## New Loads, New Problems:

# Why Harmonics Destroy Transformers

by **Gabe Paoletti**, P.E.

Don’t move one step forward with new loads that save money or improve capabilities, and then one step backward with outages and transformer failures. New Transformer Technology includes being aware of the new problems associated with new high-tech loads; and understanding how they can impact the life of a transformer.

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Gabe Paoletti has applied his 40-plus years of electrical power distribution experience to support the electrical power industry by providing professional engineering services to increase system reliability, resiliency, equipment life extension, personal safety, power system personnel training, failure and root-cause analysis, feasibility studies, quality systems and new solution creation. He is a Registered Professional Engineer in New York, Pennsylvania and Delaware and has authored and presented numerous technical publications for IEEE and other organizations. He received his BSEE in Electrical Engineering at Drexel University in 1976 (Magna Cum Laude), and an MBA from Rutgers in 2009 (Summa Cum Laude). Mr. Paoletti has also been on the forefront of many power system innovations and was awarded the IEEE Engineer of the Year Award for 2009 (Northern New Jersey Chapter) for new product and service innovation which improved the efficient distribution of electrical power. He currently provides services such as failure analysis, project engineering, owners representative and engineering and feasibility studies, with his company Paoletti Engineering PLLC.

Being involved in root-cause failure evaluations and harmonic studies provides a history of practical experience related to why harmonics destroy transformers. New Transformer Technology includes being aware of the new problems associated with new loads; and understanding how they can impact the life of a transformer.

Some examples of new loads, which are implemented for very good reasons are: adjustable speed drives and/or electronic ballasts both resulting in reduced electrical power demand and the associated cost savings; improving the capabilities by installing new data processing equipment in office buildings, industrial sites and institutions. When these new loads are being planned, it is imperative that harmonics be reviewed.

There has been substantial research and publications regarding the effects of harmonics on transformers. While harmonics can be linked to overloading neutral conductors and causing nuisance tripping of circuit breakers, we’re focusing on the impact of harmonics on transformers. This background has been extracted from an excellent article by C. Sankaran [1].

## Harmonics

Some loads cause the current to vary disproportionately with the voltage during each half cycle. These loads are classified as nonlinear loads, and the current and voltage have waveforms that are non-sinusoidal, containing distortions, whereby the 60 Hz waveform has numerous additional waveforms superimposed upon it, creating multiple frequencies within the normal 60 Hz sine wave. The multiple frequencies are harmonics of the fundamental frequency.

Examples of nonlinear loads are uninterruptable power supplies (UPSs), adjustable speed drives, battery chargers, electronic ballasts, variable frequency drives, and switching mode power supplies (normally used in computer loads and other data processing equipment). As nonlinear currents flow through a facility’s electrical system and the distribution-transmission lines, additional voltage distortions are produced due to the impedance associated with the electrical network. Thus, as electrical power is generated, distributed and utilized, voltage and current waveform distortions are produced.

Power systems designed to function at the fundamental frequency, which is 60 Hz in the United States, are prone to unsatisfactory operation and, at times, failure when subjected to voltages and currents that contain substantial harmonic frequency elements. Very often, the operation of electrical equipment may seem normal, but under a certain combination of conditions, the impact of harmonics is enhanced, with damaging results.

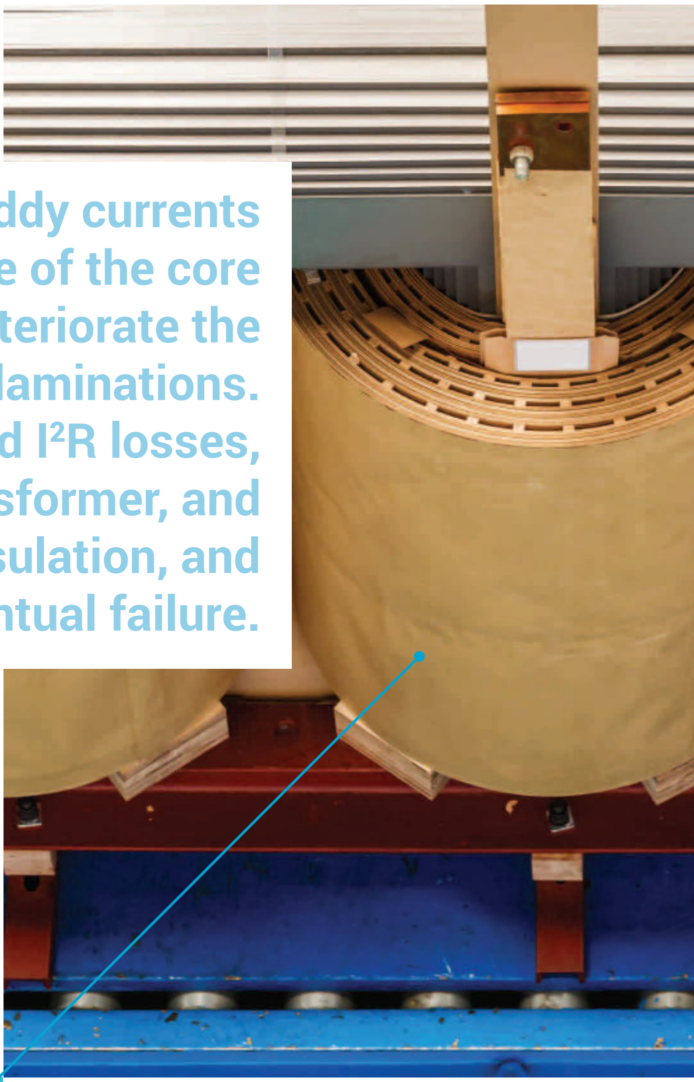
As previously discussed, changes to a system that will lead to the potential of failure due to harmonics could include installation of variable frequency drives, electronic ballasts, power factor improvement capacitors, arc furnaces, or the addition or removal of large motors.

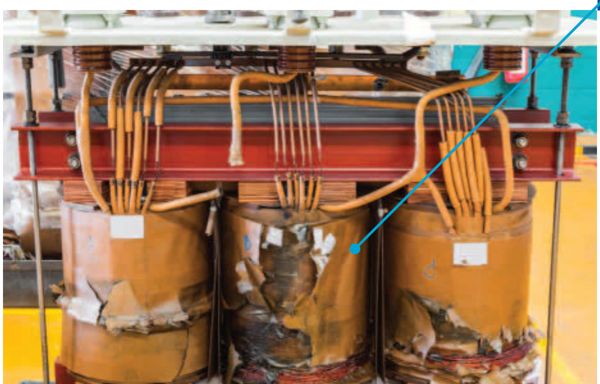
## Eddy Currents

Application of non-sinusoidal excitation voltages to transformers increase the iron losses in the magnetic core of the transformer in much the same way as in a motor. A more serious effect of harmonic loads served by transformers is due to an increase in winding eddy current losses. Eddy currents are circulating currents in the conductors induced by the sweeping action of the leakage magnetic field on the conductors. Eddy current concentrations are higher at the ends of the transformer windings due to the crowding effect of the leakage magnetic fields at the coil extremities. **The eddy current losses increase as the square of the current in the conductor and the square of its frequency.** The increase in transformer eddy current loss due to harmonics has a significant effect on the operating temperature of the transformer. Transformers that are required to supply power to nonlinear loads must be de-rated based on the percentages of harmonic components in the load current and the rated winding eddy current loss.

**The resultant increase in eddy currents increases the operating temperature of the core iron, which in turn begins to deteriorate the insulation between the core iron laminations. This leads to greatly increased $I^2R$ losses, beyond the design limits of the transformer, and overheating of the actual winding insulation. Once the winding insulation allows the energized copper winding to contact the grounded core-iron, an internal failure will result. This process is illustrated in Figure 1.**

> The harmonic related increase in eddy currents increases the operating temperature of the core iron, which in turn begins to deteriorate the insulation between the core iron laminations. This leads to greatly increased $I^2R$ losses, beyond the design limits of the transformer, and overheating of the actual winding insulation, and eventual failure.





The insulation between the laminations is deteriorated and damaged.

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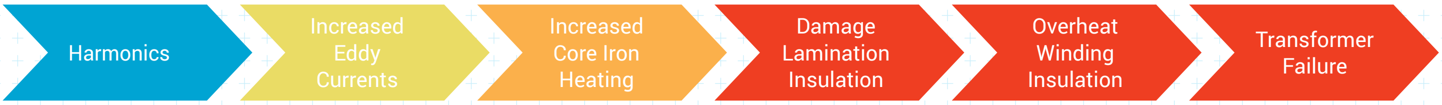
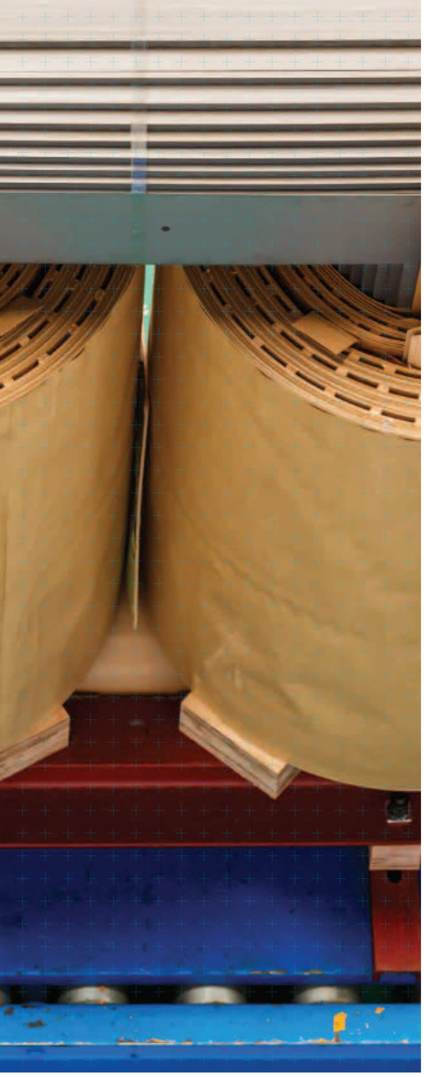


*Figure 1. Pathway from harmonics to transformer failure*

*Figure 2. 5-Why analysis of harmonics related transformer failure*



As previously stated, the eddy current losses increase as the square of the current in the conductor and the square of its frequency; therefore, with higher and higher harmonics, this heating is further increased.

When looking at a transformer, it appears that the high and low voltage winding are wrapped around a solid iron core; but, if you look more closely, you'll see that the "solid" iron core is made up of a series of thin laminations, usually of silicon steel, and these thin laminations are insulated from each other with an insulating coating that is applied to both sides of the thin metal laminations. The purpose of insulating the laminations is to limit the heating effect of eddy currents during normal operation.

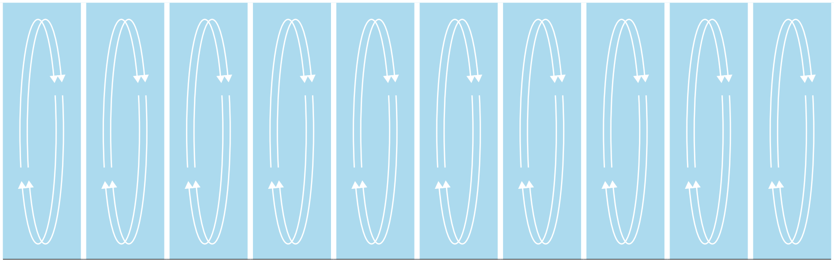
Even without taking into account the increased heating effect of the harmonic's higher frequencies, Figure 3 clearly illustrates the effect on the $I^2R$, heating losses that occur within the core-iron as the insulation between the laminations is deteriorated and damaged.

**Many end-users are familiar with protection for transformer voltage surges, therefore they do apply transient voltage surge suppression and/or lightening arrestors, but many do not fully address the potential high harmonic currents of new, or added, computer loads or solid-state drive systems.**

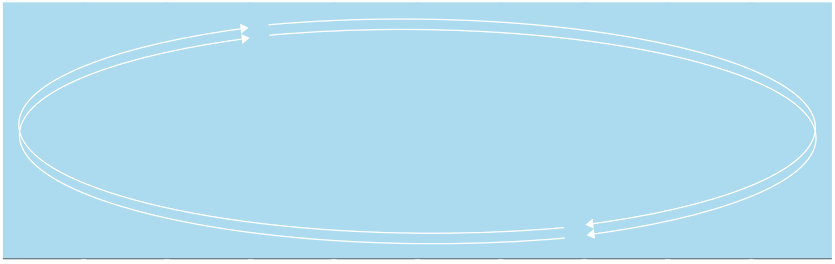
In the second illustration, we have the same 10 amperes of eddy currents, but now the insulation membrane between the iron core laminations has been deteriorated and damaged to the point that all ten sections of the iron core are in contact with each other. As shown, the total heating effect has increased from 5.0 watts to 50.0 watts, or a 900% increase heating.

This increased heating effect, which does not include the added effect of the increased frequency associated with harmonics will overheat the primary and/or secondary winding insulation, resulting in a transformer internal winding failure.

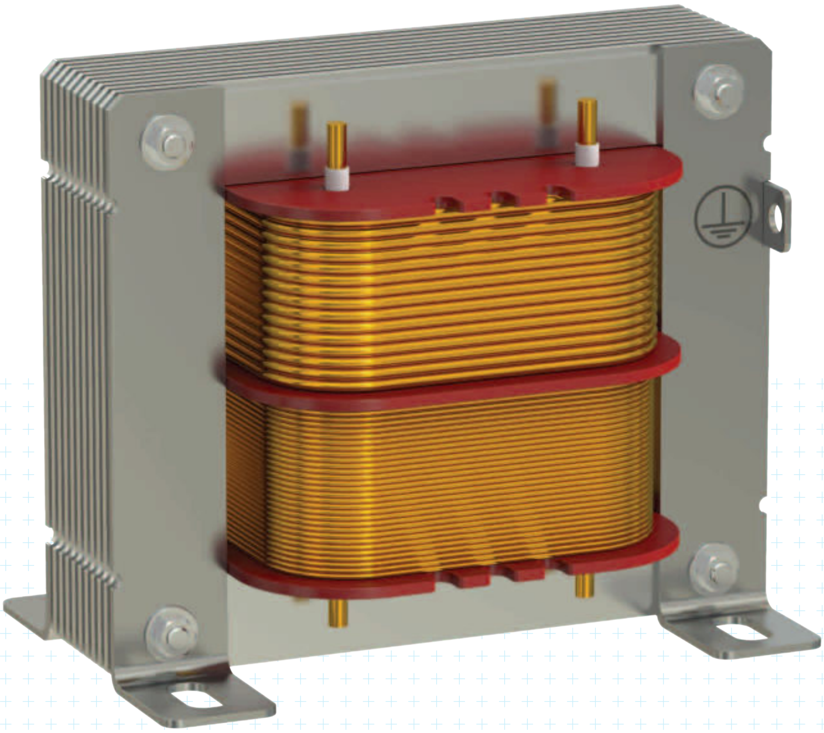
*Figure 3. Illustrative effect of deteriorated iron-core lamination insulation failure*



| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Eddy Current | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | |
| Impedance | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | Heating |
| I²R | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 5.0 |



| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Eddy Current | 1 | 1 | 1 | 1 | 10 | 1 | 1 | 1 | 1 | 1 | |
| Impedance | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | Heating |
| I²R | 0 | 0 | 0 | 0 | 50 | 0 | 0 | 0 | 0 | 0 | 50.0 |



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## Solutions

**Many end-users are familiar with protection for voltage surges, therefore they do apply transient voltage surge suppression and/or lightening arrestors, but many do not fully address the potential high harmonic currents of new, or added, computer loads or solid-state drive systems.**

The first step when redesigning or altering your current power distribution system to support new power loads is to model your electrical system to simulate the harmonics from the new loads. It is also highly recommended to measure the actual current harmonics that exists, and after the new loads are installed, to then again measure the actual current harmonics.

**If the changes are being made to an existing power distribution system, you can cautiously add the new loads and then immediately obtain the harmonic measurements resulting from these new loads.** A transformer supplying these new loads will hopefully not fail within days of the new loads being installed.

Once the level of harmonics is determined, you should disconnect them from the transformer and determine your next steps. A solution can be to install harmonic filtering or reconfiguring transformers connections to allow for cancellation of harmonics, or changing the transformer to accommodate the harmonics.

Another option to support long-term diagnostics is to install a permanent harmonics meter. Should you have a transformer failure, and you have not applied the types of new loads discussed above, then a review of harmonics should be part of the root-cause analysis. As an example, IEEE standard 519-1992 [2] states the total harmonic distortion (THD) of the voltage waveform provided by the utility cannot exceed 3% of the ideal sine wave. To ensure that harmonics are not generated by the utility, you would obtain this measurement at the point of common coupling (PCC). This is where the utility and facility wiring meet (usually at the meter box). If the voltage distortion exceeds 3%, the utility should provide some form of mitigation to correct the problem.

**References**

[1] C. Sankaran, Effects of Harmonics on Power Systems, 1999, retrieved from https://www.ecmweb.com/power-quality/effects-harmonics-power-systems

[2] IEEE standard 519-1992, Recommended Practice and Requirements for Harmonic Control in Electric Power Systems