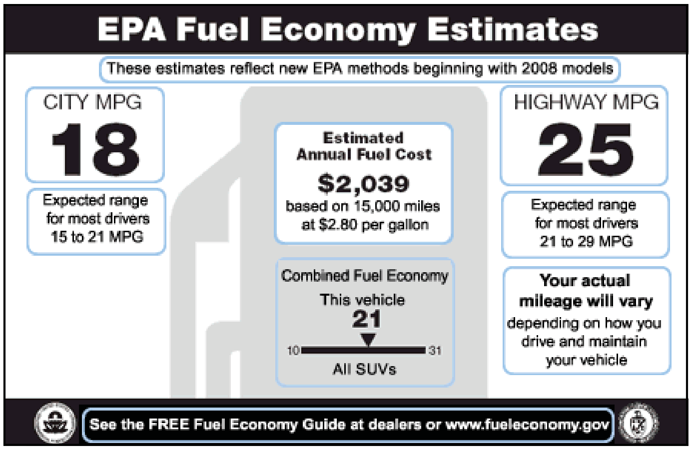
Tech Byte 14: The Truths About Transformers—Part 1

Designing a Transformer to Achieve High Efficiency in the Real World

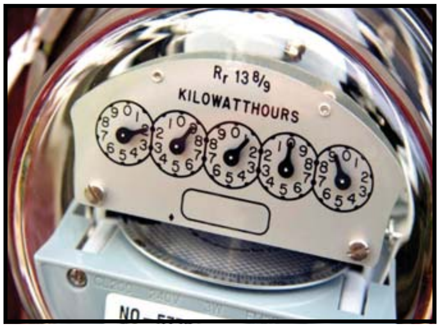
So you finally pulled the trigger. Because you put a lot of miles on your automobile, you decided to get rid of your V8, gas-guzzling SUV and purchase a more fuel efficient XUV to keep more money in your pocket. You made a smart purchase of a new, 2009 GMC Acadia with a 6-cylinder engine. With your SUV you were lucky to get 11 to 12 MPG in the city, so it seemed like a great decision to go with the Acadia, based on the combined EPA mileage estimate of 21 MPG, city EPA of 18 MPG, and highway EPA of 25 MPG. After a few weeks however, things just weren't adding up. You filled up your tank and set your trip meter, and sure enough, you found you were only getting an average of 16 MPG! What happened? Were you lied to?



After further investigation of your car's EPA window sticker, you found that for your new vehicle, the expected MPG range for "most drivers" is 15 to 21 in the city and 21 to 29 on the highway. Wow, that's a much different story! How can they get away with this? You don't care about typical averages, you care about you and this is not what you bargained for! Then you see the words that you didn't catch when you bought the vehicle: "Your Actual Mileage Will Vary."

Several factors can affect your mileage, including how and where you drive, your vehicle condition and maintenance practices, fuel variations, and engine break-in. So you could possibly meet those numbers, but you would need to change your driving habits.

This is the case with practically anything that comes with a MPG or efficiency performance estimate on it. The numbers are based on specific tests conducted in controlled environments. The real world environment in which you operate the product will have an effect on its published performance. Therefore, when selecting a product for an application, it is important to correlate the product's published performance to the method in which the product was tested, so you can adjust your design accordingly or temper your expectations of real world performance.



This same story exists for distribution transformers. Since energy efficiency has become such a critical topic today, any device that consumes energy during the normal course of operation is being designed to use LESS. And transformers are a good place to start if you are looking to identify ways to conserve energy. A 2005 Leonardo Energy study titled *The Potential for Global Energy Savings from High Efficiency Distribution Transformers* notes that distribution transformers are the second largest loss-making component in electricity networks, behind distribution and transmission lines. The study estimates that in the 6 largest world economies, transformer ***losses*** were totaled at approximately 285 TWh. It isn't difficult to imagine the transformer loss potential here in the United States, given the study estimates that in America, one distribution transformer exists for every five to ten citizens. That's a lot of transformers!

Because of the knowledge of energy losses attributed to distribution transformers, the United States enacted a transformer efficiency standard, NEMA TP-1, on January 1, 2007, defining minimum transformer efficiencies based on transformer size. Any

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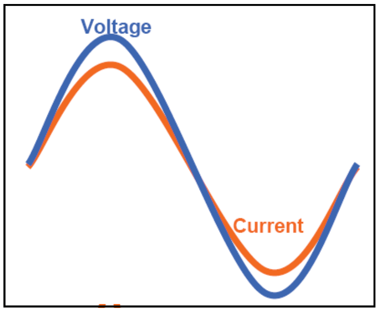
transformer not meeting the minimum efficiency level can not be sold for use in the United States as of that date. If the transformer passes the efficiency test, it is stamped that it meets the standard, and goes out the back door to a customer that is expecting a transformer that meets a specified operating efficiency.

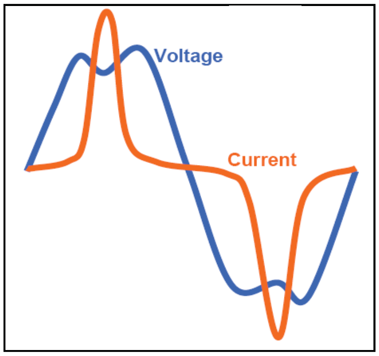
Wait, time out. We have heard this story before, haven't we? The car and the mileage story? Let's scratch the surface this time and see if there are any "gotchas" pertaining to this transformer high efficiency story, so we don't get fooled again. To do this, we need to take a look at the NEMA TP-1 standard and identify ***how*** transformers are tested to meet their published efficiency number.

Rating kVA	Eff. %
15	97.0
30	97.5
45	97.7
75	**98.0**
112.5	98.2
150	98.3
225	98.5
300	98.6
500	98.7
750	98.8
1000	98.8

Table 1
NEMA TP-1 35% Full Load Efficiency Requirements



Picture 1
Linear Load Waveforms



Picture 2
Non-Linear Load Waveforms

To do this, there are some questions we should ask: What type of load was used for the test and what was the load level? How does this test procedure align itself with the real world scenario that we are going to apply the transformer in? This is where we find the story that the vast majority of transformer manufacturers don't want customers to hear: The majority of transformers installed in the U.S. today **will never meet the efficiency value published by the NEMA TP-1 standard once they begin supporting real-world load**. To add to this, transformers are not labeled with information that states that its efficiency "will vary based on connected load", like cars are with the new EPA sticker. So most customers will never know the degree to which their transformer efficiency actually declines from the published value. This is because there is nothing on their monthly power bill that tells them exactly what penalty they are paying for excessive transformer efficiency losses.

Unlike the car scenario, there isn't much that can be done IF it is determined that a given transformer's real world efficiency is less than expected. Customers cannot simply "change the way they drive" the transformer. The connected loads cannot be made to operate differently, and customers are not going to select these loads based on their being compatible with a given transformer. The fact is, transformers need to be correctly selected up front for the expected load profile that they will be connected to.

This discussion should have raised a few questions for anyone that owns, purchases, or specifies transformers. How are transformers required to be tested for efficiency performance? How do we know that different load profiles affect transformer operating efficiency? Do we have choices when selecting transformers for specific applications and if so, how are they different from each other? These are questions we will address in this paper.

Let's begin with determining the testing criteria by which transformers are tested and how we arrive at an energy efficiency performance figure. To do this, we will look into the *NEMA TP-1 Standard for the Labeling of Distribution Transformer Efficiency*.

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Two significant items jump out when you evaluate the efficiency standard. First is that the standard calls for efficiency testing of the transformers using a 100% ***linear*** connected load, which would mean connecting the transformers to a resistive load bank when tested in the factory. This means that the published efficiency (Table 1 on the previous page) would not be applicable if the transformer is connected to loads that exhibit ***non-linear*** characteristics. Why is this significant? Because the vast majority of the loads (VFDs, computers, fax machines, servers, electronic ballast lighting, copy machines, laser printers, etc.) in today's buildings and facilities ***are non-linear***! Think about this a different way: What loads in today's facilities are actually linear in nature? The coffee maker, toaster, maybe the few incandescent lights that are still used. There are not many linear loads in existence anymore. The reason for this is because non-linear loads allow a specific technology to operate more efficiently. A non-linear load has a lower power utilization factor, because of how the switched mode power supply works. The down side to proliferation of non-linear loads is that these devices create problems elsewhere in the power distribution system if attention is not paid to correcting them.

	Harmonic Order							
Load description	**1**	**3**	**5**	**7**	**9**	**11**	**13**	**15**
Six-pulse rectifier	100	—	17	11	—	5	3	—
Twelve-pulse rectifier	100	—	3	2	—	5	3	—
Eighteen-pulse rectifier	100	—	3	2	—	1	0.5	—
Twenty-four pulse rectifier	100	—	3	2	—	1	0.5	—
Electronic/computer	100	56	33	11	5	4	2	1
Lighting/electronic	100	18	15	8	3	2	1	0.5
Office with PCs	100	51	28	9	6	4	2	2
VFD's (range)	100	1 to 9	40 to 65	17 to 41	1 to 9	4 to 8	3 to 8	0 to 2

***Table 2*: Harmonic Current Magnitudes for Given Non-Linear Load Types**
Taken from *The How's and Why's of Harmonic Distortion*, EC&M, June 2006

The problem these non-linear loads create is harmonic distortion. Harmonic distortion is what creates the efficiency or "penalty" losses in an electrical distribution system. The magnitude of the harmonics in the facility will determine how much of a penalty the facility will suffer. Just how much harmonic distortion should be expected in a given facility's electrical distribution system? It is fairly predictable. In a paper titled *The How's and Why's of Harmonic Distortion,* published in the June 2006 EC&M magazine, the typical amounts of harmonic currents are detailed in a table (Table 2 above) given a specific load and load magnitude. So for example, if a facility has 100 Amps of office computer (PC) loads, we would expect to have 51 Amps of 3rd harmonic currents, 28 Amps of 5th harmonics, 9 Amps of 7th harmonics, etc, down to the 15th harmonic order.

Contrary to the beliefs of some, harmonics have not gone away. They have not been designed out of electronic loads. What has happened over time is the introduction of design practices for treating the ***symptoms*** of harmonics, not removing the harmonics themselves. Many of these legacy design practices are still in place today, and have given the impression that harmonics have gone away. However, the impact of penalty losses and power quality degradation due to harmonics are still as significant as ever, and in many cases—worse. The symptoms have just become less visible. Although over-heating may not be as prevalent, power bills are more than they should be because of excessive losses. Sensitive electronics suffer operational problems, and no one seems to know why. These problems exist because the harmonics have not been removed. The legacy design practice to treat harmonics has been, and still is, to oversize everything to eliminate the symptom of over-heating. However, over-sizing negatively impacts operational efficiency. The more lightly loaded a transformer is, the worse its efficiency.

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Let's investigate this topic further, and determine the impact of harmonics on transformer operating efficiency. This topic has already been addressed in a 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.* In this paper, Key analyzes and calculates penalty losses in electrical distribution systems. A summary of his findings illustrates that powering non-linear electronic load equipment can result in more than **double the losses** than those attributed to linear load equipment. He also shows that the distribution transformer suffers the most dramatic penalty losses in the electrical distribution system, due to non-linear connected loads.

In Key's example of transformer penalty losses for a distribution transformer feeding a highly non-linear load, the 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***. He also showed that because of this harmonic distortion, a 112.5 kVA transformer was overloaded by only 60kW of computer loads. This is the reason why the legacy design practice of over-sizing was conceived. Harmonics created by non-linear loads create their OWN losses, and because of this, consume capacity and overheat the electrical distribution even when the fundamental load is much less than the available capacity in the electrical system.

In Key's conclusion to this paper, he notes that failure to correct for harmonic distortion can increase power bills and consume capacity within the electrical distribution that could otherwise be used to supply additional facility equipment. He notes that by correcting the harmonic distortion problem, significant energy can be saved resulting in a quick payback on the money invested.

The conclusions reached by Key are also supported in the Leonardo Energy Study introduced earlier in this paper. The study states that harmonic currents have a significant effect on transformer losses, and that load losses in a transformer supplying non-linear loads can be twice the losses of the fundamental frequency. The study goes on to recommend that the preferable strategy for dealing with harmonics is to "...use a transformer especially designed to minimize losses with non-linear loads."

So now, after digging into this efficiency topic a little deeper, we can reach the following conclusions:

- Transformers are labeled with an efficiency value, per the NEMA TP-1 standard, based on being connected to a ***100% linear load profile*** at 35% full load.
- The vast majority of today's real-world facility loads are ***non-linear*** type.
- Non-linear loads create harmonic distortion.
- Harmonic distortion will cause penalty losses in electrical distribution equipment, especially transformers.
- Because of the penalty losses, typical transformers will not be able to meet the linear load efficiency value they are labeled for under the NEMA TP-1 standard.
- Standard or oversized (K-Rated) transformers do not solve the problem of harmonics, and their use in non-linear load environments increases operational costs.

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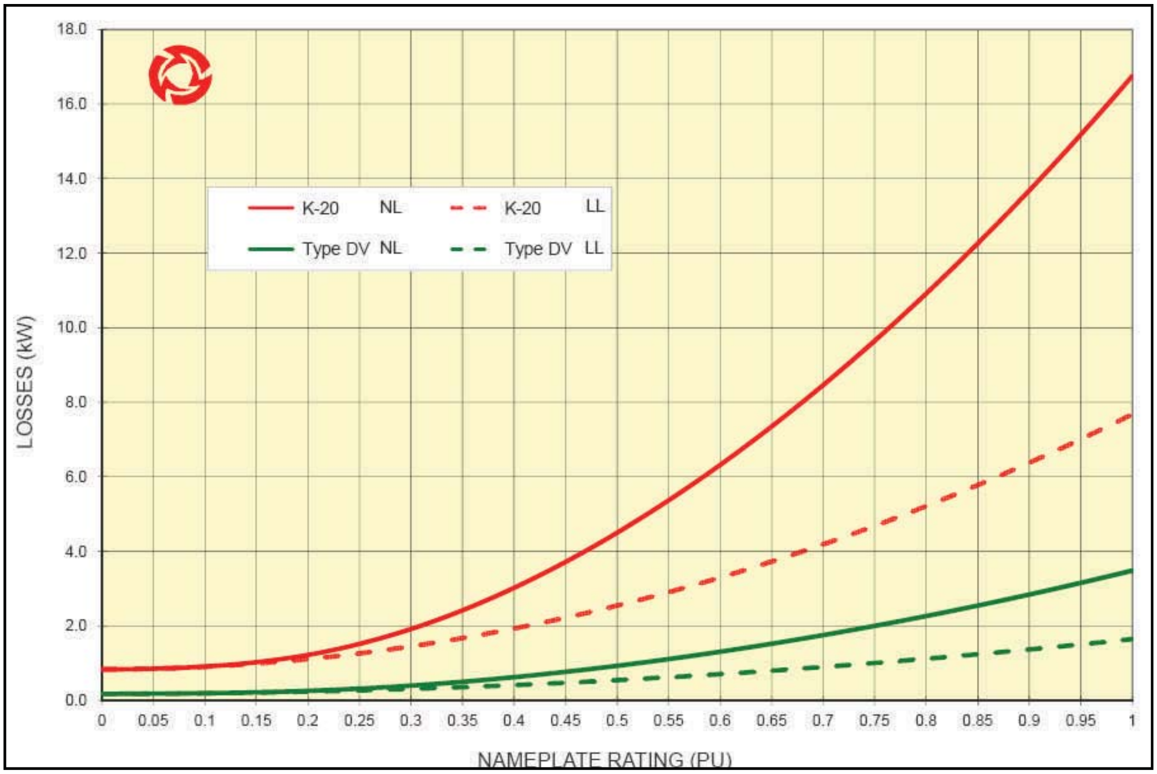
So where do we go from here? Is there anything that can be done to allow us to realize high operating efficiency of our transformers in the non-linear world we are living in? The answer is yes, but it requires that we use the right tool for the job. Transformers today can not just simply perform voltage transformation if they are to operate more efficiently. Non-linear loads are not going away. Today's transformers need to correct the problems that cause penalty losses—harmonics. The solution to this is utilizing high efficiency, harmonic mitigating transformers (HMTs). By utilizing HMTs, we can put back in our pockets the money that is currently wasted on losses due to harmonic distortion.

To illustrate this summary more effectively, take the graph (Graph #1) below, for a 75kVA K-20 rated transformer versus a 75kVA PQI "DV" type HMT transformer manufactured by Power Quality International (PQI). The dashed red line in the chart represents the K-20 transformer losses based on load level, when connected to a linear load. The solid red line represents that same standard transformer when connected to a 100% non-linear load. This illustrates why it can be concluded that the overwhelming majority of transformers installed will not meet the NEMA TP-1 efficiency that they are labeled for, once installed in the real world.



Graph #1 ***- Comparison of Transformer Losses By Load Type***
75kVA K20 Rated Transformer vs. 75kVA PQI "DV" Type HMT Transformer

By contrast, the dashed green line on the chart illustrates the PQI HMT when connected to a 100% linear load, and the solid green line illustrates the PQI HMT when connected to a 100% non-linear load. The PQI HMT is able to meet the NEMA TP-1 standard under ALL connected load profiles.

Graph #2 on the following page further illustrates this performance difference by comparing the non-linear load operating efficiencies of the 75kVA K-20 rated transformer versus the 75kVA PQI "DV" type HMT transformer. There is a significant difference here, and to the end user, the difference translates into an increase or decrease in operating costs to do the same work. Do you want to pay less, or do you want to pay more?

***Graph #2* - Comparison of Non-Linear Load Operating Efficiency**
75kVA K20 Rated Transformer vs. 75kVA PQI "DV" Type HMT Transformer

In conclusion, there have been many studies and technical papers aimed at identifying ways to increase the efficiency of electrical distribution systems, and many of these studies have gone on to identify the impact of non-linear loads and harmonics as a challenge to achieving higher efficiencies. However, most transformer manufacturers are not actively designing products to operate at high efficiency when connected to these real world non-linear loads. Why is this? There are a few significant reasons why. End users are not aware of the losses they are currently paying for, and they do not know that they have a choice in the matter. Many consultants hired by end users are not aware of the differences that exist in today's transformer products, or the efficiency impacts associated with powering non-linear loads. And the secret is, many of the large transformer manufacturers are not in a hurry to break the news to them. The law (NEMA TP-1) is not requiring them to change their ways, and standard transformers are much easier to manufacture than HMT products.

Hopefully this paper has raised some additional questions about transformers. Now we need to investigate just what exactly a HMT transformer is. How does it work and how is one applied? Can we calculate cost savings that would be introduced by using HMTs? These questions will be answered in **Part 2** of ***The Truths About Transformers***.

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Power Quality International (PQI)
www.powerquality.net

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