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MIRUS International Inc.

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.

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 moderate to high 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.

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

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 1 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 1: 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	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.

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 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 wider ranging can be determined.

To this end, Mirus offers two ultra-low loss transformer (ULLTRA) designs – ULLTRA-L for light loads and ULLTRA for a wider load range. 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 a wider load range in commercial applications, the CEC equation should be modified slightly. 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 load and wider load ranges 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 wider load range:

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

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

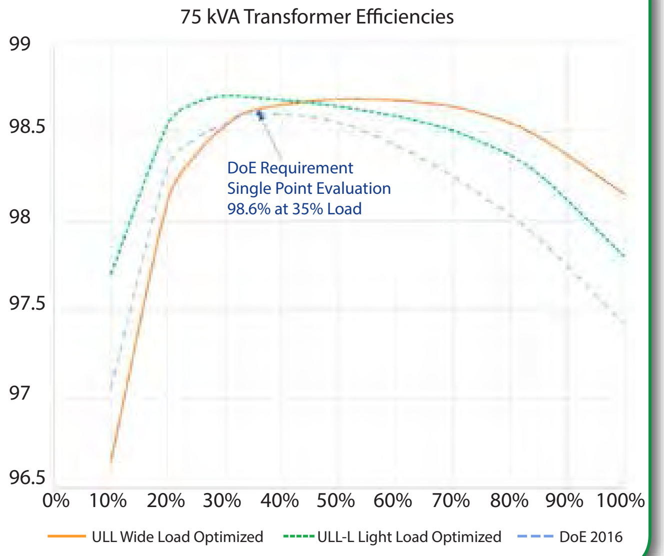
The next step is to determine what target efficiency should be used for these weighted averages. Mirus recommends the use of the same high efficiencies that DOE 2016 has established for 35% loading. If these efficiencies are good at 35% load, then they should also be good for other load levels. By specifying 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.

Table 2 and Fig. 1 show the % efficiency values at various load levels for a typical 75 kVA DOE 2016 transformer and Mirus ULLTRA transformers in both standard, ULL, and light load, ULL-L, configurations.

Table 2: 75 kVA Mirus ULL & ULL-L vs typical DOE 2016 Efficiencies

	75 kVA		
Load Percent	**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

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



To compare transformers, we can calculate the weighted average efficiency using the wider load range equation for a Mirus ULLTRA and a conventional DOE 2016 75 kVA transformer.

ULLTRA

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

DOE 2016

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

As can be seen, the weighted efficiency of the DOE 2016 transformer is significantly lower than that of 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%. By choosing transformers with high weighted average efficiency, the energy savings can be substantial depending upon the transformer's actual loading.

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.

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.

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.

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. 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.

Fig. 2: Flux Orientation in Interleaved Transformer Core

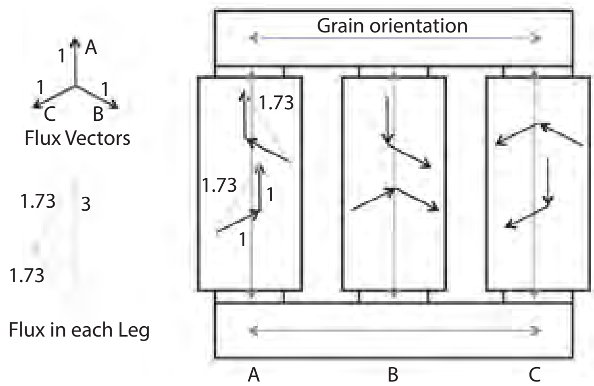


Fig. 3: Flux Orientation in Distributed Gap, Wound Transformer Core Configuration (Evans)

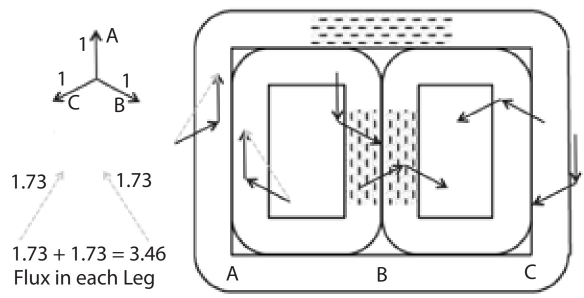
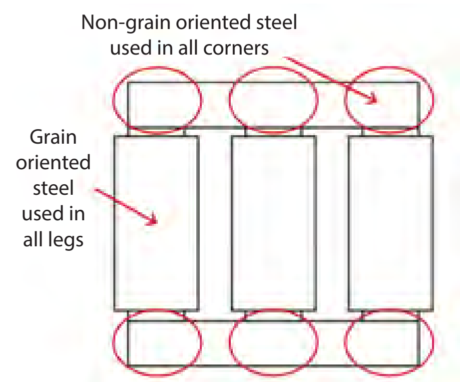


Fig. 4: Low Loss Core Configuration of Mirus ULLTRA Transformers



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.

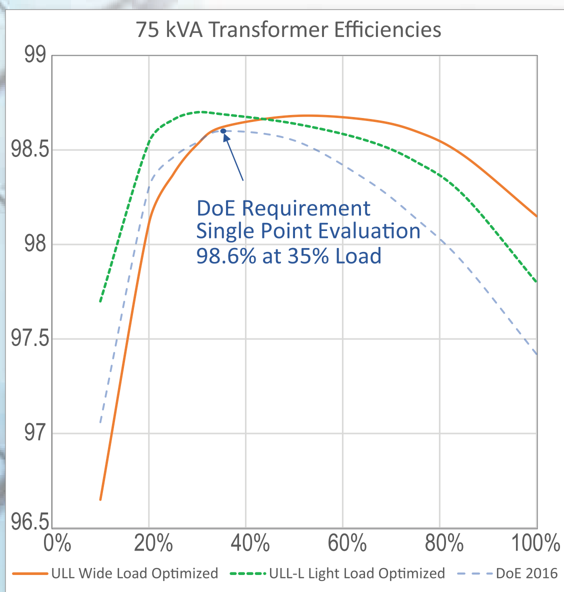
The equations are modified slightly however, to better reflect the expected loading for commercial applications. Two equations have been proposed – one for light loading and one for a wider loading range. In applications where the loading is expected to be below 35% for a majority of the time, the light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

For any other application, the wider load range 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 optimized efficiency through rightsizing a transformer rather than oversizing. 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 or visit our website at **www.mirusinternational.com**.

ULLTRA™ High Performance Transformers

ULLTRA transformers are designed to be the most energy efficient transformers on the market. Providing high efficiency under both linear and non-linear loading, they maintain these efficiency levels not only at 35% loading, but over a wide load range.



- Exceeds DOE 2016 and NRCan 2019
- Optimizes efficiency based on Weighted Average
- HMT model improves reliability by reducing voltage distortion
- Allows for Rightsizing to achieve best ROI

Mirus also offers a wide range of harmonic filters for VFDs

AUHF Lineator Advanced Universal Harmonic Filter

HP High Performance

ED Extreme Duty

ATL Auto-Trans Lineator

AUHF Water-Cooled

1Q3 Single Phase

AUSF Inversine Sinewave Filter

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