Optimal Transformer Efficiency Using Weighted Average

In order to improve the efficiency of electrical distribution in commercial buildings, the US Department of Energy (DOE) introduced regulations with more stringent minimums on transformer efficiencies in January 2016. This was covered under the Code of Federal Regulations 10 CFR Part 431.192 and has become more commonly known as DOE 2016. It improved on the previous regulation by requiring 30% lower losses at 35% loading which was determined to be the most common operating load.

Although this has resulted in an improvement in electrical system efficiency when transformers are, in fact, operating at light loads, it falls short in more heavily loaded applications and when high levels of harmonic generating non-linear loads are present. Rarely do we find that actual electrical circuits precisely operate at an 'expected average value'? Every circuit is different, every application is different.

DOE 2016 recognizes this with the following reference:

> *Transformer loading is an important factor in determining which types of transformer designs will deliver a specified efficiency, and for calculating transformer losses. Transformer losses have two components: no-load losses and load losses. No-load losses are independent of the load on the transformer while load losses depend approximately on the square of the transformer loading. Because load losses increase with the square of the load, there is a particular concern that, during times of peak system load, load losses can impact system capacity costs and reliability.*

The problem is that by applying a limit only at 35% loading, manufacturers are encouraged to reduce costs by designing transformers that have higher losses at higher loading levels. This is to the detriment of customers who might have higher loading levels. A transformer designed instead to maintain high efficiencies at both light loads and heavier loads and with non-linear loads would, more effectively, meet this need.

Optimizing No-Load vs Load Losses in Transformer Design

It isn't easy to design a transformer with high efficiency at both light loads and heavy loads. For highest efficiency at light loading, as required by DOE 2016, no load losses need to be minimized. Using conventional engineering techniques to minimize no-load losses, load losses will be compromised. Table 1 shows conventional design techniques for reducing no load losses and their negative effect on load losses.

Table 1: Techniques for Reducing No-Load Losses

	No-load losses	Load losses	Cost impact
To decrease no-load losses			
Use lower-loss core materials	↘	–	↗
Decrease flux density by:			
a) increasing core cross-sectional area	↘	↗	↗
b) decreasing volts per turn	↘	↗	↗
Decrease flux path length by decreasing conductor cross-sectional area	↘	↗	↘

For example, core losses can be reduced by increasing the core cross-sectional area, but this would result in longer windings to wrap around the bigger core. Longer windings have higher resistance and therefore, higher I^2R losses.

The reverse is also true. Designing for high efficiency at heavier loading will compromise no load losses (see Table 2).

Table 2: Techniques for Reducing Load Losses

	No-load losses	Load losses	Cost impact
To decrease load losses			
Use lower-loss conductor materials	–	↘	↗
Decrease current density by increasing conductor cross-sectional area	↗	↘	↗
Decrease current path length by:			
a) decreasing core cross-sectional area	↗	↘	↘
b) increasing volts per turn	↗	↘	↘

Load losses can be decreased by increasing conductor size to lower current density, but the

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resultant larger winding would increase the core leg length and thereby, increase no load losses.

Instead of a 'one size fits all' approach, it would seem better to establish a load range profile and tailor the efficiency requirements for the transformer based on that projected load profile. This is precisely what the California Energy Commission (CEC) did when establishing efficiency levels for solar inverters.

California Energy Commission (CEC) Efficiency Calculation for Solar Inverters

Recognizing that solar inverters vary widely in operating load from no-load at night to full load during bright sunny days, the CEC determined that efficiencies must be optimized over this wide load range. To do this, they created a weighted efficiency equation based on the estimated average operating time at various loading levels, as follows:

$$\eta CEC = 0.04\times\eta_{10\%load} + 0.05\times\eta_{20\%load} + 0.12\times\eta_{30\%load} + 0.21\times\eta_{50\%load} + 0.53\times\eta_{75\%load} + 0.05\times\eta_{100\%load}$$

Where, $\eta_{XX\%load}$ = inverter efficiency at XX% load

As can be seen, this equation puts a higher emphasis on heavier loading with a weighting of 0.21 at 50% load and 0.53 at 75% load. This was believed to better match typical installations. A DOE 2016 transformer would definitely not be appropriate for a solar inverter application because of its sole emphasis on low load efficiency.

Following this logic, Mirus International developed a solar transformer line that optimizes efficiency to match the CEC weighting schedule. Table 3 compares a 50 kVA unit against a conventional DOE 2016 design. The Mirus transformer's CEC efficiency is 0.45 points higher which equates to an average of 21% lower losses when operating in a typical solar system application.

Table 3: 50 kVA Mirus ULL-Solar vs DOE 2016 Efficiencies

	Efficiency						
Transformer	10%	20%	30%	50%	75%	100%	CEC
50 kVA DOE	96.89	98.1	98.39	98.27	97.7	96.76	97.84
50 kVA ULL-S	96.91	98.16	98.51	98.6	98.29	97.74	98.29
Difference	0.02	0.06	0.12	0.33	0.59	0.98	0.449

Of course, a solar application is different than a typical commercial installation since the heaviest weighting is applied at 75% loading, so it is probably not appropriate to apply the weighting coefficients of CEC. But most would agree that with varying load profiles, a weighted average would provide a better design than one optimized to only one load level, regardless of what that load level might be.

In recent discussions with an engineering consultant, we were asked about the efficiencies of our ultra-low loss transformers, ULLTRA, over their entire operating range. These were examined over the range from 10 % to 100% at 10%, 15%, 20%, 25%, 30%, 35%, 50%, 75% and 100%. He had found it difficult to get this information from other manufacturers and therefore, was questioning whether these transformers were truly efficient over the entire load range. Manufacturers will often only provide information as required by the standard so for DOE 2016 that means efficiency at only 35% loading.

Table 4 and Fig. 1 show the % efficiency values at various load levels for typical 75 kVA DOE 2016 and Mirus ULLTRA transformers in both standard, ULL, and light load, ULL-L, configurations.

Table 4: 75 kVA Mirus ULL & ULL-L vs typical DOE 2016 Efficiencies

Load Percent	75 kVA DOE 2016	ULL	ULL-L
10%	97.06	96.65	97.7
20%	98.30	98.11	98.54
25%	98.46	98.37	98.66
30%	98.54	98.53	98.7
35%	98.6	98.62	98.69
50%	98.55	98.68	98.64
65%	98.34	98.66	98.55
75%	98.14	98.6	98.44
100%	97.42	98.15	97.8

In addition to the loading level percentages required for the CEC equation, this table also shows efficiencies at 25%, 35% and 65% loading. 35% is shown to provide a comparison to DOE 2016 requirements. 25% and 65% are shown because they are more appropriate loading levels for commercial applications and therefore are

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considered for the weighted average equation proposed in this paper.

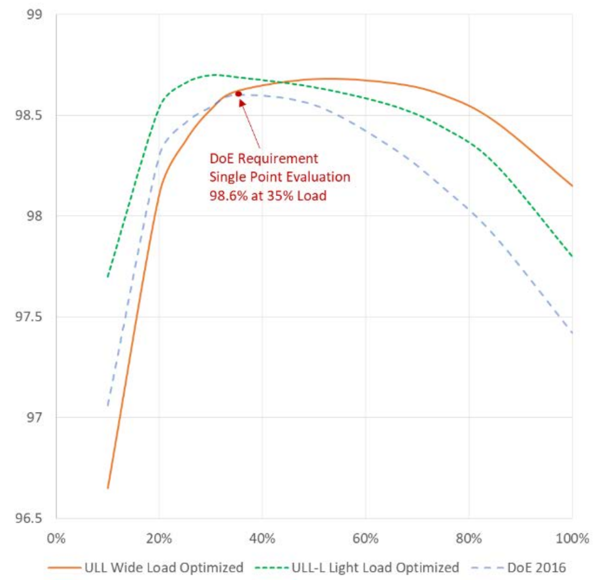

Fig. 1: 75 kVA Mirus ULL & ULL-L vs DOE 2016 Efficiencies

Determining Appropriate Weighted Averages for Optimal Transformer Efficiency

Defining a load-based weighted average efficiency equation for commercial transformers following CEC's approach for inverters, should provide a better, more energy efficient, cost effective solution for the end user. The initial installation cost of a transformer is small when compared to the "total cost of ownership" which includes the energy component.

On some hospital projects, loading is often in the 40% to 60% range while on some school projects, a more typical load might be in the 20% to 30% range. Every project is different so it seems wise to treat the efficiency of the electrical distribution system as an engineering evaluation, just as short circuit coordination and load flow criteria is established for 'sound engineering design'.

Therefore, if actual loading can vary, it seems doubtful that optimizing a transformer's efficiency at a single loading level (i.e. 35%) would always provide the best overall energy efficiency. A better approach would certainly be to offer more than one design to allow selection based on the expected load levels. It's rarely easy to anticipate loading in a precise manner but usually a prediction of whether the loading will be light or heavy can be determined.

To this end, Mirus offers two ultra-low loss transformer (ULLTRA) designs – ULLTRA-L for light loads and ULLTRA for heavier loads. To achieve optimal energy efficiency, both are designed to exceed DOE 2016 efficiency requirements at 35% loading but also at an average weighted efficiency that is appropriate for the application.

To determine suitable weighting equations for light loads and heavier loads in commercial applications, the CEC equation for solar inverters must be modified slightly. Solar inverters often operate at high loading levels during the day, so 75% and 100% loading is appropriate for that application. But for commercial buildings, a heavier loading level would likely be in the 50% to 65% range. And since DOE 2016 is based on 35% loading, that level should also be included in the calculation. To keep to a total of 6 load points, 25% is used in place of 20% and 30%. Therefore, the following weighted average efficiency equations are proposed for light loads and heavier loads respectively.

For light loading:

$$\eta_{TranLL} = 0.05\times\eta_{10\%load} + 0.35\times\eta_{25\%load} + 0.52\times\eta_{35\%load} + 0.05\times\eta_{50\%load} + 0.03\times\eta_{65\%load} + 0.0\times\eta_{100\%load}$$

For heavier loading:

$$\eta_{TranHL} = 0.01\times\eta_{10\%load} + 0.03\times\eta_{25\%load} + 0.22\times\eta_{35\%load} + 0.5\times\eta_{50\%load} + 0.22\times\eta_{65\%load} + 0.02\times\eta_{100\%load}$$

Where, $\eta_{XX\%load}$ = transformer efficiency at XX% load

The next step is to determine what target efficiency should be used for these weighted averages. Mirus recommends the use of the same high efficiencies that DOE 2016 has established for 35% loading. If these efficiencies are good at 35% load, then they should also be good for other load levels. By specifying both DOE 2016 compliance at 35% loading and a weighted efficiency compliance at the same efficiency level, the end user is guaranteed to get a transformer that has high efficiency over a wider load range. This is especially true when the heavier loading equation is used.

Let's use the 75kVA transformers shown in Table 4 as an example. For light loads, we select the values in the ULL-L column as that transformer is optimized for lighter loads.

$$\eta_{TranLL} = 0.05 \times 97.7 + 0.35 \times 98.66 + 0.52 \times 98.69 + 0.05 \times 98.64 + 0.03 \times 98.55 + 0.0 \times 97.8 = 98.62\%$$

For heavier loading, we select the values in the ULL column.

$$\eta_{TranHL} = 0.01 \times 96.65 + 0.03 \times 98.37 + 0.22 \times 98.62 + 0.5 \times 98.68 + 0.22 \times 98.66 + 0.02 \times 98.15 = 98.62\%$$

Both calculations exceed the DOE 2016 minimum efficiency requirement of 98.6% ensuring that the transformers are more efficient over a wider load range.

Using the typical efficiency levels for a conventional 75kVA DOE 2016 transformer rather than the Mirus ULLTRA, the weighted average calculations become:

$$\eta_{TranLL} = 0.05 \times 97.06 + 0.35 \times 98.46 + 0.52 \times 98.6 + 0.05 \times 98.55 + 0.03 \times 98.34 + 0.0 \times 97.42 = 98.46\%$$

$$\eta_{TranHL} = 0.01 \times 97.06 + 0.03 \times 98.46 + 0.22 \times 98.6 + 0.5 \times 98.55 + 0.22 \times 98.34 + 0.02 \times 97.42 = 98.47\%$$

This weighted efficiency is significantly lower than the DOE 2016 minimum and therefore, the transformer is less efficient overall than the Mirus ULLTRA. By specifying high efficiency at only one load level (35%), the conventional DOE 2016 transformer often has significantly lower efficiencies at load levels on either side of 35%. <u>By choosing transformers with high weighted average efficiency, the energy savings can be substantial depending upon the transformer's actual loading.</u>

What makes Mirus ULLTRA Transformers Different

Understanding that a better transformer design meets high efficiencies over a wider load range, Mirus addressed the challenge of lowering no load losses without compromising load losses. Conventional interleave transformer cores using grain oriented steel have 2 to 3x higher losses in the corners. This is due to the flux going against the grain when it moves from vertical orientation in the legs to horizontal orientation in the top and bottom yokes.

Mitered core configurations reduce this effect but more recently, many manufacturers have been using wound core configurations. In a wound core configuration, the flux maintains the same direction as the grain orientation even in the corners, which reduces the corner losses.

Wound cores have a negative effect however, which is often overlooked by manufacturers. This is related to how the fluxes add vectorially between phases in the core. Fig. 2 shows an interleaved core with the fluxes shown in each transformer leg.

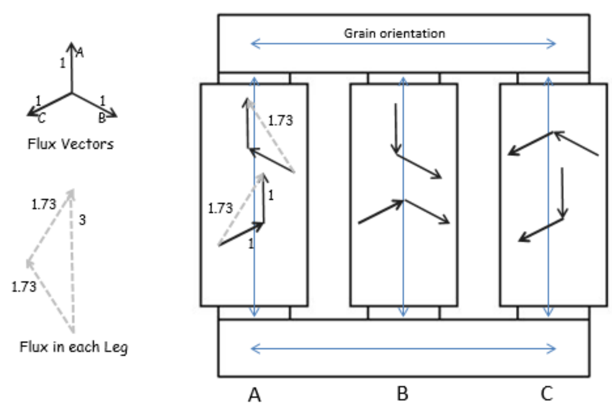

Fig. 2: Flux Orientation in Interleaved Transformer Core

Each transformer leg carries the flux of that phase and each of the other two phases as shown. The flux vectors mix evenly in the core leg with the total flux being the vector sum and 3x the individual phase flux magnitude.

The most common configuration of wound transformer cores is the Evans Core, often referred to as Distributed Gap or DG Core. Fig. 3 shows this core and the related flux vectors.

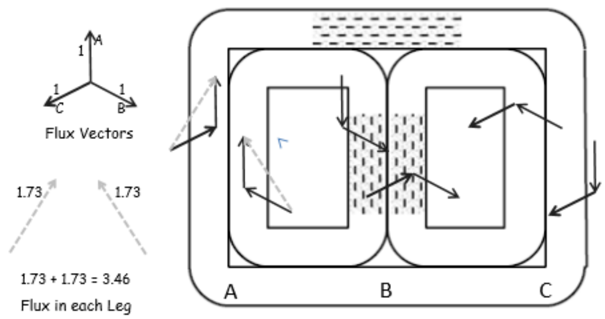

Fig. 3: Flux Orientation in Distributed Gap, Wound Transformer Core Configuration (Evans)

Although the same flux vector pairs exist, they will not mix evenly in the core because the paths tend to be contained within each wound section as shown. The flux pairs sum vectorially but the total flux is the arithmetic sum of these pairs rather than the vector sum. The result is 3.46x the individual phase flux magnitude which is about 15% higher than the flux in the interleaved configuration. 15% higher flux produces higher core losses which somewhat offset the reduction in corner losses.

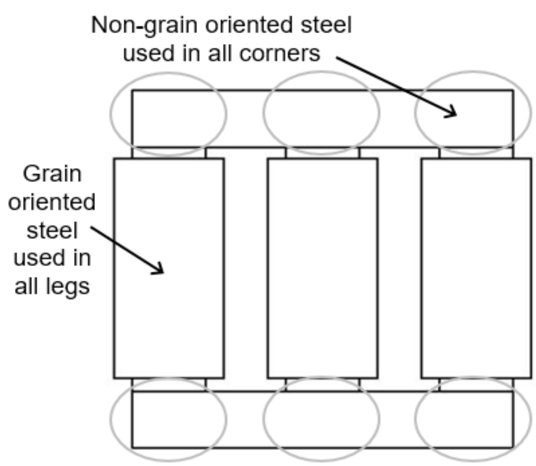

Fig. 4: Low Loss Core Configuration of Mirus ULLTRA Transformers

The ideal transformer therefore, is one that lowers the corner losses while allowing the fluxes to fully mix in the core. Fig. 4 shows a Mirus ULLTRA transformer core with a configuration referred to as 'staggered core'. In this configuration, a mix of core steels is used with grain oriented (GO) steel in the legs and non-grain oriented (NGO) steel in the corners. <u>Corner losses are reduced since the flux never goes against the grain in the corners. Losses in the legs are reduced because the fluxes mix evenly unlike wound cores.</u>

Non-linear Loads and Harmonic Mitigation

As the original inventors of harmonic mitigating transformers (HMTs), Mirus naturally offers ULLTRA transformers in HMT versions. HMTs reduce harmonic losses by cancelling the 3rd and other triplen harmonic fluxes in the secondary of the transformer. This reduces eddy currents and I^2R losses in the primary windings. In addition, power system losses can be further reduced by alternating between 0^o and 30^o models to get cancellation of 5th and 7th harmonic currents upstream. Power Quality improvement through lower voltage distortion is also achieved. When harmonic generating, non-linear loads are prevalent, the addition of harmonic mitigation to an already inherent high efficiency design, provides the potential for enhanced energy savings.

Rightsizing for Optimal Payback

When power systems are utilized at lightly loaded conditions, there is substantial waste of energy as well as infrastructure cost. Oversized transformers lead to higher no-load losses and a higher purchase price. Transformers designed for the type of load (i.e. linear or non-linear) and heavier loading, allow for 'rightsizing' to the expected load.

A rightsizing analysis can be done comparing a conventional 75 kVA DOE 2016 compliant transformer with a 45 kVA ULLTRA transformer. Fig. 5 and 6 show efficiency graphs for 75 kVA DOE compliant and 45 kVA ULLTRA transformers respectively. These graphs were generated by the Transformer Efficiency Calculator associated with CSA standard C802.5-16, 'Guideline for evaluating the efficiency of dry-type transformers under non-linear loading'.

Although by % loading, the efficiencies are higher on the 75 kVA transformer, for an actual load of 22.5 kVA (i.e. 30% on the 75 kVA transformer and 50% on the 45 kVA transformer), the 75 kVA losses are actually higher (see Table 5). This is true for both linear and non-linear loading. Rightsizing certainly makes sense when you consider that both the purchase price and installation cost of the 75 kVA transformer is substantially higher than the 45 kVA transformer. Also worth noting is that from an environmental perspective, with less materials and lower weight, the energy to produce and deliver the 45 kVA transformer is less than that for the 75 kVA unit.

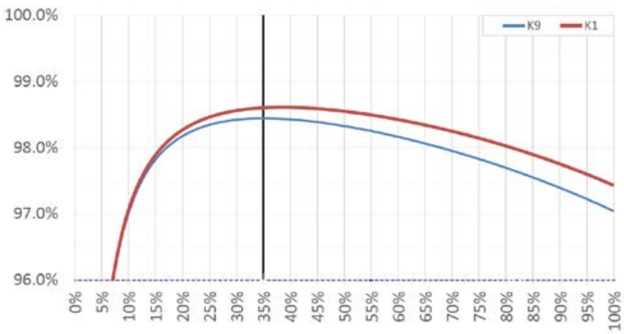

Fig. 5: Efficiency Curves for 75 kVA DOE 2016 Transformer based on C802.5 Calculation

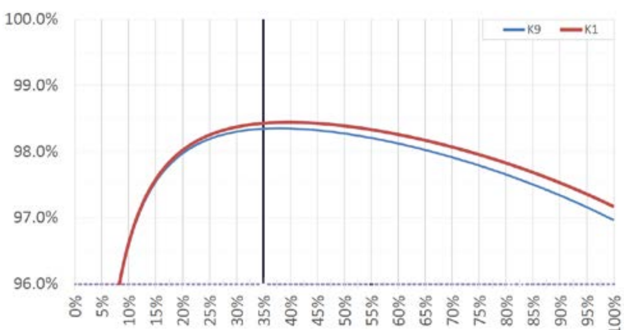

Fig. 6: Efficiency Curves for 45 kVA ULLTRA Transformer based on C802.5 Calculation

Table 5: Rightsizing Comparison with 22.5 kVA Load on 75 kVA and 45 kVA transformers

	75 kVA DOE 2016	45 kVA ULLTRA
Loading	30%	50%
No load losses	215 W	150 W
Total losses linear load	363 W	339 W
Total losses K-9 load	410 W	380 W

Summary:

If transformer loading was always near 35%, no other consideration for transformer efficiencies than DOE 2016 would be required. However this is certainly not the case, so a transformer designed for high efficiencies over a wider load range is definitely warranted. To achieve this, weighted efficiency equations are proposed based on the approach used by the California Energy Commission (CEC) for solar inverter design.

The equations are modified slightly however, to better reflect the expected loading for commercial applications. Two equations have been proposed – one for light loading and one for heavier loading. In applications where the loading is expected to be below 35% for a majority of the time but with peaks at higher load levels, the light loading equation should be used when specifying a transformer.

For any other application, the heavier loading equation should be used because it guarantees that the transformer would meet the high efficiency level defined by DOE 2016 at 35% load as well as at the average weighted loading level. Using this higher weighting equation, allows for rightsizing of a transformer rather than oversizing to optimize efficiency. This saves significant capital cost on a project without sacrificing any operational cost. This transformer would always be as efficient or better than a conventional DOE 2016 design no matter what the loading but especially when operating at load levels between 35% to 65%.

For assistance in designing your high efficiency transformer application, please feel free to contact Mirus directly, using the information found in the footer.