Tech Byte 16: The Truths About Transformers—Part 2

Designing a Transformer to Achieve High Efficiency in the Real World

In "The Truths About Transformers—Part 1", the discussion focused on the reality that not all transformers are created equal. Today, more than ever, there is a need to look at every transformer application and determine what type of transformer product makes the most sense to apply. If the selection is made correctly, a user can expect to experience the best in operating efficiency, coupled with improved power quality in their electrical distribution system. If the selection is made poorly, the user can expect the opposite: low operating efficiency, higher costs of operation, and poor power quality - which leads to operational issues with electronic equipment. We also discussed the fact that a given transformer's published NEMA TP-1 efficiency is ***conditional****. NEMA TP-1 efficiency values only apply for transformers supporting 100% linear connected loads, which in today's world is quite rare. We concluded Part 1 by introducing transformer technology that offers the basic requirement of voltage transformation along with the added benefits of power quality improvement and high operating efficiency in non-linear load environments. These transformers are commonly referred to as Harmonic Mitigating Transformers (HMTs).*

In Part 2 of *The Truths About Transformers,* we will analyze HMT technology and try to better understand how it works and how it differs from other transformer technologies. To begin, let's focus on the theory behind how the HMT works, and how it compares to other transformer technologies. We will look at two specific areas of the Power Quality International (PQI) HMT design to illustrate how it provides high efficiency in operation, regardless of connected load type.

Engineered Secondary Windings for Treatment of Harmonics:

First of all, a Harmonic Mitigating Transformer is designed to do one thing that other transformer technologies cannot do. It is designed to remove or "treat" harmonics. To accomplish this, it must be designed and manufactured differently than that of a standard or K-rated type transformer. In the case of a PQI HMT transformer, the technology to treat harmonics exists in the way the secondary windings of the transformer are oriented. It is important to note that there are no tank circuits or other added components in the PQI transformer that eliminate the harmonics.

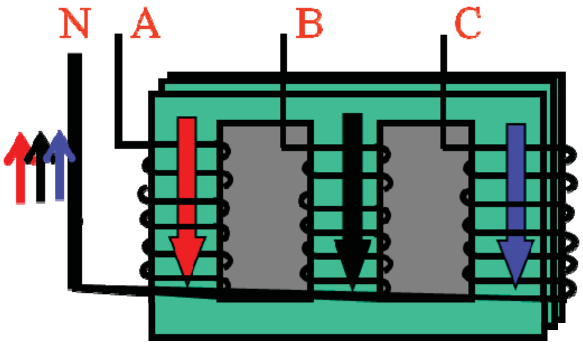

Figure #1 - Standard or K-Rated Type Transformer Secondary Winding Illustration

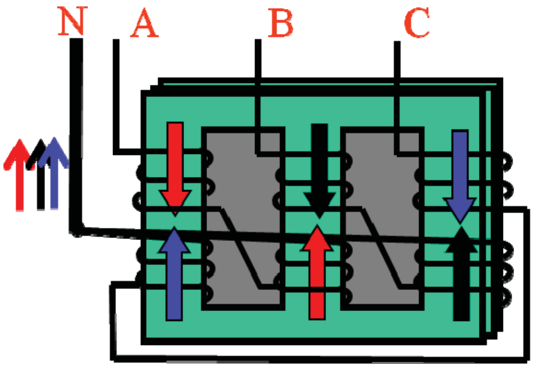

Figure #2 - PQI HMT Type Transformer Secondary Winding Illustration

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This element of the PQI design makes for a very reliable product that introduces no materials than would not be found in a standard or K-rated transformer. The *way* in which the PQI HMT transformer is designed is what creates its superior performance.

To illustrate this, take a look at the figures on the previous page. **Figure #1** is illustrating the secondary winding configuration that would be found in a standard or K-rated type transformer. Each leg of the core has a specific phase wound around it. By contrast, note the configuration of the PQI HMT secondary windings in **Figure #2**. In this design, we see that each leg has two *DIFFERENT* phases wound around it, and in each case, they are wound in opposite directions. In the case of the first leg, we see phase "A" wound from the top of the transformer towards the bottom on the upper half of the first leg. Phase "C", however, is wound from the bottom of the transformer towards the top, on the bottom of the first leg. Interesting, but how does this treat harmonics?

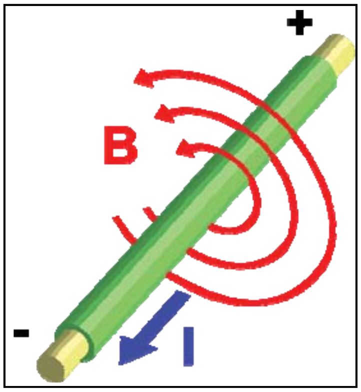

Figure #3: Magnetic Field Induced By Current Flowing Through A Conductor

To understand this, we must understand something about the harmonics we are aiming to treat with this design. The majority of non-linear loads in a given facility are line-to-neutral connected, 120V electronic loads (For example, a PC workstation in an office or at home would qualify). These types of electronic loads create what are commonly called "triplen" harmonics. These are the harmonics we are focused on treating with the special secondary winding design. In a three-phase distribution system, the triplen harmonics from each phase (A, B, and C) add up on the neutral conductor. Because of the fact that they add together on the neutral conductor, we know that these harmonics are ***in phase with one another***. So what does this do for us? It allows us to utilize the laws of physics to prevent the harmonics from causing penalty losses in the transformer.

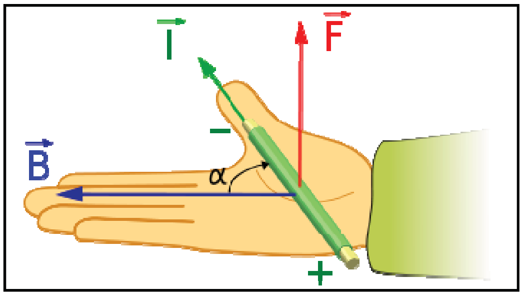

Figure #4: The Right-Hand Rule

Let's take a moment to rewind the clock and revisit some physic's basics we learned back in our school days. First, it is important to recall that all moving charges create a magnetic field. For example, take Figure #3 above. In this figure, current (I) is flowing through the green conductor from the positive end to the negative end. Because of this current flow, a magnetic field, (B) is induced. Second, we need to recall the "Right-Hand Rule". The purpose of the Right-Hand Rule is to easily illustrate the ***direction*** of the induced magnetic field, given a specific direction of current flow through a conductor. If we use our right hand, per Figure #4, and point our thumb in the direction of the current (I), the fingers of our right hand point in the direction of the magnetic field (B) as the hand is closed around the conductor. If the current flows in the opposite direction, the right hand would be flipped over, and would result in a magnetic field being induced in the opposite direction.

So what does this physics experiment have to do with the HMT? Let's imagine that we have ***two*** conductors, each passing equal, alternating currents that are in-phase with one another. However, we will force the direction of current flow in each conductor to be in opposite directions relative to one another. The result of these equal, opposing currents would be two

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induced magnetic fields, equal in intensity, opposite in orientation. This can be visualized by using the right-hand rule. In Figure #4 on the previous page, as current is flowing from South to North in the image, and the magnetic field circles **clockwise** around the conductor (imagine the fingers in the hand closing around the conductor). If the current were flowing from North to South, the hand would be flipped over (as the thumb must point in the direction of current flow), causing the magnetic field to circle **counter-clockwise** around the conductor.

Let's revisit Figure #2 on page 1, now that we understand the science behind the design. By winding phase A from top to bottom, and phase C from bottom to top (and so on for each phase and each leg), we intentionally oppose the magnetic fields produced by the current flowing in each phase. The result is that we cancel out the balanced portion of each phases' triplen-harmonic induced magnetic flux in the transformer core. From the perspective of the transformer, it essentially makes the non-linear connected load look like a linear load. The significant penalty losses associated with triplen harmonics are eliminated or significantly reduced, based on how effective the load balance is achieved across the three secondary-side phases.

Figure #5: Noise Cancelling Headphones Utilize Frequency Cancellation Technology

An often asked question is "Why doesn't this affect the fundamental (60Hz) frequency?" The answer is because only the magnetic flux from the ***in-phase currents*** are cancelled out. The phases in a three-phase AC system are each 120 degrees displaced from one other. Therefore, this secondary side winding orientation does not affect them. Again, only triplen harmonics are in phase with each other across the three phases.

Let's compare PQI's HMT technology to some other technology that more of us will be familiar with. Magnetic flux cancellation is similar in intent to that of noise-cancelling headphones. In both applications, there are "noise" waveforms present that are undesirable. In the case of the headphones, they are designed to eliminate or reduce distracting sounds in a given surrounding environment. The technology used in noise cancelling headphones is often referred to as "active noise control", and is achieved by analyzing the waveform of typical background noise, and generation of a signal-reversed waveform to cancel it out by interference. Since audible noise is typically a combination of various sound frequencies, the "interference" waveform consists of a band of various reversed-waveform frequencies, aiming to control as many "noise" frequencies as possible. The ratio of the magnitudes of the original noise waveform versus the signal-reversed waveform will dictate how much of the original noise remains audible.

In a PQI HMT, the intent is basically the same. We are aiming to eliminate "noise" in the electrical distribution system. The noises we are aiming to eliminate are specific harmonic frequencies. We know the frequencies that require cancellation, as they are the same for every line-to-neutral connected electronic load. However, instead of *creating* an interference waveform, like the active noise control technology uses, the HMT simply pits the load-generated harmonics against each other by orientation of the transformer secondary windings. In this way, the HMT eliminates or reduces the "noise".

So let's revisit the benefits of treating the load-generated harmonics. Recall from *The Truths About Transformers Part 1:* in the 1995 IEEE technical paper written by Thomas Key, titled *Costs and Benefits of Harmonic Current Reduction for Switch-Mode Power Supplies in a Commercial Office Building,* Key analyzed penalty losses due to harmonic distortion in electrical distribution systems. A summary of his findings illustrated that powering non-linear electronic load equipment can result in more than **double the**

losses than those attributed to linear load equipment. He also showed that non-linear load losses in the transformer were 2.7 times the base linear load losses. The copper losses in the transformer doubled, and the eddy current losses increased by more than ***17 times***. So what would be the benefit of cancelling these harmonics? We essentially turn a non-linear connected load into a ***linear*** load, from the perspective of the transformer, and this eliminates the excessive load losses. This would be the first step in dramatically increasing the operating efficiency of the distribution transformer, and it is something that cannot be accomplished by any type of standard or K-Rated transformer.

High Efficiency Transformer Core Design:

In a distribution transformer, there are two types of losses present. They are typically referred to as *load losses*, and *no-load losses*. In the first part of this paper, we discussed how the HMT drastically reduces load losses as compared to standard or K-rated type transformers that are currently on the market. It accomplishes this by treating load generated harmonics with the engineered secondary windings. To further improve the operating efficiency of a transformer, we can then focus on reducing the no load losses, which are essentially a function of the amount of energy required to simply energize the transformer. No-load losses are always present and at equal magnitude whether the transformer is connected to zero load or full load. The magnitude of these no load losses are determined by the transformer core construction design and the materials used to manufacture it. The major contributors to no-load losses are eddy current losses and hysteresis losses. Let's take a brief look at these two types of losses and how they are strategically reduced courtesy of the unique core design of the PQI HMT.

Eddy Current Losses:

When a transformer is energized, the alternating current from the windings creates a magnetic field which induces current in the core of the transformer. The current induced in the core causes undesirable "eddy currents" (See the circulating currents in the cores on Figure # 6 to the right). These currents create losses that produce heat and can likewise increase resistance and losses within the core. To reduce the no-load losses created by eddy currents, the core of the transformer is created by laminations of steel stacked together, rather than large chunks of steel. The thickness of these laminations have an effect on the magnitude of eddy current losses: The thinner the laminations, the less the eddy current losses. In the PQI HMT, the core construction incorporates very thin laminations in comparison to standard transformer core construction. This can be seen in Figures #7 and #8 on the following page. The difference between the core laminations of the standard transformer and those of the PQI HMT are significant.

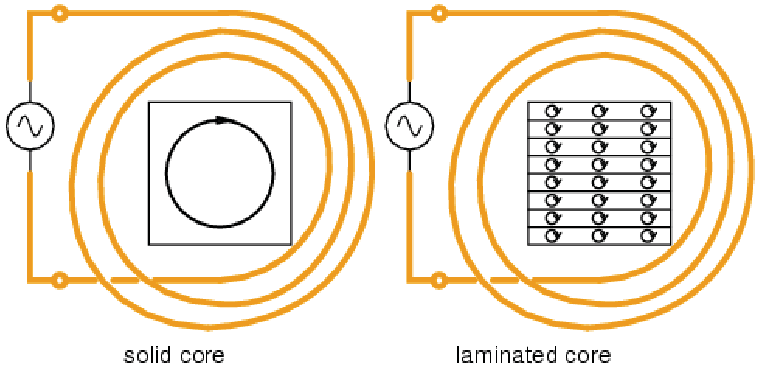

Figure #6 - Illustration of Eddy Currents, and the effect of a laminated core versus a solid core.

Hysteresis Losses:

Hysteresis losses are defined by how easily a transformer core can be magnetized. In order to reduce hysteresis losses, a transformer core must have a low resistance to magnetic flux. A low resistance core design is accomplished through proper choices

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Figure #7—Picture of the core construction of a standard transformer. This core construction incorporates thicker laminations.

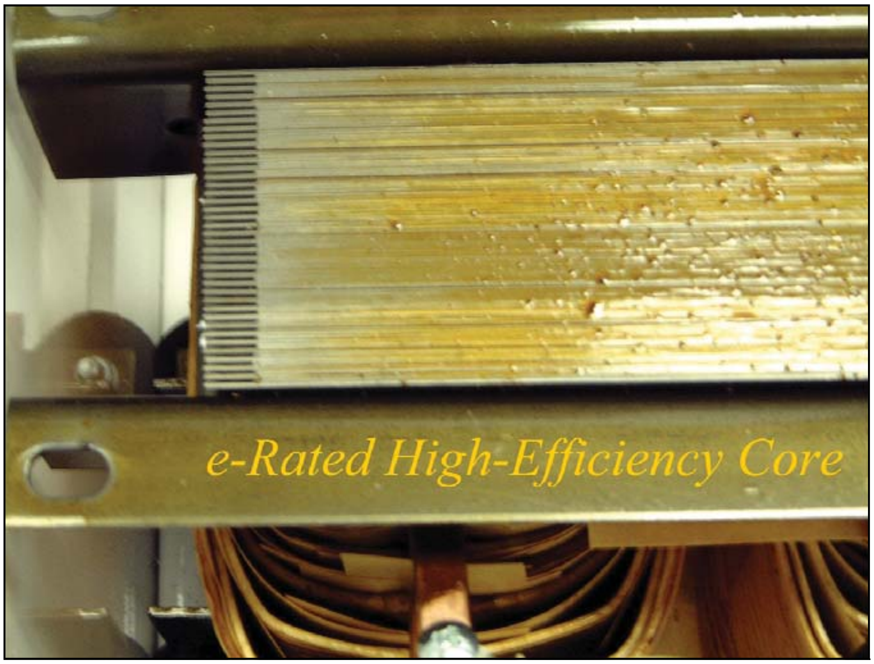

Figure #8—Picture of the core construction of a PQI HMT transformer. This core construction incorporates much thinner laminations.

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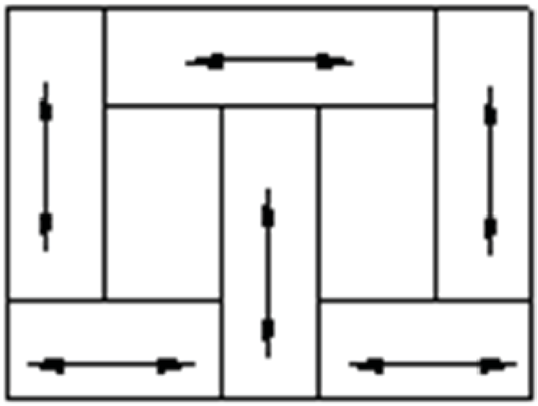

Figure #9 - A conventional transformer's butt-lap cut core construction

in core material selection and the way in which the core laminations are stacked together. Let's first compare the construction of transformer cores of a conventional transformer and a PQI HMT transformer. A conventional transformer is typically constructed with a butt-lap cut core, consisting of rectangular sheets of core steel arranged in such a way that the grain orientation of the steel is along the flux path, except in the corners where the flux path changes direction from the legs to the yoke members. A diagram of this core construction can be seen in Figure #9 to the left.

By contrast, the PQI HMT product utilizes a full and step lap mitre cut core design. This design ensures that the overlapping of the joints in the corners are mitered and staggered so that the best possible grain orientation and flux transition is achieved. This design reduces the magnetic flux resistance in the core, and likewise, reduces the hysteresis losses. Figure #10 illustrates this core construction.

PQI HMT transformers utilize ***grain-oriented electrical steel***, typically having a silicon level of 3%. It is processed such that the optimum properties are developed in the rolling direction. Due to the special orientation, the magnetic flux density is increased by 30% in the coil rolling direction. Grain oriented steel is used for the cores of high-efficiency transformers, electric motors, and generators.

So what does this core cut and material selection story come down to? It comes down to a decision of cost versus performance. The butt-lap cut core construction of the conventional transformer is easier and less costly to manufacture, and the thicker laminations are easier to manufacture and stack. By designing the conventional transformer in this fashion, manufacturers can bring a less costly product to market. However, what they have really done is passed the cost of on-going operation on to the end user, in the form of a product that operates at a lower efficiency level. Unfortunately, because of the inability of the NEMA TP-1 standard to be more representative of the real world connected loads, the true efficiency penalty is not revealed to the end user. The end user believes that the transformer will achieve its published efficiency, when in fact, that efficiency value only applies to linear connected loads.

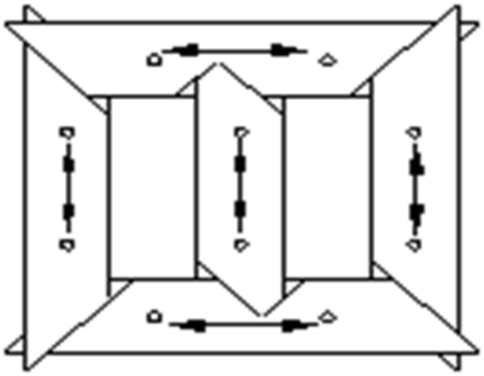

Figure #10 - A PQI HMT's full and step lap mitre cut core construction

Conclusion:

Let's now put aside the technical discussion of how these transformers are designed and summarize the value to the owner. After all, what is of utmost importance is that the transformer owner obtains the "right" product for the application. In regards to a transformer application, the "right" product would translate to a transformer that offers the ability to improve power quality problems created by connected equipment, and also reduces energy utilization due to losses. The harmonic mitigating transformer offers both of these performance characteristics. We have shown that the HMT can treat harmonic distortion, which improves power quality, and we have also shown that doing this reduces penalty losses. But just how significant can these savings be?

Take for example a 30kVA transformer supporting a school building. In school applications, we expect a blend of linear and non-linear loads to exist, with the majority being non-linear type. If we compile a return on investment comparison between a K13 rated transformer and PQI HMT transformer based on a typical school load profile and power utilization factor, the HMT transformer provides a return on investment in **less than two years**. It provides an operational cost savings of approximately $550.00 annually. The larger the transformer, the more annual savings we expect. Also, with higher levels of harmonic distortion, we expect much higher annual savings as well, when compared to a K13 or K20 rated transformer. And this is for a SINGLE transformer. How many transformers are in your facility?

As an owner, the decision to purchase a particular transformer comes down to this choice: Do you choose to pay a little more now for the right product and ***save*** a lot more over time thru better performance? Or will you choose to save a little up front with the lesser cost product and ***pay*** a lot more over its life because of inferior performance? To ensure that transformers you select will provide high energy efficiency, here are some things to consider when evaluating the product:

- Does the transformer manufacturer test for the transformer's efficiency when connected to a non-linear load? Can you get a copy of the test data?
- Does the transformer treat harmonics? What technology is employed to accomplish this?
- What is the core construction and what type of steel material is used to construct the core?

This information will allow you to make a better decision on the transformers you install in your facility.

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Power Quality International (PQI)
www.powerquality.net

References:

Thomas Key, Jih-Sheng Lai, "*Costs and Benefits of Harmonic Current Reduction for Switch-Mode Power Supplies in a Commercial Office Building*", IEEE IAS Annual Meeting, October 1995, Orlando, Florida