# Electrical Fires : Harmonics in Electrical Systems

A guide for insurance loss adjusters and legal professionals

From fundamental principles of electricity to Fourier series and why harmonics present in non-linear electrical systems can provoke increased heating, failure and the onset of fire in electrical conductors

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**Abstract**

*The intent of this paper is to aid the understanding of the origins and consequences of harmonics inherent in the supply voltage and load current of electrical power systems. The paper is intentionally non-technical to allow an appreciation of the circumstances should harmonics become prevalent for whatever reason. The paper content starts from the fundamental principles of electricity to Fourier series and why harmonics present in non-linear electrical systems can provoke increased heating, failure and the onset of fire in electrical conductors.*

**What is electricity?**

Electricity is the flow of electrical charge, carried by free-flowing negatively charged electrons. loosely held to atoms of conductive materials such as gold, silver and copper.

In general the flow of electrons, 'electricity', is referred to as Direct current (DC), in that negatively charge electrons flow towards a point/location in an electric field of positive charge.

If the physical location of the positive charge or the magnitude or polarity of the charge changes with respect to time (*t*), then the degree and direction of the flow of electrons will also change. In particular if the direction of current flow changes this is referred to as Alternating Current (AC).

**How is electrical energy produced?**

Electricity is a secondary energy source which means that electricity is generated from the conversion of other energy sources, like coal, natural gas, oil, nuclear power and other natural sources, which are referred to as primary energy sources.

In general, electrical energy for the use in homes and commerce etc., is generated by utilizing rotating machines powered by a primary energy source. The machines, referred to as generators are designed and constructed to exploit the natural phenomena of 'electromagnetic induction'.

**Electromagnetic Induction and the work of Michael Faraday FRS (1791 - 1867)**

Following the discovery of Oersted [1] which revealed that a current-carrying conductor creates a magnetic field, Faraday hypothesized that a magnetic field should also produce an electric current. He conducted several experiments in his laboratory in London for over ten (10) years. These experiments finally led to the discovery of Electromagnetic Induction.

**Faraday's first law of induction**

Faraday's first law of induction states that "*an electromotive force will be induced in an electrical conductor placed in a varying magnetic field*". This phenomenon is known as electromagnetic induction.

A static/stationary magnetic field will not induce electromagnetic induction. So the magnetic field of a 'bar magnet' if placed next to an electrical conductor will not induce an electrical current in the conductor, if both conductor and magnet are stationary .

For the phenomena of electromagnetic induction to occur, relative motion between the magnetic field and the conductor must exist. For example, either the magnet or the wire has to physically move or the position or strength of the magnetic field has to vary with respect to time (*t*). If a varying magnetic field exists the field will exert a force on the charged particles in the wire to provoke a flow of electrical current. This force is known as the electromotive force (EMF or emf).

The diagram presented in Figure 1 indicates the 'components' of electromagnet induction phenomena given an electrical conductor and a magnetic field.

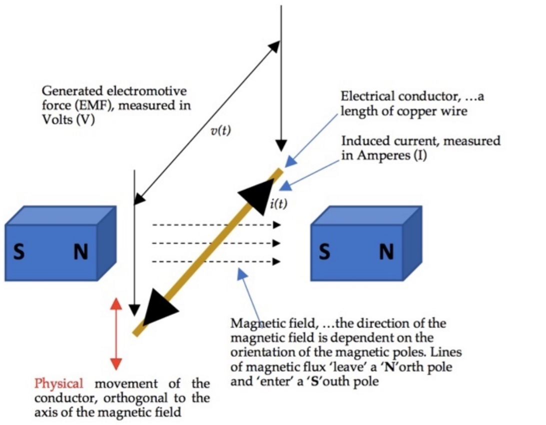


Figure 1 Diagram indicating the 'components' of electromagnet induction

**Faraday's second law of induction**

Faraday's second law of induction states that "*the magnitude of the induced EMF is proportional to the rate of change of the magnetic field in which the wire is placed*", which is expressed by the equation, …

$$e = -N \times \frac{\emptyset}{dt} \qquad \text{Equation 1}$$

Where, …

$e$ is the magnitude of the induced EMF,
$\phi$ is the amount of magnetic flux linking the coil
$N$ is the number of turns of the coil.
$t$ is time

The negative sign indicates that the induced current will flow in a direction so as to oppose the change in magnetic field.

The equation is referred to as "Faraday's Law Equation" and indicates that the EMF induced in the coil can be increased by, …

- Increasing the number of turns of coil.
- Increasing the speed of relative motion between the coil and the magnetic field, i.e. faster the change in the magnetic field, higher will be the induced EMF.
- Increasing the strength of magnetic field, i.e. higher the amount of flux linking the coil, higher will be the induced EMF.

**Electrical supplies**

The standard domestic/industrial/commerce electrical supply has an alternating current (AC) format. The widespread use of AC grew from the ease of use and distribution of AC as opposed to direct current (DC) format in the early twentieth century when Thomas Edison (1847 - 1931) and George Westinghouse Jr. (1846 – 1914) fought for commercial dominance of the electrical supply market.

Alternating current, is an electrical energy source that alternates in polarity, which establishes that the EMF and induced current changes direction/polarity with respect to time ($t$). The signature or the format of the alternating/ change in polarity, follows the form of a sine wave or sinusoid. A sine wave is a mathematical curve that describes a smooth periodic oscillation over time ($t$). A pendulum swings/oscillates in accordance with 'sine' wave function as does an undamped vibrating string of a musical instrument.

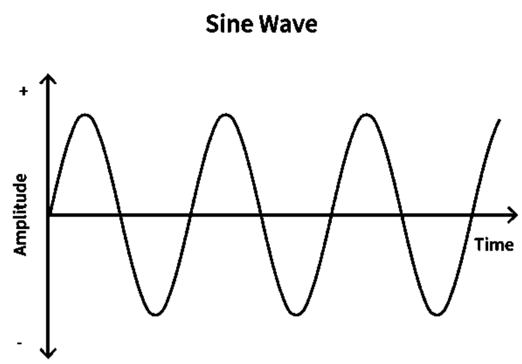


Figure 2 Graphical representation of a sinusoidal oscillation

It follows that many other natural phenomena also have sinusoidal oscillations and generally the circumstance is referred to as possessing "Simple Harmonic Motion" (SHM), which describes a repetitive movement back and forth through an equilibrium, or central, position, so that the maximum displacement on one side of this position is equal to the maximum displacement on the other side. The time interval of each complete vibration is the same.

Yet given that electrical energy is a secondary energy source, why is alternating current (AC) sinusoidal?

### Why is alternating current (AC) sinusoidal?

Alternating current (AC) is sinusoidal simply due to nature of the physical construction of an AC generator. Figure 3 present a generator where a coil of wire rotates at constant angular velocity in a homogenous magnetic field. Given the construction of the generator and the phenomena of electromagnetic induction the induced EMF and current within the conductor will be sinusoidal.

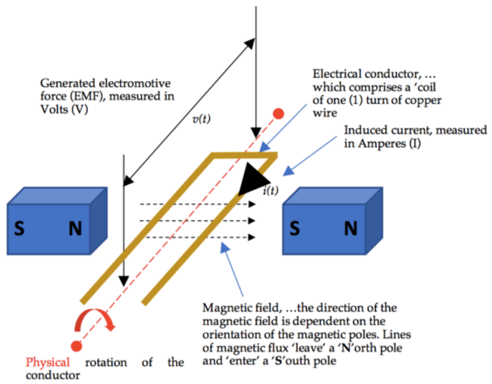


Figure 3 Diagram indicating the induced electromagnetic force circumstances, given the rotation of a coil of wire in a stable homogenous magnetic field

Conversely if the magnetic field rotates at a constant angular velocity, as in the case of Figure 4, similarly the induced EMF and current within the conductor will be sinusoidal again due to electromagnetic induction phenomena.

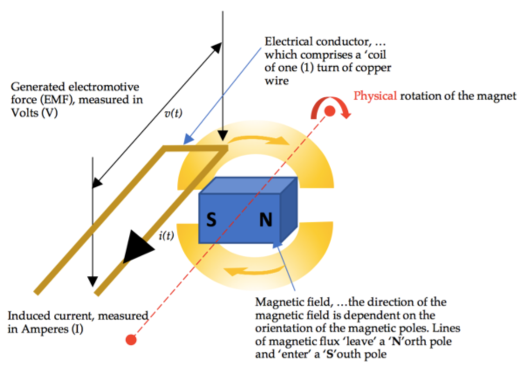


Figure 4 Diagram indicating the circumstances given the rotation of a a stable homogenous magnetic field and the induced electromagnetic force in a stationary conductor

### Applications of Faraday's law

Given the latter electromagnetic induction forms the basis for the operation of electric transformers, motors and generators.

- In a transformer, electric energy is transferred from the primary to the secondary coil by electromagnetic induction.
- In electric motors and generators, power is transferred from the rotor to the stator and vice-versa by electromagnetic induction.

However, in operation and in correlation with electrical loads, i.e. consumers of electrical current/energy, sinusoidal electrical supplies can become distorted or non-sinusoidal. In other words, a load is said to be non-linear when the current it draws from the supply does not have the same waveform as the supply voltage.

Fundamentally, the non-linear load provokes the flow of 'harmonic' currents through the system which in turn creates 'voltage' harmonics, which distort the supply voltage.

Equipment comprising power electronics circuits are typical non-linear loads and generate harmonic currents. Such loads are increasingly frequent in all industrial, commercial and residential installations.

### Examples include:

- Industrial equipment (welding machines, arc and induction furnaces, battery chargers),
- Variable Speed Drives for AC or DC motors[1],
- Uninterruptible Power Supplies,

### Fourier Series

In 1822, French mathematician Joseph Fourier discovered that sinusoidal waves can be used as simple building blocks to describe and approximate any 'periodic' waveform. Fourier used it as an analytical tool in the study of waves and heat flow.

Figure 5 presents an array of waveforms and in particular a distorted non-linear load current waveform (highlighted yellow).

Fourier discovered that fundamentally the distorted wave form is a 'summation' of individual sinusoidal harmonic waveforms and the fundamental, supply sinusoidal waveform

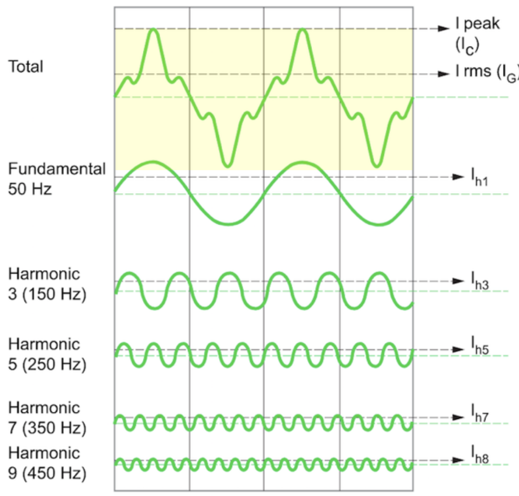


Figure 5 Graph indicating harmonic components of a 'distorted' non-sinusoidal current waveform.

Given Fourier's mathematical separation of a non-linear waveform, the distorted electrical current can be subdivided to represent two circuits, one representing the flow of current at the fundamental frequency, and a further circuit representing the flow of current of the harmonic frequencies as depicted in Figure 6.

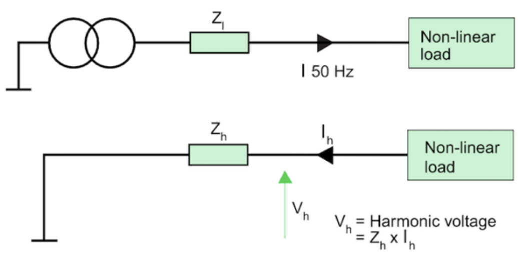


Figure 6 Two circuits representing fundamental and harmonic currents

## Joule Heating of electrical conductors

All electrical conductors in the process of conveying electrical current produce heat. Heat generation in electrical conductors is a natural phenomenon hence engineers, designers have to take measures to control the heating process by providing a suitable method/vehicle/environment to transfer the heat energy from the electrical conductor to another physical system, i.e. to allow air to freely circulate around an electrical conductor. However if a suitable method/vehicle to transfer heat is not provided, then logically conductor temperature will rise and in time fire ignition will ensue.

The amount of heat generated is proportional to the magnitude of the electrical current and the electrical impedance/resistance of medium through which the electrical current flows.

Joule's first law, also known as the Joule–Lenz law, states that the power of heating generated by an electrical conductor is proportional to the product of its impedance/resistance and the square of the electrical current:

Mathematically, Joule's first law is expressed as,…

$$p(t) = i^2 r(t) \qquad \text{Equation 2}$$

Hence excessive heating of an electrical conductor will come about given an increase in the magnitude of electrical current or electrical resistance, such that the electrical conductor will rise in temperature and if continual will physically change state, i.e. a phase change, say from solid to liquid or liquid to gas.

Consequently, in the process of continual joule heating and evolving phase/state change of an electrical conductor, logically any combustible material in close proximity to the conductor will in most cases ignite and promote the generation and proliferation of fire.

## Design of electrical systems

A simple relationship exists between the three principal parameters of an alternating current (AC) system, i.e. voltage, current and impedance and in simple terms the current is derived from the quotient/ratio of voltage and impedance.

Consequently, to determine the level of load current drawn by an electrical system at a specific supply voltage, the attributes of system impedance have to be assessed. In simplistic terms this can be achieved given knowledge of the fundamental frequency of the system AC supply and of reactive components of the system, i.e. inductance and capacitance. However, this will derive the flow of current only at the fundamental frequency.

Importantly at the design stage the 'additive' flow of current of the harmonic frequencies has to be considered, since this current component is present in the Equation 2, so Joules first law becomes:

$$p(t) = (i + i_h)^2 r(t) \qquad \text{Equation 3}$$

**Consequences of harmonics**

As discussed, a major effect of electrical power system harmonics is to increase the electrical current within the system.

Consequently, to neglect or to pay inadequate assessment of harmonic currents will lead to increased heating within electrical conductors and components of the parent system with ensuing damage and possible fire ignition as evidenced in the transformer presented in Figure 7.

Figure 7 Evidence of increase heating within the core of a transformer winding due to harmonic currents

**References**


[1] Oersted, John Christian (1820). ”Experiments on the effect of a current of electricity on the magnetic needle". "*Annals of Philosophy*. **16**: 273–276


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