V_n \sin(2\pi f_n t) \dots \dots \dots (2.17)$$

where

- V_1 = amplitude of fundamental voltage
- t = time
- f_1 = fundamental voltage
- V_n = amplitude of interharmonics n
- n = fractional real number of interharmonics order

The variation of the supply voltage amplitude is calculated from the difference between the maximum and minimum peak values ($V_{\max}$ and $V_{\min}$) recorded over several cycles of the function $V(t)$. Therefore:

$$\Delta V = V_{\max} - V_{\min} \dots \dots \dots (2.18)$$

Note: The measurement of interharmonics, compared to that of integer harmonics, poses considerable problems for traditional harmonic measuring equipment, which uses phase-locked loops and Fast Fourier Transform (FFT) techniques. This is due to the interharmonic frequency components being non-related to the fundamental frequency and non-periodic. However, for the measurement and identification of interharmonics it may not be necessary to perform an analysis which depends on the supply fundamental frequency. Methods of analysis used in the communication industries have been adapted for use in the measurement and analysis of interharmonics components.

8 Subharmonics

“Subharmonics” is an unofficial but common definition given to interharmonics whose frequency is less than that of the fundamental (i.e., $f > 0$ Hz and $f < f_1$). The more technically correct term, “sub-synchronous frequency component”, is also used to define subharmonics.

Therefore, it should be noted that the calculations provided above associated with interharmonics are valid for “subharmonics” also.

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SECTION 3 Effects of Harmonics

1 Generators

In comparison to shore-based utility power supplies, the effects of harmonic voltages and harmonic currents are significantly more pronounced on generators due to their source impedance being typically three to four times that of utility transformers.

The major impact of voltage and current harmonics is the increase in machine heating caused by increased iron losses, and copper losses, both frequency dependent. [On shore installations, it is relatively common practice to “derate” (reduce the output of) generators when supplying nonlinear loads to minimize the effects of harmonic heating.] In addition, there is the influence of harmonic sequence components, both on localized heating and torque pulsations.

1.1 Thermal Losses

The iron losses comprise two separate losses, “hysteresis losses” and “eddy current losses”.

The *hysteresis loss* is the power consumed due to nonlinearity of the generator’s flux density/magnetizing force curve and the subsequent reversal in the generator’s core magnetic field each time the current changes polarity (i.e., 120 times a second for 60 Hz supplies). Higher hysteresis losses occur at harmonic frequencies due to the more rapid reversals compared to those at fundamental frequency. Hysteresis losses are proportional to frequency and the square of the magnetic flux.

Eddy currents circulate in the iron core, windings and other component parts of the generator induced by the stray magnetic fields around the turns in the generator windings. Eddy currents produce losses which increase in proportion to the square of the frequency. The relationship of eddy current losses and harmonics is given by:

$$P_{EC} = P_{EF} \sum_{h=1}^{h_{\max}} I_h^2 h^2 \dots\dots\dots (3.1)$$

where

- P_{EC} = total eddy current losses
- P_{EF} = eddy current losses at full load at fundamental frequency
- I_h = rms current (per unit) harmonic h
- h = harmonic number

On linear loads, the eddy current losses are fairly minor but become more significant as the harmonic loading increases.

Copper losses are dissipated in the generator windings when current is passed through the winding resistance. For a given load, when harmonic currents are present, the total rms value of the current passing through the windings will be increased, thereby increasing the losses according to:

$$P_{CU} = I_{rms}^2 R \dots\dots\dots(3.2)$$

where

P_{CU} = total copper losses

I_{rms} = total rms current

R = resistance of winding

The copper losses are also influenced by a phenomenon termed “skin effect”. Skin effect refers to the tendency of current flow to be confined in a conductor to a layer close to its outer surface. At fundamental frequency, the skin effect is negligible and the distribution of current across the cable is uniform. However, at harmonic frequencies, skin effect is substantially more pronounced, significantly reducing the effective cross sectional area of the conductor and increasing its resistance. The higher the resistance, the higher the I^2R losses.

The harmonic stator current drawn by the nonlinear load will result in air gap fluxes, similar in shape to the fundamental but rotating at harmonic frequencies, inducing currents in the rotor iron and windings, adding to rotor losses and the associated temperature rise.

1.2 Effect of Sequence Components

Harmonic currents occur in pairs each having a negative or a positive sequence rotation. The 5th harmonic is negative sequence and induces in the rotor a negatively-rotating 6th harmonic; the 7th harmonic is positive and similarly induces a positively-rotating 6th harmonic in the rotor. The two contra-rotating 6th harmonic systems in the rotor result in “amortisseur” or “damper” winding currents which are stationary with respect to the rotor, causing additional, localized losses and subsequent heating. Within the rotor, this effect is similar to that caused by single-phase or unbalanced-phase operation, and overheating is unlikely provided the rotor pole faces are laminated. Similarly, the 11th and 13th harmonics will induce both negatively and positively rotating 12th harmonics in the rotor.

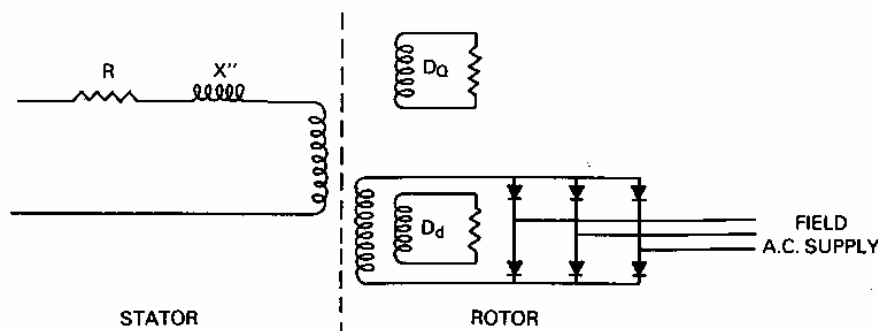
Harmonic pairs, in addition to causing additional heating, can create mechanical oscillations on the generator shaft. For 5th and 7th harmonic frequency, for example, the torque pulsations will be at six times for fundamental (360 Hz based on 60 Hz fundamental, relative to the stator). These result from the interaction between harmonic and fundamental frequencies exciting a specific mechanical resonant frequency. Shafts can be severely stressed due to these oscillations.

1.3 Voltage Distortion

A generator is designed to produce sinusoidal voltage at its terminals, but when nonlinear current is drawn, the harmonic currents interact with the system impedances to produce voltage drops at each individual harmonic frequency, thereby causing voltage distortion.

A simplified equivalent circuit for one phase of a three-phase generator is shown in Section 3, Figure 1. Note that the resistances are ignored as they are relatively small compared to the reactance. The iron and damper windings, D_d and D_q , respectively, prevent any rapid flux changes in the rotor.

FIGURE 1
Equivalent Circuit for a Generator



To calculate the rms harmonic voltage due to the respective harmonic current, the following method can be used:

$$V_h = \sqrt{3} \times I_h \times h \times X_{gen} \dots \dots \dots (3.3)$$

where

- V_h = L-L rms voltage of the harmonic h
- I_h = harmonic current at order h
- X_{gen} = generator reactance, in ohms
- h = harmonic number

To calculate the L-L rms harmonic voltage as a percentage of rms fundamental voltage:

$$\frac{V_h \times 100\%}{V_{rms}} \dots \dots \dots (3.4)$$

where

- V_h = L-L rms voltage of the harmonic h
- V_{rms} = L-L fundamental rms voltage

Example 1

Calculate the L-L rms 5th harmonic voltage for a 480 V generator with reactance X of 0.0346 ohms when the 5th harmonic current is 135 A. Also, express the harmonic voltage as a percentage of the fundamental rms voltage.

$$\begin{aligned} V_h &= \sqrt{3} \times I_h \times h \times X_{gen} \\ &= 1.732 \times 135 \times 5 \times 0.0346 \\ &= \underline{40.45 \text{ V}} \end{aligned}$$

5th harmonic voltage as a percentage of the fundamental rms voltage:

$$\begin{aligned}
 &= \frac{V_h \times 100\%}{V_{rms}} \\
 &= \frac{40.45 \times 100}{480} \\
 &= 8.43\%
 \end{aligned}$$

Note: Other percentage harmonic voltage components can be estimated by performing similar calculations for each harmonic current.

As detailed in Equation 2.6, V_{rms} , the total rms voltage including harmonic voltages, can be calculated using:

$$V_{rms} = \sqrt{\frac{1}{T} \int_0^T v^2(t) dt} = \sqrt{\sum_{h=1}^{\infty} V_h^2} = \sqrt{V_1^2 + V_2^2 + V_3^2 + \dots + V_n^2}$$

Similarly, the V_{thd} “voltage total harmonic distortion” can be expressed using Equation 2.8:

$$V_{thd} = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1} \times 100\% = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \dots + V_n^2}}{V_1} \times 100\%$$

Note: See Subsection 12/1 for practical examples of manual voltage distortion calculations.

1.4 Line Notching and Generators

Harmonic currents can cause significant problems in generators in addition to those attributable to additional losses and torsional pulsations. Modern generators use electronic governors to regulate the output voltage, to control the speed, and hence frequency, of the prime mover and to proportionally distribute the kW load of parallel connected generators.

Many electronic regulator units utilize measurement and control circuits which depend on “zero crossovers” (the point on a sine wave when the sinusoidal voltage or current cuts through the zero axis). Where “line notching” or “ringing” occurs, for example with large SCR phase control loads, additional zero crossovers may appear. The combination of harmonic distortion and line notching can cause hunting and instability in voltage and frequency regulation control loops. Many of these problems can be resolved, however, using low pass filters at the input of the appropriate sensing circuits, as shown in Section 3, Figure 2.

In addition, line notching often makes it difficult to correctly load share when parallel generators are operating. Load sharing depends on the measurement of the kW load on each generator. The rms value of current, which assumes fundamental only is normally used in the computation of the kW loading. When harmonic currents are present, false readings can occur when measurements based on average values are used. (Based on sinusoidal waveforms, the rms value is 1.11 times the average value. On waveforms containing harmonics, this assumption is no longer valid.)

Only equipment utilizing “true rms” techniques indicate correct readings for supplies containing harmonics. This is also valid for switchboard instrumentation. The effect of harmonics on instrumentation will be discussed in Subsection 3/9.

Note: For generator AVRs subject to voltage distortion, a low pass filter as detailed in Section 3, Figure 2, below, is recommended. This will result in the majority of the distortion from the voltage control signal being attenuated.