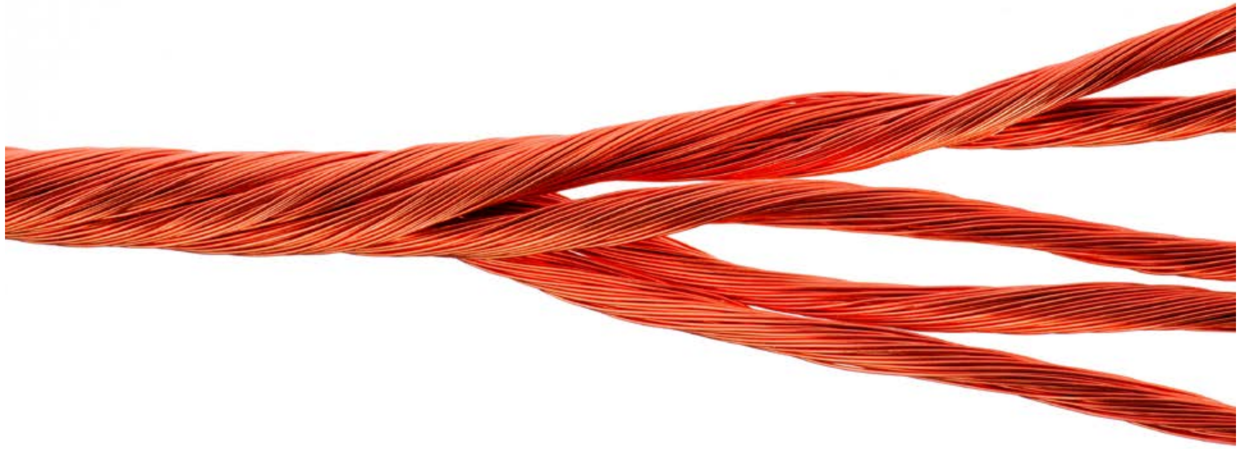
Litz Wire: Practical Design Considerations for Today's High Frequency Applications

Kyle Jensen

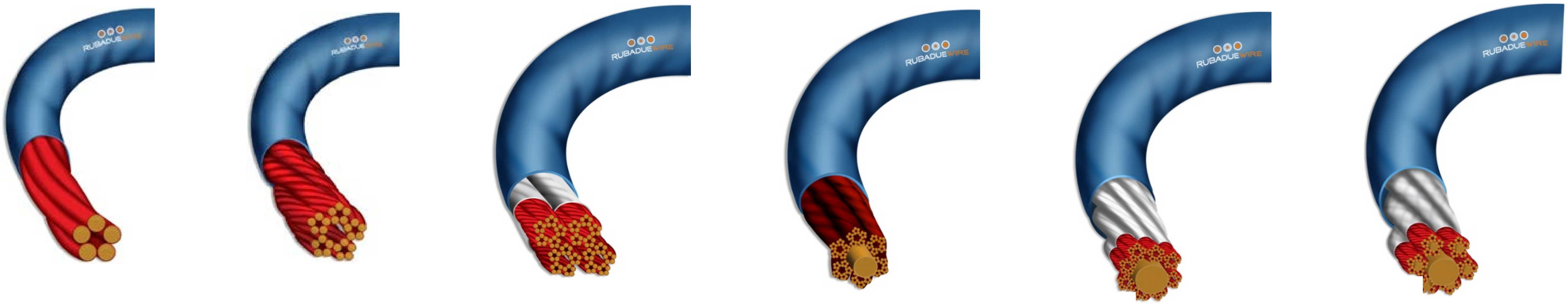


Power Magnetics @ High Frequency Workshop
May 12, 2020

What is Litz Wire?

- Litzendraht – German word for “Stranded”
- While any stranded conductor can be referred to as Litz, we use the term to describe a conductor manufactured by twisting together individually insulated wires in specific patterns to produce a desired electrical effect.

What is Litz Wire?



Type 1 **Type 2** **Type 3** **Type 4** **Type 5** **Type 6**

Most Common Constructions

Type 1: All wires twisted in same direction.

Type 2: Wires are twisted in multiple operations and in opposing directions.

More specialized constructions to help further reduce eddy currents in higher power applications.

Also found in Power Transfer and RF applications.

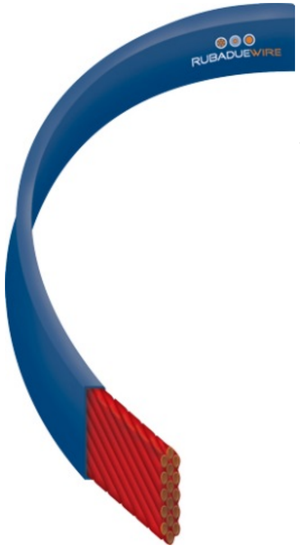
What is Litz Wire?

Type 7

Braided Construction

Very High Aspect Ratios Possible

Low Copper Fill Factor (45% - 55%)



Type 8

Twisted and Formed Construction

High Aspect Ratios

Requires use of Heavy Enamel (G2) or other forming aids to protect enamel.

Type 9 (Coaxial)

Very Specialized Construction

Used in high power transfer applications.

Typically constructed with matching copper area for inner and outer conductors.

Why Use Litz Wire?

- When designing High Frequency Magnetics, a different set of design concerns must be considered to minimize winding losses.
- **Skin Effect:** the tendency for current in an AC circuit to flow on the outer edges of the conductor resulting in increased resistance.
- **Proximity Effect** - the tendency for current to flow in other undesirable patterns (loops or concentrated distributions) due to the presence of magnetic fields generated by nearby conductors.

Why Use Litz Wire?

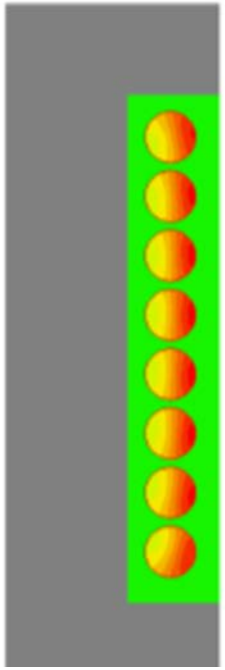
To overcome Skin Effect a Rule of Thumb is to select a conductor with a diameter no larger than 2 skin depths.

f	60 Hz	20 kHz	200 kHZ	1 MHz	10 MHz
δ	8.5 mm	.467 mm	.148 mm	66 µm	21 µm
	1/0 AWG	24 AWG	35 AWG	42 AWG	51 AWG
2δ	17 mm	.93 mm	.30 mm	132 µm	42 µm
	7/0 AWG	18 AWG	29 AWG	36 AWG	45 AWG

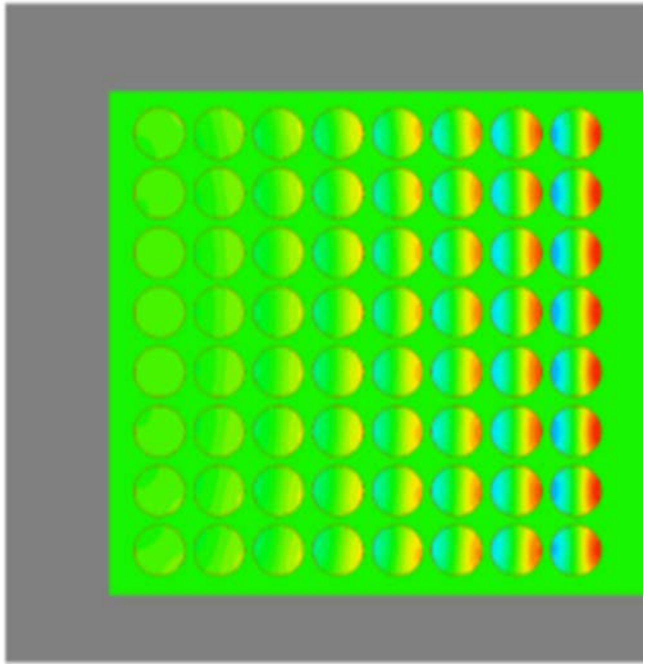
Source: C. R. Sullivan, High Frequency Windings,
APEC 2014 Industry Session Presentation

Why Use Litz Wire?

Example: Frequency = 200 kHz | Wire Diameter = 0.3 mm (approx. 29 AWG)



Rac/Rdc = 1.36



Rac/Rdc = 27.7

Source: C. R. Sullivan, High Frequency Windings,
APEC 2014 Industry Session Presentation

Why Use Litz Wire?

Designing with Proximity Effect in Mind

The effect of using many layers (Simplified 1-D analysis):

For *p* layers, the layer thickness (t) for minimum R_{ac} can be expressed as: $t = 1.3\delta/\sqrt{p}$

Achievable R_{ac} is proportional to: $1/\sqrt{p}$

A wire diameter of δ/10 is a target.

However, @ 1 MHz, δ/10 = 6.6 µm (.0002598” | 0,0065989mm nom)

For reference: 58 AWG = .00039” | 0,0991mm OD

Source: C. R. Sullivan, High Frequency Windings, APEC 2014 Industry Session Presentation

Why Use Litz Wire?

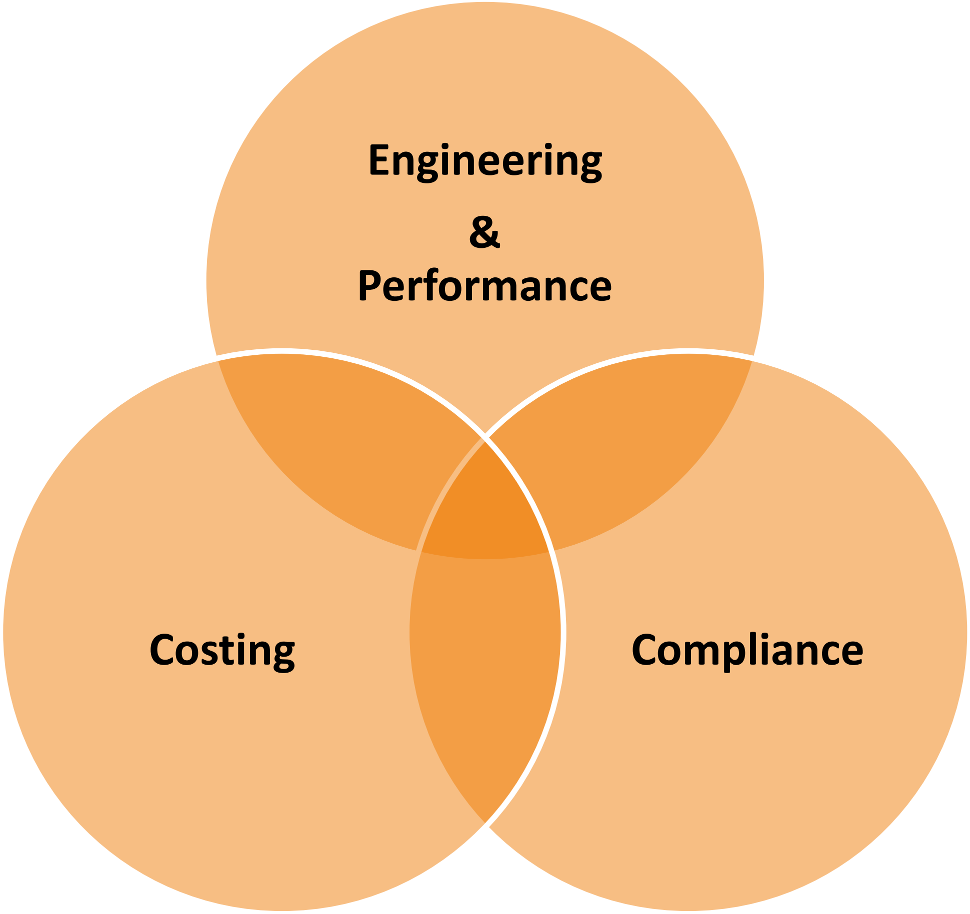
Using Litz wire has the potential for improvement over single-layer solid wire.

$$\frac{P_{litz}}{P_{solid}} \approx 0.58\frac{d}{\delta}$$

	f	300 kHz	1 MHz	3 MHz	10 MHz
	δ	.148 µm	66 µm	38 µm	21 µm
Strand Size		**Loss Reduction**			
44 AWG	51 µm	80%	55%	22%	***NONE***
46 AWG	40 µm	84%	65%	39%	***NONE***
48 AWG	32 µm	87%	72.7%	51%	11%

Source: C. R. Sullivan, High Frequency Windings, APEC 2014 Industry Session Presentation

How to Design with Litz Wire



How to Design with Litz Wire

Compliance

Needs to be included at the beginning of the conversation, *<u>not the end</u>*…

Critical for proper material selection and design considerations – insulation requirements, thickness, temp class, simple recognized components or full Electrical Insulation System required???

How to Design with Litz Wire

Design Considerations

Operating Frequency or Effective Frequency for nonsinusoidal currents.

Total Current

Voltage / Electrical Insulation Requirements

Acceptable Heat Rise

Litz packing factor / increased conductor diameter

How to Design with Litz Wire

Design Considerations

Typical Strand Size by Frequency Chart

Operating Frequency	Strand Size AWG	Bare Copper Diameter	DC Resistance (Ω/kFT nom.)
10 kHz – 20 kHz	33	.0071” | .180mm	205.7
20 kHz – 50 kHz	***36***	.0050” | .127mm	414.8
50 kHz – 100 kHz	***38***	.0040” | .102mm	648.2
100 kHz – 200 kHz	***40***	.0031” | .079mm	1079
200 kHz – 350 kHz	***42***	.0025” | .064mm	1659
350 kHz – 850 kHz	***44***	.0020” | .051mm	2593
850 kHz – 1.4 MHz	46	.00157” | .040mm	4207
1.4 MHz – 3.0 MHz	48	.00124” | .031mm	6745

Rubadue Wire typically stocks the above bolded Strand Sizes in Single MW 79-C and MW 80-C.
Ask about available stock for stranded Litz Constructions.

How to Design with Litz Wire

Design Considerations

Strand Size by Frequency Charts, while helpful for coming up with a starting point, do not take into consideration anything more than skin depth.

This narrow focus can lead to more failures.

How to Design with Litz Wire

Design Considerations

To determine the number of strands per conductor, the typical methodology is to use a factor such as Amps/mm^2 or circular mil area/Amp.

These factors were based on 50/60 Hz components and have since been applied to higher frequency applications.

How to Design with Litz Wire

Design Considerations

Typical current density factors such as 500 cma/A to 1,000 cma/A can result in less than optimal conductor designs as they do not consider the rest of winding design.

When properly evaluated and used in conjunction with the proper core material and design, windings can have significantly higher current density.

How to Design with Litz Wire

Design Considerations

When designing with Litz, you must remember that a stranded conductor of a given AWG size can be significantly larger than its solid counterpart.

22 AWG Solid Single MW 79-C = .0266” [0,6756mm] nom OD

22 AWG 5x32/44 Single MW 79-C = .0344” [0,8738mm] nom OD

This affects number of turns / layer, total layers, copper density, etc…

How to Design with Litz Wire

Design Considerations

With the two most common “Rules of Thumb” called into question, is there a better way?

In their paper: *Simplified Design Method for Litz Wire,* Charles Sullivan (Dartmouth College) & Richard Zhang (MIT), present a straightforward approach that considers the whole winding to help select an appropriate Litz Wire design.

How to Design with Litz Wire

Simplified Design Method for Litz Wire

1. Determine Skin Depth δ
2. Find breadth *b* and number of turns/section N_s
3. Find recommended number of strands using *k* from Table 1
4. Select design that fits in space and meets resistance required
5. Calculate max number of strands in 1st bunching operation $N_{1,max}$
6. Select design with fewer than $N_{1,max}$ strands and in groups of 5, 3 or 4

How to Design with Litz Wire

Strand AWG Size	33	36	37	38	39	40	41	42	44	46	48
Bare Wire (mm)	.180	.127	.114	.102	.089	.079	.071	.063	.051	.040	.031
k (mm^{-3})	203	771	1.2k	1.8k	2.8k	4.4k	6.7k	10k	24k	54k	115k
Economical F_r	1.07	1.13	1.15	1.18	1.22	1.25	1.30	1.35	1.47	1.60	1.68

Source: C.R. Sullivan, R. Zhang; Simplified Design Method for Litz Wire, Table 1

Skin Depth

$$\delta = \sqrt{\frac{\rho}{\pi f \mu_0}}$$

$\rho = 1.72\text{x}10^{-8}\ \Omega \cdot \text{m}$ (Copper @ 20°C)
$\rho = 2\text{x}10^{-8}\ \Omega \cdot \text{m}$ (Copper @ 60°C)
f = Frequency of sinusoidal current
$\mu_0 = 4\text{x}10^{-7}\ \pi\text{H/m}$ (permeability of free space)

Number of Strands

$$n_e = k\frac{\delta^2 b}{N_s}$$

k = Value in Table 1 above
δ = Skin Depth
b = Breadth of winding
N_s = Number of turns

Max Strands 1st Bunch

$$N_{1,max} = 4\frac{\delta^2}{{d_s}^2}$$

δ = Skin Depth
d_s = Diameter of Strand

How to Design with Litz Wire

Select a design that fits in space

The number strands calculation should be treated as a guideline. Strand counts can deviate up to +/- 25% without negative effect.

Evaluate various constructions for acceptable performance (and cost).

How to Design with Litz Wire

Costing

Be aware, moving from a solid wire to Litz ***WILL*** impact raw material unit cost.

How much impact is design / supplier dependent.

By evaluating various Litz constructions in a given winding, you can perform simple cost-benefit analysis.

How to Design with Litz Wire

Limitations

Effectiveness of Litz as a winding wire begins to drop off above 3 MHz.

	f	300 kHz	1 MHz	3 MHz	10 MHz
	δ	.148 µm	66 µm	38 µm	21 µm
Strand Size		**Loss Reduction**			
44 AWG	51 µm	80%	55%	22%	***NONE***
46 AWG	40 µm	84%	65%	39%	***NONE***
48 AWG	32 µm	87%	72.7%	51%	11%

How to Design with Litz Wire

Limitations

Packing Factor / Copper Density are affected due to the enamel layer and the inherent air gaps from twisting round wires together in multiple operations.

The manufacturing process can damage the enamel layer on individual strands. The use of protective layers such as textile serves, tapes, or extruded isolation layers may be needed.

How to Design with Litz Wire

Litz Wire Diameter Calculations – Type 1 & Type 2 Constructions

Standard Equation: $\mathbf{D = \sqrt{N} \times d \times \rho}$

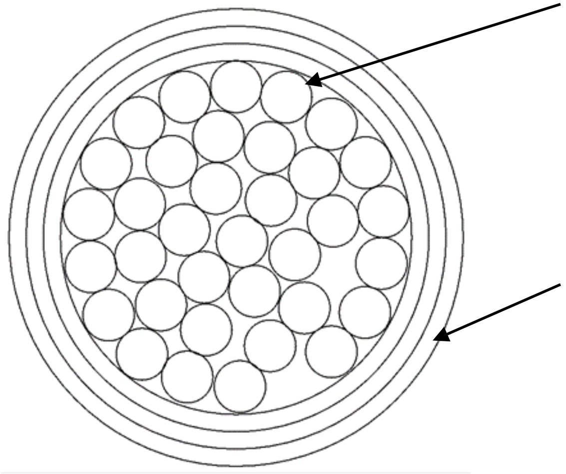
Where:
D =OD of Stranded Litz
N =Total Number of Strands
d =Diameter of Individual Strands
ρ =Packing Factor per Table 1

Litz Construction	Single End Wire Size	Packing Factor
n/##	48 - 20 AWG	1.155
n/n/## or n/n/n/##	48 - 33 AWG	1.155
5xn/## or 3xn/##	48 - 20 AWG	1.236
5xn/n/## or 3xn/n/##	48 - 33 AWG	1.236
5x5xn/## or 5x3xn/##	48 - 44 AWG	1.271
	43 - 33 AWG	1.328
	32 - 20 AWG	1.398
5x5xn/n/## or 5x3xn/n/##	48 - 44 AWG	1.271
	43 - 33 AWG	1.363
5x5x5xn/## or 5x5x3xn/##	48 - 44 AWG	1.271
	43 - 33 AWG	1.363
	32 - 20 AWG	1.536
5x5x5xn/n/## or 5x5x3xn/n/##	48 - 33 AWG	1.363
n = Number of Strands in bunch	## = AWG Size of individual strands	

Elektrisola Packing Factors	
# of Wires	Factor
3 - 12:	1.25
16:	1.26
20:	1.27
25 - 400:	1.28

How to Design with Litz Wire

Litz Wire Diameter Calculations – Type 1 & Type 2 Constructions



Litz Conductor: 23 AWG 35/38 Single MW 80-C

Nom OD: .0307" (0,780mm) | Max OD: .0321" (0,815mm)

Calculated using Nom Magnet Wire Diameter and Max Magnet Wire Diameter (NEMA MW 1000)

TIW Insulation Layer @ .0015" (0,038mm)/Layer

Nom OD: .0397" (1,008mm) | Max OD: .0417" (1,059mm)

Total Diameter Increase = 2 x Total Insulation Thickness

Example: 2 x 3(.0015"/layer)
2 x .0045" Total Thickness
.0090" Diameter Increase

Max OD Tolerance will vary by construction type, core diameter, and total insulation thickness, Contact Factory for verification.

How to Design with Litz Wire

Litz Wire Diameter Calculations – Type 1 & Type 2 Constructions

For Simple Constructions up to 25 wires:

$$\text{Max DCR} = \frac{\text{Max DCR Single Wire}}{\text{Total Number Single Wires}} \times k_1$$

Where: k_1 = 1.02 to account for take up due to twisting

For Constructions greater than 25 wires:

$$\text{Max DCR} = \frac{\text{Max DCR Single Wire}}{\text{Total Number Single Wires}} \times k_1 \times k_2$$

Where k_1 = 1.02 if 1 twisting operation
1.04 if 2 twisting operations
1.06 if 3 or more twisting operations

Where k_2 = 1.03 to allow for possible broken strands which may occur.

How to Design with Litz Wire

Insulation Comparisons

Material	Base Cost (TIW)	Dielectric Strength[1]	Tensile Strength	UL Temp Class[2]	Melt Point	Thermal Conductivity[3]	
TCA	X	1700 V/mil	5,800 psi	155°C (F)	250°C - 280°C	0.137 0.238	Btu·in/h·ft2·°F W/m·K
ETFE (1.5) ETFE (2.0)	X +5% - 10%	1700 V/mil	5,800 psi	155°C (F)	250°C - 280°C	0.137 0.238	Btu·in/h·ft2·°F W/m·K
FEP (2.0)	+20% - 25%	2000 V/mil	3,000 psi	155°C (F)	255°C (Typical)	1.45 0.209	Btu·in/h·ft2·°F W/m·K
PFA (1.5) PFA (2.0)	+15% - 25% +25% - 35%	2000 V/mil	3,600 psi	180°C (H)	302°C - 310°C	1.45 0.209	Btu·in/h·ft2·°F W/m·K

1) Dielectric Strength is per manufacturer's data sheet, based on .010" insulation thickness. TCA & ETFE, historically, outperform above values under test.
2) UL Temp Class is per UL Standard 2353 and Standard 1446. Materials may have higher service temperature ratings, depending on testing standards.
3) Thermal Conductivity are nominal values for general reference only.

Resource Materials & Citations

Dartmouth Power Electronics and Magnetic Components Group web site:

http://thayer.dartmouth.edu/inductor/index.shtml

C.R. Sullivan and R. Y. Zhang, "Simplified Design Method for Litz Wire", *IEEE Applied Power Electronics Conference,* 2014

C. R. Sullivan, "Windings for High Frequency Applications", *APEC Industry Session Presentation,* 2014

Thank you!

For Additional Information & Support:
www.rubadue.com

IEEE POWER
ELECTRONICS SOCIETY
Powering a Sustainable Future