Electric Power Waveform Distortion

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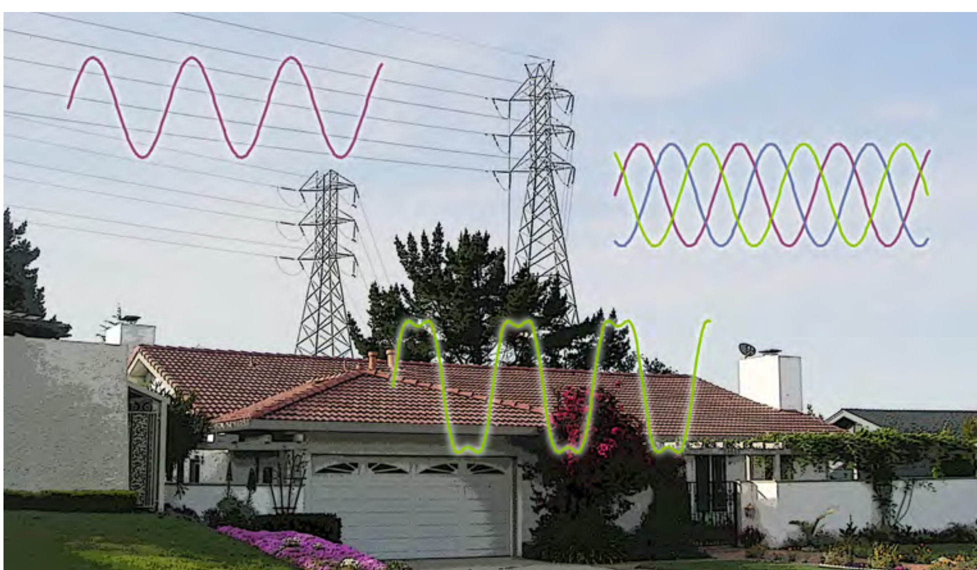
Introduction

Electricity is generated essentially as a pure sinusoidal waveform. In the process of generation, distribution, and use, this waveform is distorted, and frequencies other than the fundamental 50 or 60 Hz are created. Some people call this routine waveform distortion "dirty electricity" and imply that it is a recent development. "Dirty electricity" and "dirty power" are not engineering terms; rather, they are pejorative terms used by some to implicate electricity as a cause of some of the so-called "diseases of civilization." The term *dirty electricity* was popularized by Dr. Samuel Milham in his book of the same title[1] and has been described as "surges of high frequency voltage or electromagnetic radiation that contaminate our otherwise safe 60 Hz-frequency lines in our homes and buildings. These surges of contamination can come from radio waves, ground currents or high frequency spikes and harmonics coming from appliances, computer and entertainment electronics and other electrical sources."[2] Dirty electricity has been claimed to be implicated in cancer,[3] cardiovascular disease, diabetes, and suicide.[4]

Contrary to the implications in the literature on dirty power, 50 or 60 hertz alternating current electric power has not always been "pure." Higher frequencies in the form of harmonics and transients, including coupled radio frequencies, have been around since the dawn of the electrical age. From the earliest years, measures have been taken to limit higher frequency components. From



the utility side, there has always been the need to reduce equipment heating and power losses, to maintain the performance of electrical machinery, and to limit interference to nearby telephone circuits.

Developments in power electronics, especially devices in the home, have greatly increased the presence of waveform distortion and accompanying harmonics.

Developments in power electronics, especially devices in the home such as light dimmers, compact fluorescent lamps, and switching power supplies in computers and television sets, have greatly increased the presence of waveform distortion and accompanying harmonics. These newer applications are on the customer side of the meter—not the power company's—and are the result of people's increasing desire for the benefits of the newest electronic technology.

This resource paper introduces some of the causes of non-power frequency components that exist on the power system and provides historical perspective to help bring an understanding of the physical phenomena involved wherever electricity is present. Voltage and current waveform distortion are certainly not new but may today be more common because of trends in customers' usage. The desire of the power industry is to reduce this distortion to the maximum extent possible for its own benefit as well as that of the user.

Physical Mechanism Behind Induced Voltages and Currents

Alternating current and voltage are generated as periodic waves that repeat a certain number of times per second, much like the sound produced by a musical instrument. This repetition rate (cycles per second) is called *frequency* and is given the unit *hertz*. In a musical instrument, the higher the frequency, the higher the perceived pitch of the sound. Any waveform distortion results in higher frequency components in the wave. In the case of musical instruments, these higher frequencies are harmonics (multiples) of the fundamental frequency and are responsible for the different sounds of various instruments. The resulting waveform shape depends on the amplitude and time relationship of the harmonic components relative to the amplitude of the fundamental frequency wave. Figure 1 illustrates the wave shape of a sine wave combined with a small amount of third harmonic (three times the fundamental frequency).

An alternating electric current in a wire causes a magnetic field that can induce voltages in nearby electrically conductive objects.

An alternating electric current in a wire causes a magnetic field that can induce voltages in nearby electrically conductive objects. This is a fundamental law of physics. This induced voltage is proportional to frequency for the same geometry and magnitude of current in the wire. Harmonics and transients result in higher frequency components in the current and voltage waves with accompanying induced voltages in nearby conductive objects. Thus, the induced voltages are more complex than would be the case for a purely sinusoidal current.

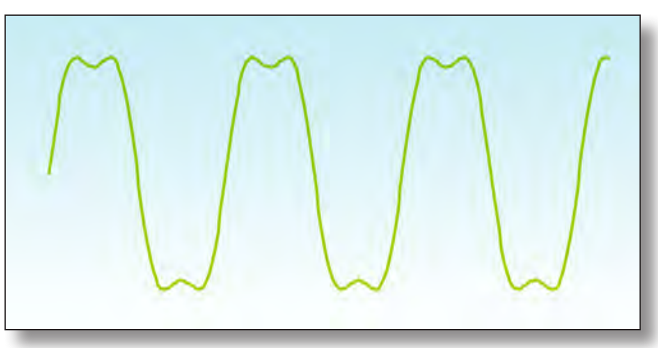


Figure 1. Wave containing third harmonic component

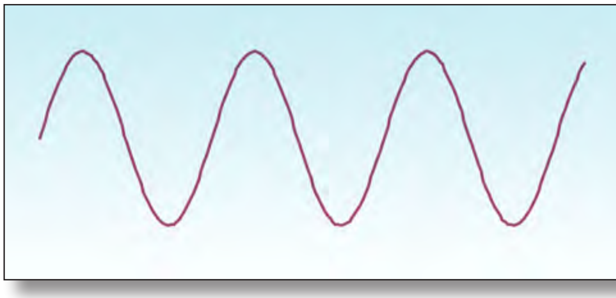


Figure 2. Sine wave

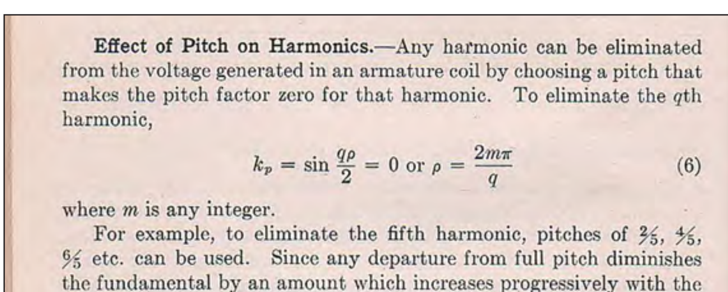
Why We Use Sine Waves for Electric Power

A more basic question is this: Why use alternating current at all? The historical answer lies in the invention of the transformer to provide a simple, efficient means of changing voltages from one level to another. If only the 240 volts that come into a home were available, the power could not be transmitted long distances and generating capability would need to be installed within blocks of the users, as in the early Edison installation in New York City. As it is, high voltages (for example, 345,000 volts) can be used to transmit power for long distances, intermediate voltages (for example, 13,800 volts) can be used for local distribution, and 120/240 volts supplied to residential users.

The sine wave is the only waveform with a shape that is unaffected by inductance and capacitance in the electrical network.

Having chosen alternating current, the question of wave shape is next. If electrical circuits only contained resistance, there would be many possible choices. However, every alternating current electrical circuit element—whether a power line, transformer, motor, or anything else—contains quantities called *inductance* and *capacitance* that affect the voltages and currents in various parts of the circuit. The sine wave (Figure 2) is the only waveform with a shape that is unaffected by inductance and capacitance in the electrical network. Any other wave shape would result in different wave shapes in every part of the circuit, which would be an unacceptable condition for the power system to function effectively.

Harmonics present in nonsinusoidal voltage and current were determined before 1900 to be an important factor in the amount of electrical power losses and heating in transformers and rotating machinery such as generators and motors. Harmonics were also found to affect torque characteristics of motors and thus their proper operation.[5] The requirement of maintaining as pure a sine wave as possible was established before 1900 and influenced the design of generators



Effect of Pitch on Harmonics.—Any harmonic can be eliminated from the voltage generated in an armature coil by choosing a pitch that makes the pitch factor zero for that harmonic. To eliminate the qth harmonic,

$$k_p = \sin \frac{q\rho}{2} = 0 \text{ or } \rho = \frac{2m\pi}{q} \qquad (6)$$

where m is any integer.

For example, to eliminate the fifth harmonic, pitches of $\frac{2}{5}$, $\frac{4}{5}$, $\frac{6}{5}$ etc. can be used. Since any departure from full pitch diminishes the fundamental by an amount which increases progressively with the

Figure 3. Design of generators to make pure sine wave voltage[6]

The requirement of maintaining as pure a sine wave as possible was established before 1900 and influenced the design of generators to minimize harmonic distortion from the earliest days of the electrical industry.

to minimize harmonic distortion from the earliest days of the electrical industry. Figure 3 illustrates design of generators to minimize harmonics from a 1940 textbook on electrical machinery, although the development of generator design for sinusoidal wave shape goes back to the first days of the alternating current generator.

Why We Use 50 or 60 Hertz for Electric Power

If sine waves are best, what is the optimum repetition rate (frequency)? This has been answered in various ways, and different frequencies are still in use in different parts of the world. The various frequencies include:

- 16 Hz, used for electric railroads, especially in Europe.
- 25 Hz, used for industrial and electric railroad use; early Niagara Falls power was 25 Hz.
- 40 Hz, a compromise promoted by Steinmetz and used for a time in a few areas, including the Capital District of New York.
- 50 Hz, used in Europe and much of the world.
- 60 Hz, used in North America and some other countries.
- 133 Hz, attempted in some of the early power systems.
- 400 Hz, used in aviation.

Series motors, as used for the traction motors in street cars and electric locomotives, work best at the lowest frequencies, hence the use of 16 Hz for some electric railways and 25 Hz for others. The lower frequencies are better for long distance transmission because of the lower inductive voltage drop, hence the use at Niagara Falls. Also, some industrial uses favored the lower frequencies. The problem with the use of 25 Hz for electric power is visibly flickering lights. Higher frequencies are better for lighting but are worse for long distance transmission when system stability is taken into consideration. Taking all factors into account, 50 and 60 Hz have come to dominate, although the reasons for the difference between them are obsolete today. Higher frequencies also require less steel in motors and transformers, driving the use of 400 Hz in aircraft to reduce weight. Long distance considerations are irrelevant in airplanes.

Why We Use Three-Phase for Electric Power

Three-phase electricity uses three sets of voltages and currents. The three voltages (and currents) are timed one third of a cycle apart.

Three-phase electricity uses three sets of voltages and currents. The three voltages (and currents) are timed one third of a cycle apart, as shown in Figure 4. Each phase (voltage/current pair) has its own wires, so there are actually three interconnected circuits. This adds a degree of complexity beyond the single-phase power that we use in our homes.

Three-phase has advantages for some applications requiring larger amounts of power than the typical house and provides advantages for generation, transmission, and distribution of power. If the three voltages shown in Figure 4 are added at any instant, they sum to zero. Thus the neutral wire could be eliminated in a three-phase system if the three voltages have identical magnitudes and the proper time relationship. In many cases of power transmission and distribution, the neutral wire is actually eliminated. When the neutral wire is included, it can often be the size of one of the phase wires. These arrangements make more efficient use of conductor material than is possible in a single-phase system.

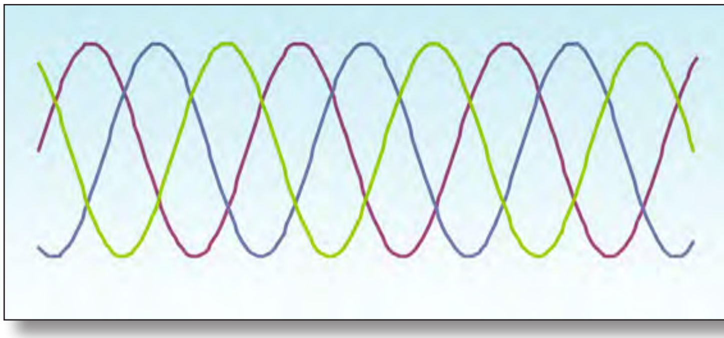


Figure 4. Three-phase voltage waveforms

Another advantage of three-phase power is that the torque output from a three-phase motor is constant and does not contain the pulsations present in the torque from a single-phase motor.

Another advantage of three-phase power is that the torque output from a three-phase motor is constant and does not contain the pulsations present in the torque from a single-phase motor. Three-phase motors are also easier to start than single-phase motors. The three-phase system is generally the least expensive overall. A three-phase power transmission line is shown in Figure 5. This line has three energized power wires (phases). The wire at the top of the pole is not a neutral wire but a shield wire installed for lightning protection.

Linear and Nonlinear Loads

While somewhat of an oversimplification, a *linear* load is one that does not change the voltage and/ or current wave shape, and a *nonlinear* load is one that does cause a change in the wave shape. An example of a linear load is a simple resistance, such as the heating element in an electric heater and, for most practical purposes, an incandescent light bulb (as with the 300-watt bulb shown in Figure 6).

In fact, the cold resistance of an incandescent light bulb is considerably smaller than the resistance of the bulb when hot (lit). Small wattage light bulbs show less difference in resistance be-

Figure 5. Three-phase power transmission line

Figure 6. Incandescent light bulb

tween cold and hot and can be considered linear loads, but there is a significant change for bulbs 300 watts and larger. Even so, the nonlinearity of an incandescent light bulb is of concern only in handling the inrush current when a large bulb is turned on.

An example of a nonlinear load that results in distortion of the current wave shape is a transformer, which consists of coils of wire wound on an iron core.

An example of a nonlinear load that results in distortion of the current wave shape is a transformer, which consists of coils of wire wound on an iron core. The effect of the iron core on the transformer magnetizing current is shown in Figure 7. The magnetization characteristics of the core are nonlinear, so the current required to magnetize the iron depends on the strength of the magnetization. As the connected voltage goes through its sinusoidal waveform, the current does not exactly track—resulting in the type of distortion shown in Figure 7. This is true for anything that contains iron and has been a concern for as long as alternating current has existed.

Other early nonlinear loads included arc lights for street lighting and arc furnaces used in processes such as steel making. In both of these applications, the current draw could be highly variable with significant current waveform distortion and resulting harmonics.

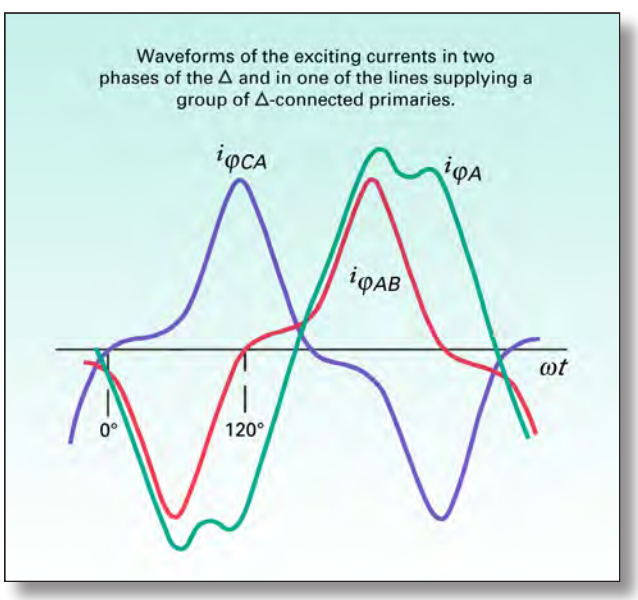


Figure 7. Transformer exciting current waveforms[7]

The previous examples of nonlinearity refer to devices whose properties change with the amplitude of the voltage and/or current. The magnetic amplifier[8] is an early motor control device that uses magnetic saturation properties of iron to vary the impedance of a circuit. Current in a dc coil varies the amount of the saturation in the iron core, which affects the inductance of an ac coil wound on the same core. As in any iron core device, the effect is nonlinear and produces harmonics and a distorted current waveform.

Various power electronics devices that involve switching have been developed over the years for the control of motors, dimming lights, and various other applications.

A second type of nonlinearity arises from devices that switch voltage or current on and off at various points in the waveform cycle. Various power electronics devices that involve switching have been developed over the years for the control of motors, dimming lights, and various other applications. The ignitron[9] was one such early device used for electric locomotives and industrial motor speed control. The ignitron was a mercury vapor tube that was capable of varying the time of conduction over a portion of the sine wave cycle. This control is called the *firing angle* and is responsible for the useful properties of the ignitron.

It was the invention of the silicon controlled rectifier (SCR; see Figure 8) in 1957 that brought electronic controls into the home. The SCR operates on the basis of a firing angle, as does the ignitron, but on a much smaller scale at a much lower cost. Immediately the issue of harmonics was pushed up a notch because the quick firing time of the SCR resulted in higher frequency components that caused interference with audio equipment and radios. In a relatively short time, these devices were in common use.

Waveform Distortion Is Not New

Power system voltage and current waveform distortion antedates the SCR, magnetic amplifier, and ignitron. Harmonics present in power system current induce voltages into parallel telephone wires. Harmonics at frequencies corresponding to those present in sounds audible to a person can cause annoying sounds in a telephone receiver. To relate the harmonic content of the power line current and resulting interference to the frequency response of the human ear, frequency weighting curves called the *telephone interference factor* or *telephone influence factor* were developed as early as 1919 (Figure 9). These curves were used to assess the annoyance of the power line interference to the telephone user and guide mitigation attempts.

When the New Haven Railroad was electrified in the early years of the twentieth century,[10] one of the considerations in the design of the overhead wire system was the reduction of telephone interference.

When the New Haven Railroad was electrified early in the twentieth century,[10] one of the considerations in the design of the overhead wire system was the reduction of telephone interference. A system using periodic balancing transformers was used to bring the currents coming to and

Figure 8. Silicon controlled rectifiers circa 1965

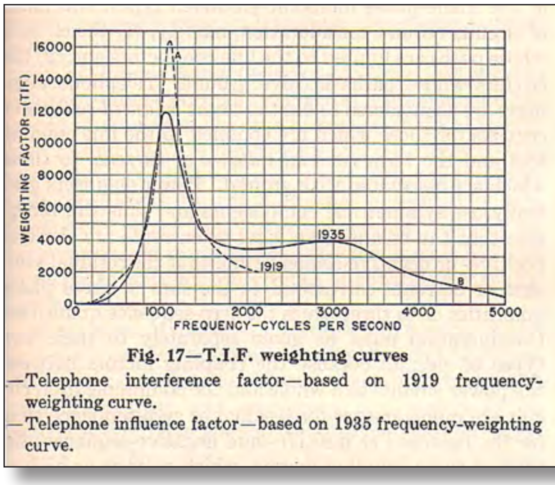


Figure 9. Telephone interference factor[11]

returning from the train together in closer proximity to one another to reduce the magnetic fields and consequent induction of voltages from the power system into telephone wiring. The unusual triangular-shaped catenary of the original New Haven electrification is shown in Figure 10.

Power Electronics in the Home

The introduction of devices such as the silicon controlled rectifier into the home in the form of light dimmers and variable speed appliances brought additional harmonics and radio noise into the home with them.

The introduction of devices such as the silicon controlled rectifier into the home in the form of light dimmers and variable speed appliances brought additional harmonics and radio noise into the home with them. With the introduction of compact fluorescent lamps (CFLs) and switching power supplies, consumer equipment has become a major contributor to waveform distortion that is sometimes now called “dirty power.”

Figure 11 shows the control circuit inside a CFL. Because there is no shielding, electromagnetic

Figure 10. New Haven railroad electrification circa 1915

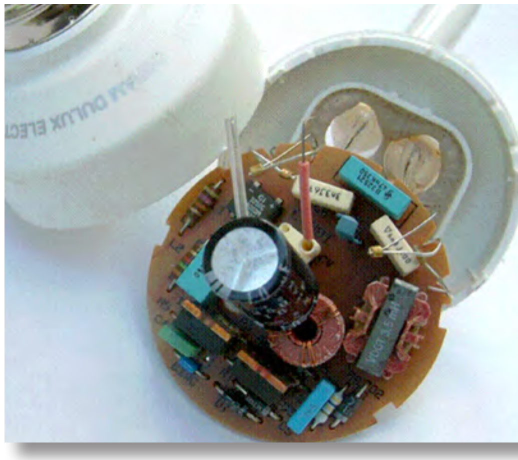


Figure 11. Compact fluorescent lamp

noise can freely escape to the point that it is sometimes necessary to turn off the CFLs in order to listen to the radio. Even over-the-air television interference has resulted from CFLs. The current wave shape and frequency spectrum of an example CFL are shown in Figure 12; measured harmonics shown in the figure reach into the audio range and beyond.

A waveform distortion and electromagnetic interference producing device that has become ubiquitous is the switching or switch mode power supply.

A waveform distortion and electromagnetic interference–producing device that has become ubiquitous is the switching or switch mode power supply. Until relatively recently, consumer entertainment equipment such as radios and televisions had a power supply that used an iron core transformer to transform the 120-volt line voltage to those needed by the device together with rectifiers and appropriate dc filtering. The small size of the magnetizing current in these transformers relative to the total line current meant that their contribution to harmonic distortion was negligible. The cost, weight, and size of electronic devices in the home (Figure 13) have been considerably reduced by the introduction of the switching power supply. In this type of power supply, the incoming ac is rectified to dc, then chopped (switched) electronically to make a high frequency nonsinusoidal ac that can be converted to the desired voltage using a very small transformer, perhaps on a ferrite core. These small power supplies produce electrical noise at their switching frequency and its harmonics and can result in electromagnetic noise well into the radio frequency range.

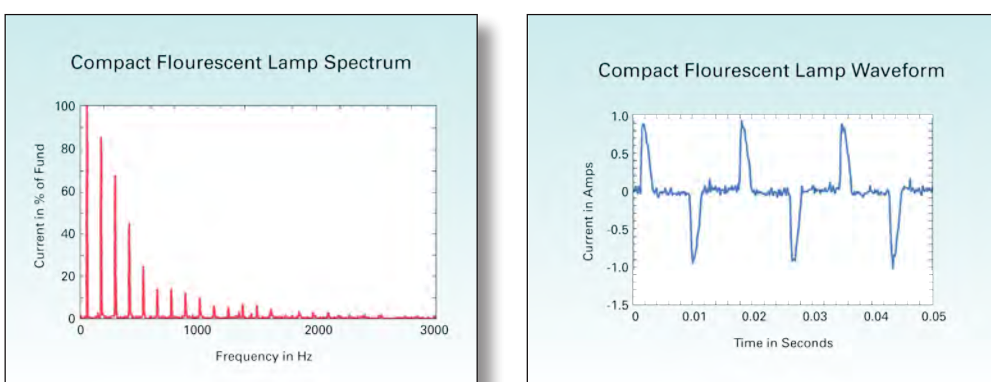


Figure 12. CFL harmonic spectrum and wave shape [12]

Figure 13. Consumer entertainment devices with switching power supplies

The switching power supply has even penetrated into the "wall wart" power supply—the little boxes that plug directly into the wall to power all sorts of home devices.

The switching power supply has even penetrated into the "wall wart" power supply—the little boxes that plug directly into the wall to power all sorts of home devices such as cordless telephone base units and Internet routers and for recharging batteries on most portable electronic devices (Figure 14). These small items have been known to cause difficult-to-locate electromagnetic interference problems because their electrical noise can reach well into the radio frequency spectrum. The noise can be both radiated through the air and conducted via household wiring. A case involving the power supply for an Internet router manifested itself as noise that could be heard on radio receivers at 30 kHz intervals as the radio's tuning dial was adjusted. This radio interference was conducted into the house power wiring and radiated from there. The noise was also conducted into the router and could have gone everywhere in the house through unshielded Ethernet wiring.[13]

Every computer that plugs into the wall has a switching power supply. They are everywhere—and their consequences are increasing due to their injection of harmonics into the electricity supply. The introduction of battery chargers associated with electric automobiles provides an additional expected source of waveform distortion.

Figure 14. "Wall wart" switching power supply

Three-phase power is commonly supplied to industrial and commercial electric power customers to satisfy their higher power requirements.

Effects on Wiring and Apparatus

Three-phase power is commonly supplied to industrial and commercial electric power customers to satisfy their higher power requirements. In the traditional three-phase distribution system, the neutral wire is sized equal to one of the phase wires—or even smaller—because of the cancellation effect described earlier. However, when significant harmonics are present, there can be a problem due to "triplen" harmonics: harmonics of order 3N times the power system frequency. For a 60 Hz system, these could be 180, 360, 540 Hz, and higher. Triplen harmonics are *zero sequence*—they add up (combine) in the neutral wire in three-phase wiring rather than cancel each other out. Triplen harmonics are caused by nonlinearity in a transformer's iron core and switching power supplies, among other things. Because triplen harmonics add rather than cancel, the presence of large amounts of triplen harmonics has been known to cause excessive neutral wire heating and current returning in building steel. They are another reason power companies want to reduce harmonics. The subject of neutral wire size in industrial and commercial three-phase installations needs to be reconsidered in situations where triplen harmonics are present.

Excessive heating of transformers and rotating machinery is another consequence of large amounts of harmonics. Resonant overvoltages are also possible. This entire area falls under the general subject of harmonics and power quality.

A different phenomenon that can result in radio frequency voltages on electric power facilities is coupling of electromagnetic energy from communications transmitting facilities.

Radio Frequency Coupling

A different phenomenon that can result in radio frequency (RF) voltages on electric power facilities is coupling of electromagnetic energy from communications transmitting facilities to power lines. This also is not new. Figure 15 shows a 345 kV overhead transmission line and parallel distribution circuits near the four towers of a 5000 watt AM radio station. In this case, because of a resonance in the power transmission line at the radio station transmitting frequency, the coupling was sufficiently strong that measures had to be taken to reduce the effect of the power line on the radiation pattern of the transmitting antenna.[14] This kind of effect can occur with any metallic structure, not just power lines. In some cases, sufficient radio frequency voltage has appeared on power line structures and conductors to cause RF burns on workers at the structures.[15]

Even in situations that are not as extreme, resonances on the power system can cause radio frequency voltages higher than those that would otherwise be expected. Sometimes these resonances can be heard on a car radio as a sudden increase in signal strength while driving. These elevated levels of radio frequency voltage can sometimes be found in a home and appear as interference on other reception devices. It must be stressed that in these cases the voltages involved are very tiny—and of a magnitude that must be detected with a radio receiver—not levels that are perceptible to people.

Another in-home cause of the presence of radio frequency voltages is sometimes found when the power wiring is used by the residents for home computer network connections.

Similar electromagnetic noise voltages are present in the home from a multitude of sources, especially universal motors that are found in many types of appliances such as kitchen mixers and blenders. Another in-home cause of the presence of radio frequency voltages is sometimes found when the power wiring is used by the residents for home computer network connections. These sources are the property of the electricity user and are not the result of facilities owned by the electric utility.

Figure 15. AM radio station near power transmission and distribution lines

Conducted Electromagnetic Noise

Noise is unwanted electromagnetic energy and if directly injected into the power lines is called conducted noise or conducted emissions.

The type of radio frequency voltage described in the previous section is called *radiated noise* in the electromagnetic compatibility community because the coupling is through the air rather than through wires. Noise is unwanted electromagnetic energy and if directly injected into the power lines is called *conducted noise* or *conducted emissions*.[16] This issue has also been around for many decades. Figure 16 shows a coupling device for measuring conducted radio frequency (electromagnetic) interference that was built by Stoddart Radio Company in the early 1950s. At that time, the dominant sources of conducted radio noise included appliance motors, fluorescent lamps, and some forms of electronic equipment of the day. Modern consumer equipment such as switching power supplies and compact fluorescent lamps can produce both radiated and conducted electromagnetic noise. While standards and regulations exist for both types, they are not always sufficient to prevent interference issues.

Figure 16. Conducted electromagnetic interference measuring device

Transients

An entirely different area concerns transients, those momentary conditions that exist when something such as a transformer is initially turned on or when some sort of fault occurs.

So far the discussion has focused on phenomena that occur during steady-state operation of electrical equipment. An entirely different area concerns transients, those momentary conditions that exist when something such as a transformer is initially turned on or when some sort of fault occurs. An everyday example of a transient is a pop sometimes heard in a radio when a light is turned on. Figure 17 illustrates the inrush current when a transformer is initially connected by flipping a switch. Large short-duration currents are possible. Old television sets sometimes made a "boing" sound when turned on. This sound was the transformer being magnetized and occurred when the switch was turned on at the proper time on the 60 Hz sine wave to maximize the transformer inrush current.

Part of the design of any electrical system is properly accounting for transients. Power transmission and distribution lines must be able to handle the momentary overvoltages that happen on energizing and switching operations. These momentary overvoltages can be several times normal operating voltage. On the utilization level, fuse or circuit breaker protection of branch circuits must protect the wiring, but not operate falsely for momentary overcurrents resulting from such things as a motor starting. This is why "slow blow" fuses used to be applied on distribution circuits that supplied a large motor load.

Transients can also couple voltages into nearby conductive objects, so they have also entered the range of considerations that have come under the heading of "dirty power."

Summary and Conclusions

Engineering issues regarding waveform distortion, harmonics, radio frequency noise and the like have been with us as long as there has been a power industry.

Engineering issues regarding waveform distortion, harmonics, radio frequency noise, and the like have been with us as long as there has been a power industry. These deal with issues as diverse as heating of transformers and machinery and telephone interference. While waveform distortion has been around a long time, the sources of harmonics and electromagnetic noise owned by the electricity customer have proliferated in recent years:

- Switching power supplies
- Compact fluorescent lamps
- Light dimmers
- Motor speed controls (variable speed drives)

More and more of these devices are being introduced, especially at the residential level. Between industrial power electronics and consumer devices such as switch mode power supplies and compact fluorescent lamps, waveform distortion occurrences are increasing. A large part (majority in most places) of this is at the customer level. These issues have now become another source of

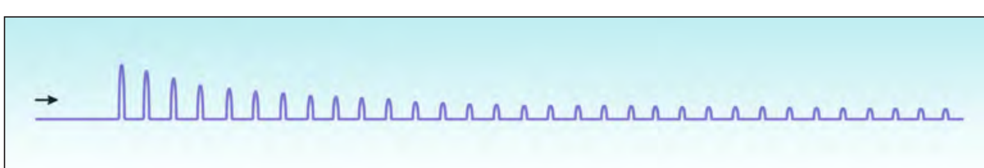


Figure 17. Transformer inrush current[17]

Now people are talking about "dirty electricity," when the fact is that waveform distortion has always been a part of electricity use.

public concern and involvement that engineers have to deal with. Now people are talking about "dirty electricity," when the fact is that waveform distortion has always been a part of electricity use.

Glossary

Capacitance—a property of the elements in an electrical circuit to store electric charge proportionally to the voltage.

Ferrite—a magnetic ceramic material used for higher frequency transformers and inductors.

Firing angle—the angle in degrees from the start of the 360 degree cycle of a sine wave when a power electronic device starts to conduct current.

Frequency—the repetition rate of a periodic wave in cycles per second (Hertz).

Fundamental frequency—the primary repetition rate in a periodic wave, generally the desired frequency.

Harmonic—a component of a periodic wave that exists as a multiple of the fundamental frequency.

Inductance—a property of the elements in an electrical circuit to store magnetic energy related to the current in the circuit element.

Magnetizing current—the electric current required to magnetize the iron in a transformer or motor as part of its normal operation.

Neutral wire—the wire at near ground voltage in an electric current that returns the current to the source.

Nonlinear—adjective describing an electrical device whose characteristics vary depending on the amount of applied voltage.

Periodic wave—a wave that repeats itself in time as the sine wave in trigonometry.

Phase—an energized wire where the alternating (ac) voltage has a particular time relationship to some reference. Primary feeders and service to customers may be either single or three phase. Also used in a mathematical sense to describe the time relationship of one sine wave to another.

Rectifier—a device that converts alternating current to direct current.

Resistance—a property of the elements in an electrical circuit that relates to power loss in the circuit element.

Resonance—a physical phenomenon in which a small stimulus produces a large response, for example, a vibration.

Silicon controlled rectifier (SCR)—a solid-state power electronic device that conducts current over an adjustable portion of the sine wave voltage cycle.

Transient—a non-recurring effect passing with time.

Triplen harmonic—a harmonic whose order is divisible by 3, for example, third, sixth, ninth.

Waveform distortion—deviation of a voltage or current from a single frequency pure sine wave.

Zero sequence—a term used in the method of symmetrical components used in power system analysis, related to current returning to the source by a path other than the phase wires.

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