HIGH FREQUENCY POWER FILM HARMONIC FILTER CAPACITORS

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APEC 3/16/19

LET ME INTRODUCE MYSELF

- Hector Casanova
- Director of Engineering for Cornell Dubilier Electronics, 13 Years
  - New Bedford MA
- 38 Years film capacitor experience
  - Engineering and plant management
- BSEE Fairfield University / Bridgeport Engineering Institute
- MBA University of Phoenix

FOCUS ON AC POWER FILM CAPACITORS FOR HIGH FREQUENCY AC HARMONIC FILTERING

- Larger AC power film capacitors
- Dielectric – Metalized polypropylene
- Enclosed in large aluminum cases
- Single or 3 Phase
- Capacitance 50 to 300µF (460µF special)
- Voltage up to 1000 Vac
- Protected / UL Approved

PRESENTATION DISCUSSION TOPICS
INDUSTRY TRENDS DRIVING THE NEED FOR HIGHER FREQUENCY HARMONIC FILTER CAPACITORS

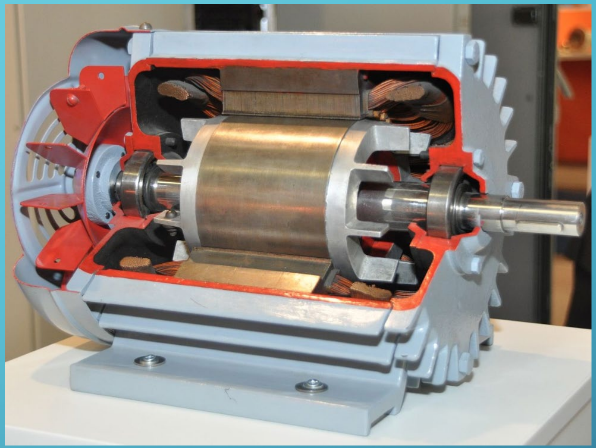
- Applications for AC harmonic filter capacitors, focus on variable frequency drives
- Conventional Induction motors used with VFD's
- Permanent Magnet Motors PMM paired with variable frequency drives VFD
- Evolution of switching technology in AC motor drives
- Passive Harmonic filter design
- Effects on capacitor design
- Design considerations for higher frequency capacitors
- Future trends for higher frequency applications

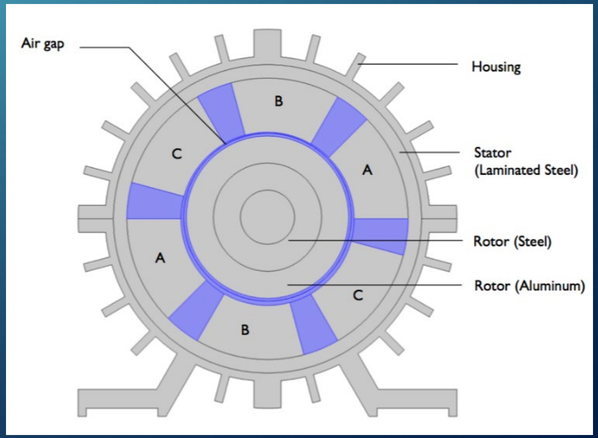
APPLICATIONS FOR AC HARMONIC FILTER CAPACITORS

- Power Inverters
- Deep well pumps
- Conveyors
- HVAC
- Ventilation
- Process controls
- Renewable energy inverters
- Variable frequency power drives – focus of presentation

CONVENTIONAL INDUCTION MOTORS USED WITH VFD

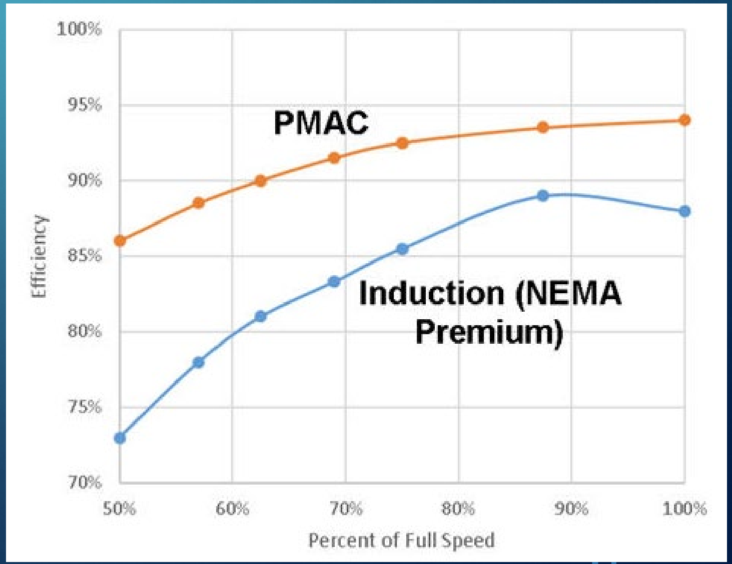
- NEMA rated Induction motors
  - Current in the stator produces torque
  - Operate at lower frequency <3 kHz
  - Require large filter
    - Inductor / capacitor
    - Heavier
    - Larger footprint
  - Energy inefficient at higher frequency due to high losses





INDUSTRY TREND
PERMANENT MAGNET MOTORS IMPROVED EFFICIENCY

- Motors, permanent magnet v. induction motors
  - Greater Efficiencies, energy savings
  - Higher power densities
  - Improved control
  - Overall cost, over the life of system is lower
- Smaller, lighter systems
- Smaller sinewave filters

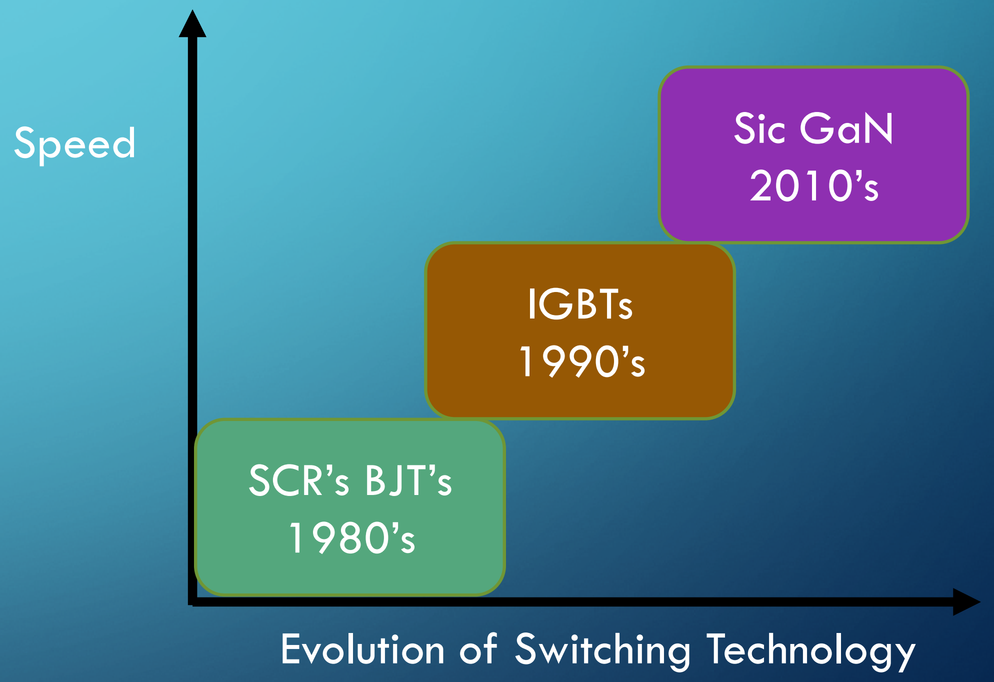


PERMANENT MAGNET MOTOR PMM DRIVE CHALLENGES / BASICS

- Higher up front cost
- Compatible drives needed
  - Higher frequencies required to achieve same speeds
- VFD and sinewave filter selection critical to protect the motor
  - PMAC motors are sensitive to higher temperatures which cause demagnetization
  - Optimized filters perform best
- Higher switching frequencies, >4 kHz
- Higher fundamental frequency >150 Hz

INDUSTRY TRENDS
EVOLUTION OF SWITCHING TECHNOLOGY IN AC MOTOR DRIVES

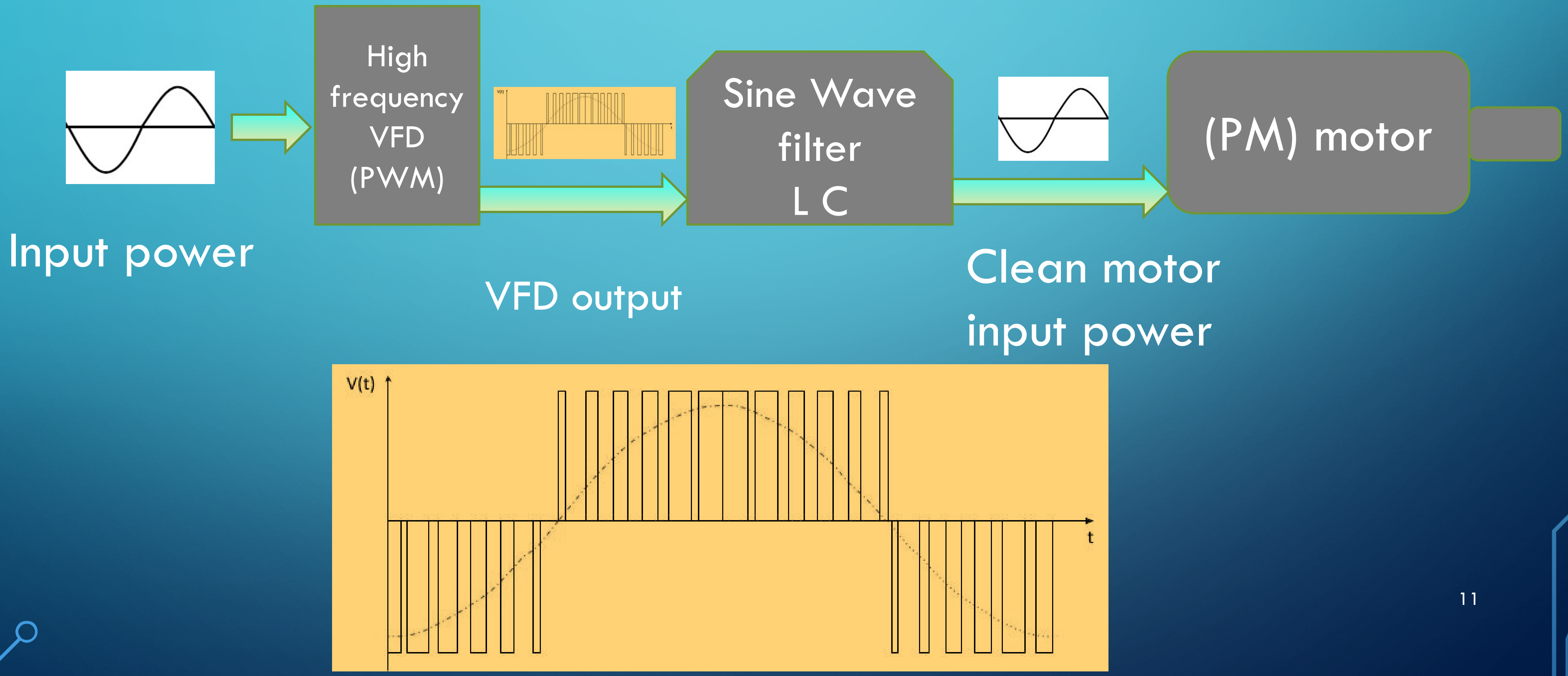
- Switching devices
  - SCR's & BJTs
  - IGBT's 20 kHz switching frequency
  - Silicon carbide (SiC) and gallium nitride (GaN) power switches v. IGBT
    - Higher frequency drives PWM
    - 50Khz to 200Khz switching speeds
    - Smaller sinewave filters
    - Efficiencies, energy savings
    - Higher power densities
    - Improved control
    - Lower overall cost



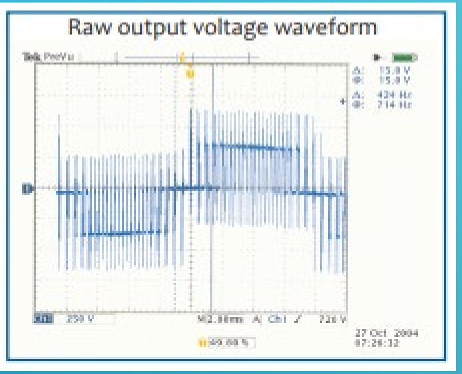
HIGH FREQUENCY PULSE WIDTH MODULATION PWM DRIVES CHALLENGES / BASICS

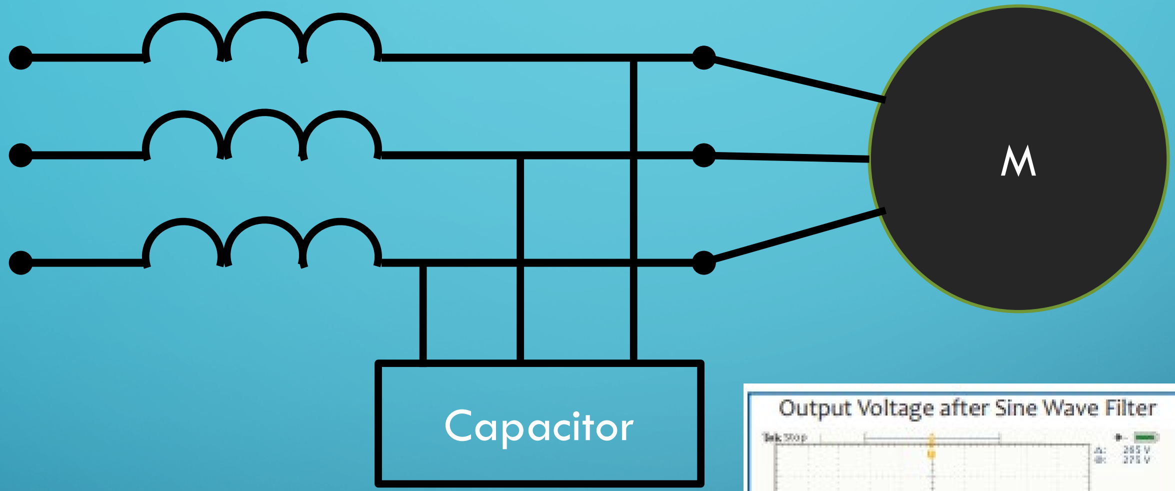
- Much higher cost (SiC, GaN)
- VFD and sine wave filter selection critical to protect the motor
  - Optimized filters required
- Higher switching frequencies, >20 kHz
- Higher fundamental frequency >300 Hz

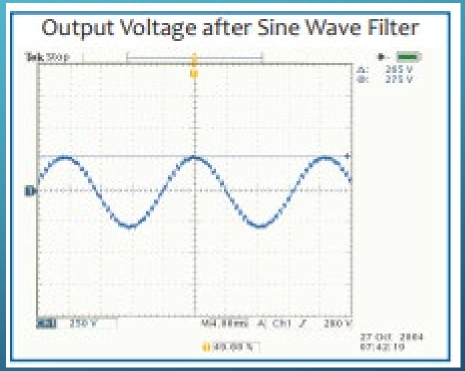
HARMONIC SINE WAVE FILTER TYPICAL APPLICATION



SINE WAVE FILTER







Motor protection
Increased motor reliability
Reduction in motor heating
Reduction in motor audible noise

Inductor / Capacitor "trap" filter
Material selection designed to operate at higher frequency

FUNDAMENTAL CAPACITOR PERFORMANCE REVIEW
POWER LOSSES – I^2 ESR

ESR = tan δ / omega * C

ESR = tan δ / 2 * PI * f * C

Dielectric losses are high at low frequencies

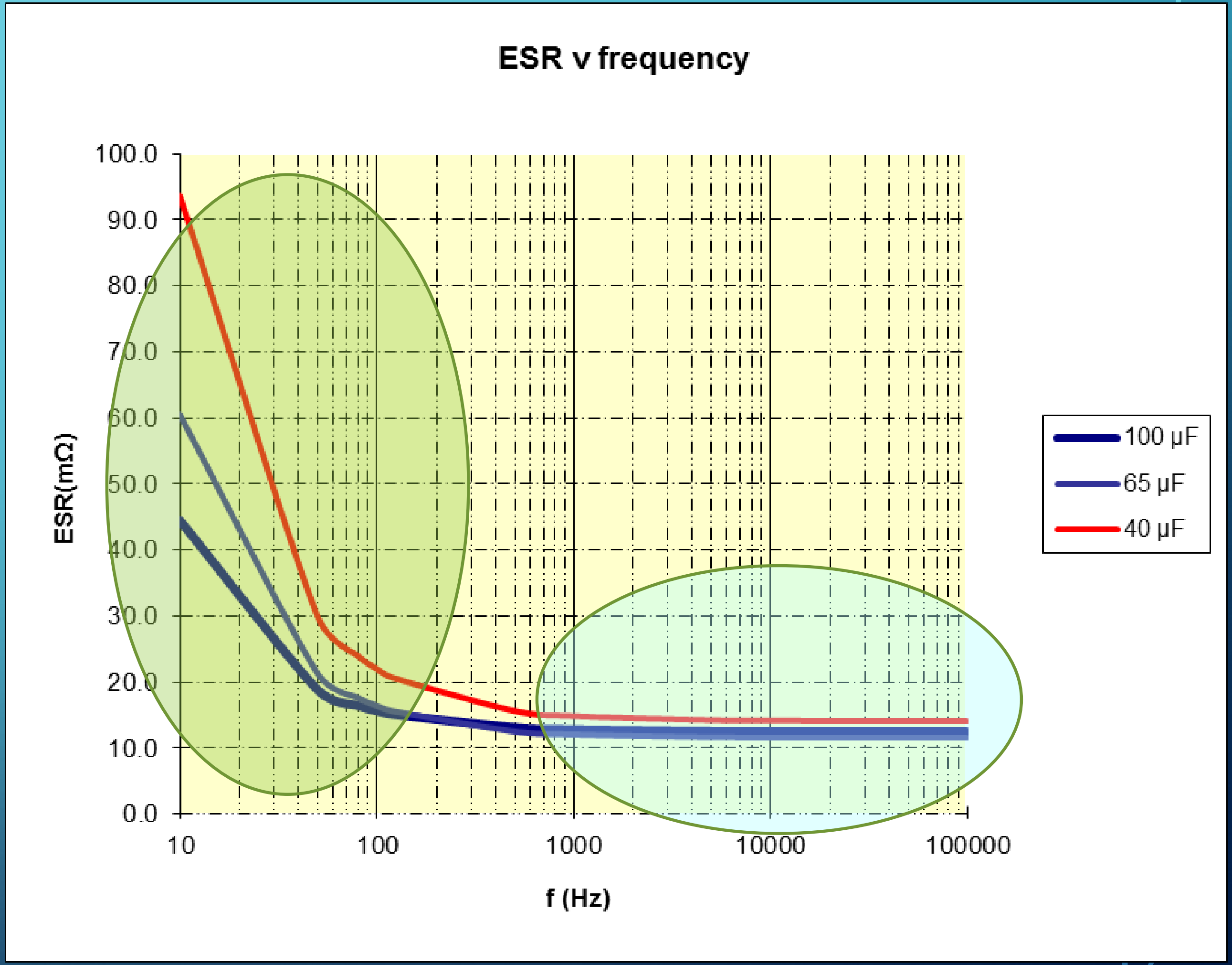
Become ohmic losses Rs at higher frequencies

ESR - Effective Series Resistance

Tan delta – DF

C – Capacitance

Rs – Ohmic losses

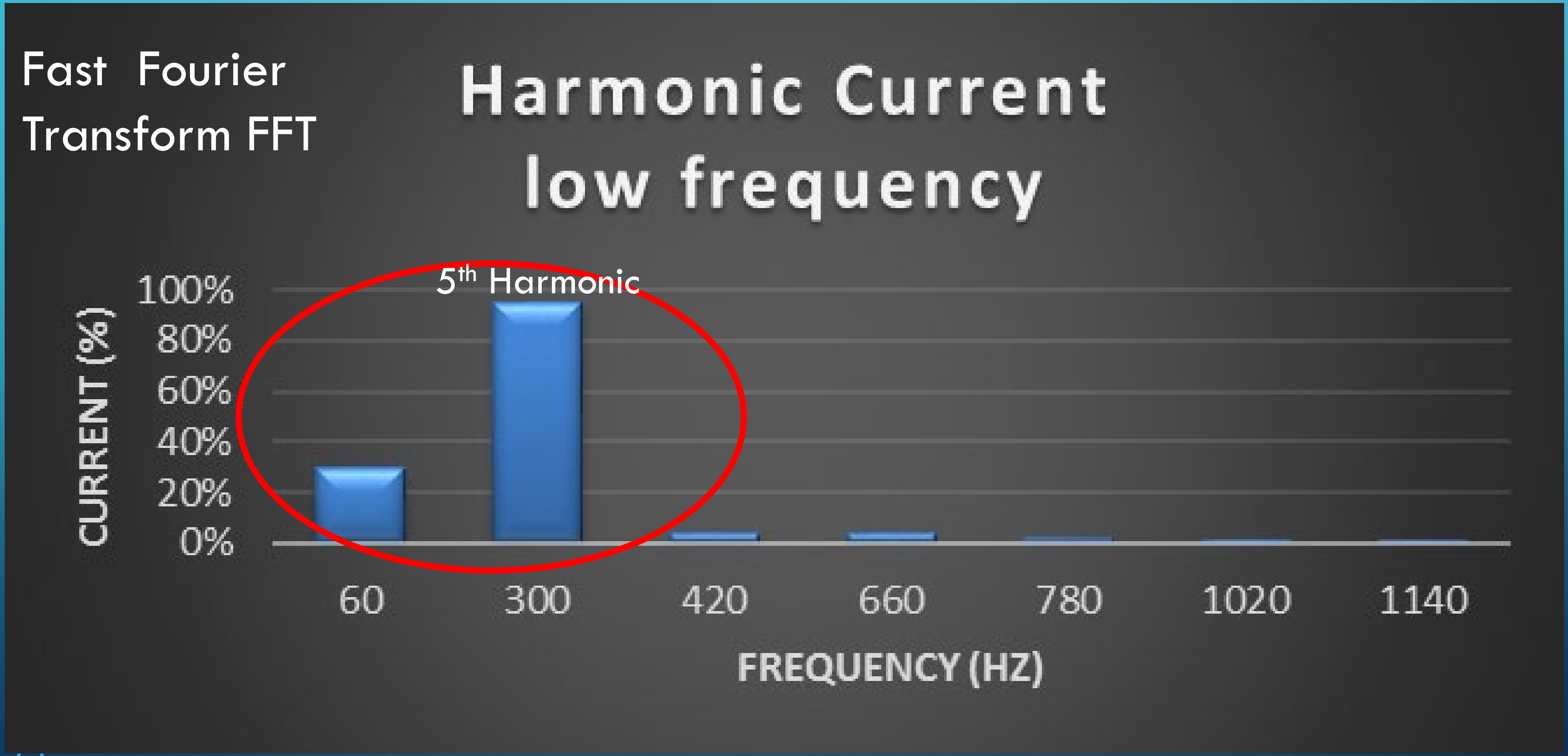


ESR curves for typical CDE AC filter capacitors

SINE WAVE FILTER COMBINATIONS & FFT ANALYSIS

- Traditional, with off the shelf filter
  - Induction motor / VFD
- Mid Frequency, customized
  - PMM / VFD
- High Frequency, specialized
  - PMM / HF VFD

SO WHAT DOES THIS MEAN FOR THE CAPACITOR? HARMONIC CONTENT FROM **TRADITIONAL** SYSTEMS



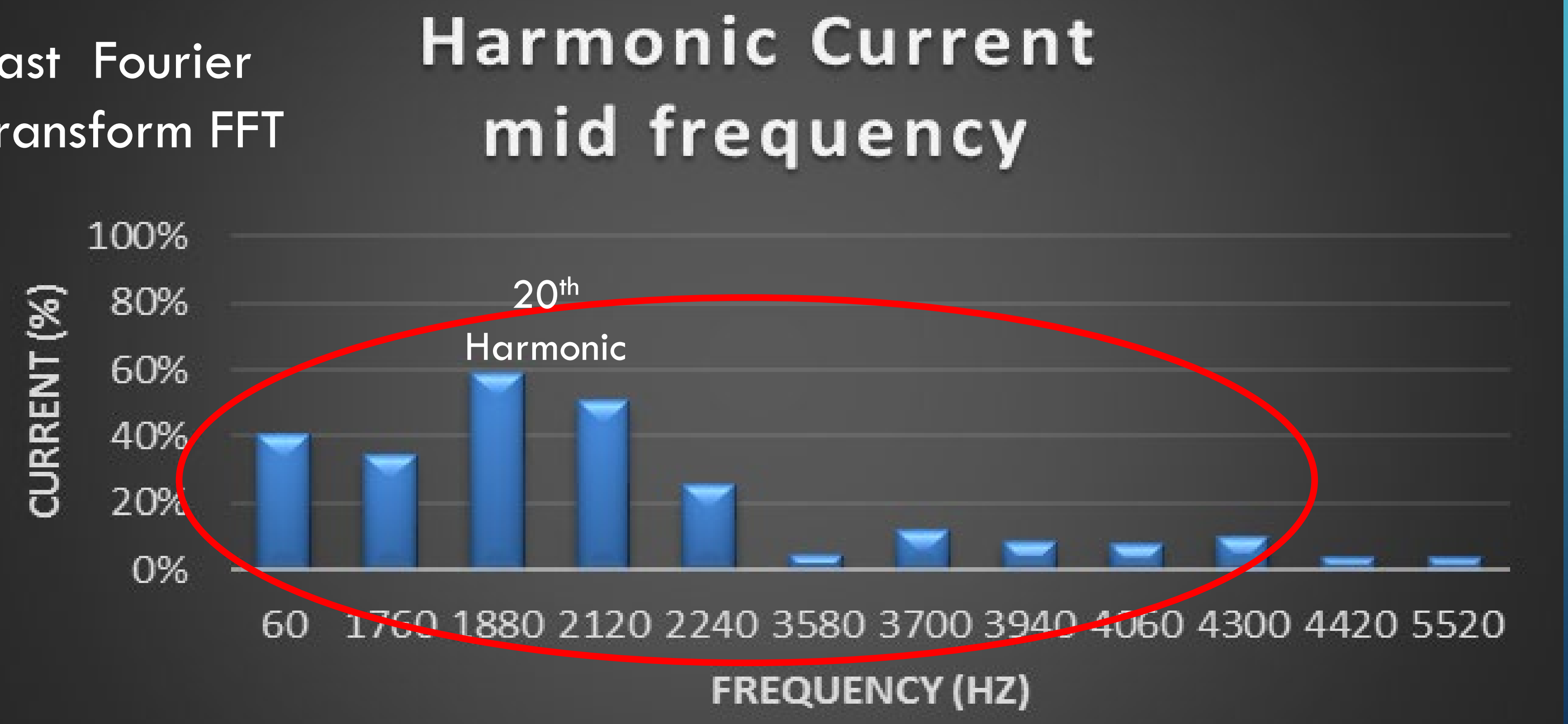
$$\mathrm{ESR} = \frac{\tan \delta}{2 * \pi * f * C}$$

SO WHAT DOES THIS MEAN FOR THE CAPACITOR? HARMONIC CONTENT FROM **TRADITIONAL** SYSTEMS

- Predominantly fundamental and low frequency harmonic content
  - 60 Hz and 300 Hz (5^{th} Harmonic)
- Capacitor will need to handle mainly dielectric losses
- Results typically in larger capacitor to handle the power losses

SO WHAT DOES THIS MEAN FOR THE CAPACITOR? HARMONIC CONTENT FROM **PMM** & **VFD** SYSTEMS

Fast Fourier Transform FFT

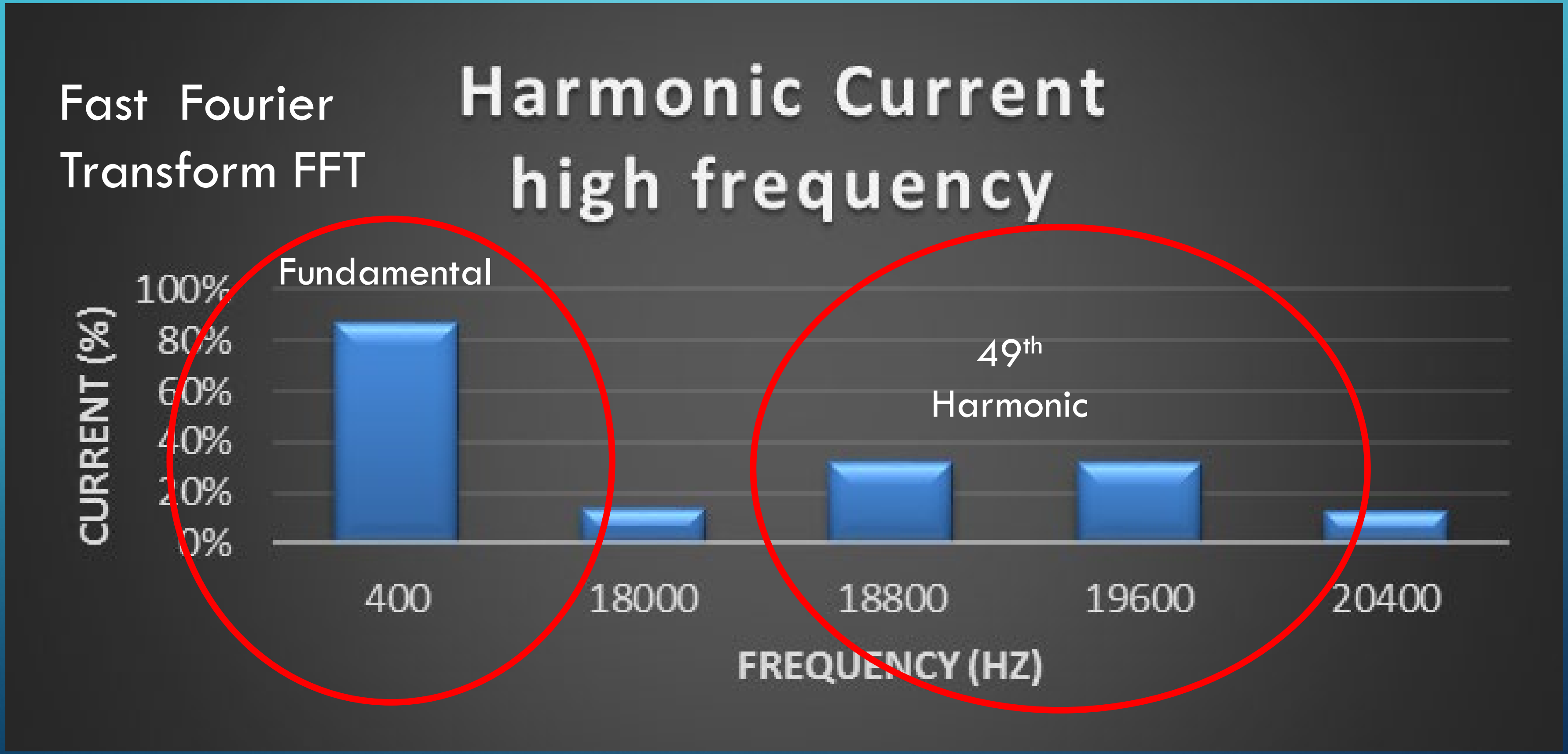


$$ESR = \frac{\tan\delta}{2 * \pi * f * C}$$

SO WHAT DOES THIS MEAN FOR THE CAPACITOR? HARMONIC CONTENT FROM <u>**PMM**</u> / <u>**VFD**</u> SYSTEMS

- Mainly fundamental and mid frequency harmonic content < 3 kHz
- Some higher frequency content is present ~ 2 kHz
- Capacitor will need to handle mostly dielectric losses and some higher frequency ohmic losses
- Results typically in larger capacitor values

SO WHAT DOES THIS MEAN FOR THE CAPACITOR? HARMONIC CONTENT FROM **HIGH FREQUENCY VFD'S**



$$ESR = \frac{\tan \delta}{2 * \pi * f * C}$$

SO WHAT DOES THIS MEAN FOR THE CAPACITOR? HARMONIC CONTENT FROM **HIGH FREQUENCY VFD'S**

- Fundamental frequency shifts higher to 300 Hz or 400 Hz
- Higher frequency harmonics are present ~ 20 kHz
- Capacitor will need to cope with a combination of dielectric and ohmic losses
- Capacitance values are typically lower than traditional filter capacitors

CAPACITOR DESIGN CHALLENGES HIGH FREQUENCY

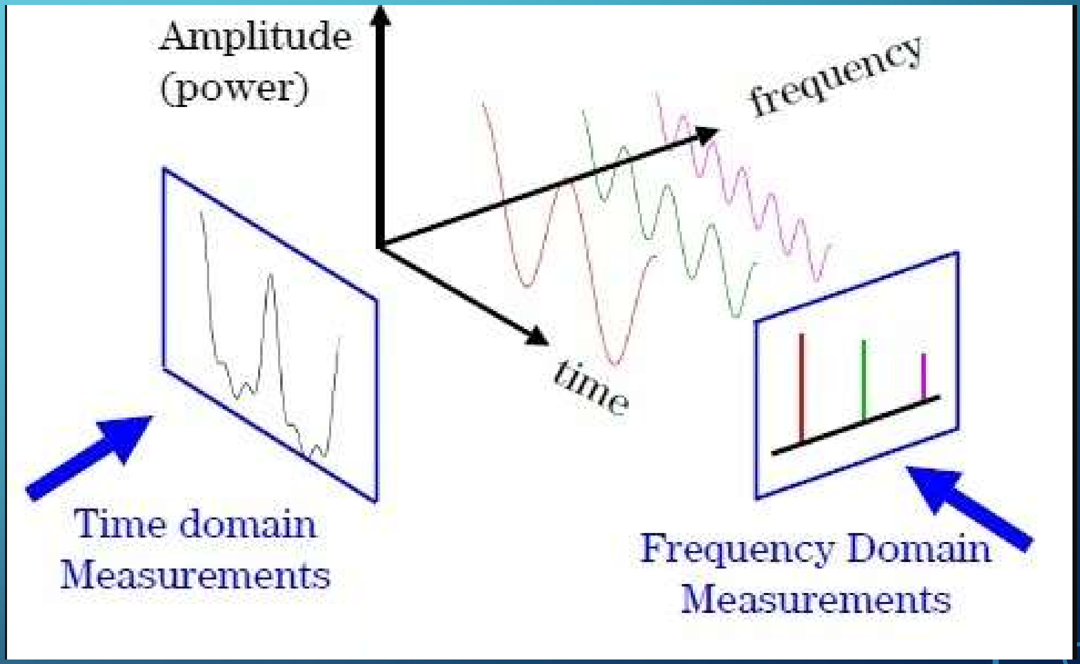
- Standard low frequency capacitors
- Harmonic content feedback not given or understood
- Losses due to skin effect
- Ohmic losses
- Dielectric losses
- Misapplication

STANDARD HARMONIC CAPACITOR
LOW FREQUENCY < 3 KHZ HARMONIC CONTENT

- Standard construction
- Ferrous hardware
  - Steel covers
  - Steel terminals
- Capacitor internal section design not so critical
- Not worried about skin effect

HARMONIC CONTENT FEEDBACK
SO HOW MUCH POWER SHOULD THE CAPACITOR BE REQUIRED TO HANDLE?

- Low frequency, mixed frequency, or high frequency ?
- Fast Fourier Transform FFT
  - Converts signal from Time Domain to Frequency Domain
  - Shows designer where the harmonic frequencies are and amplitudes
- Keep power generated below capacitor max power dissipation

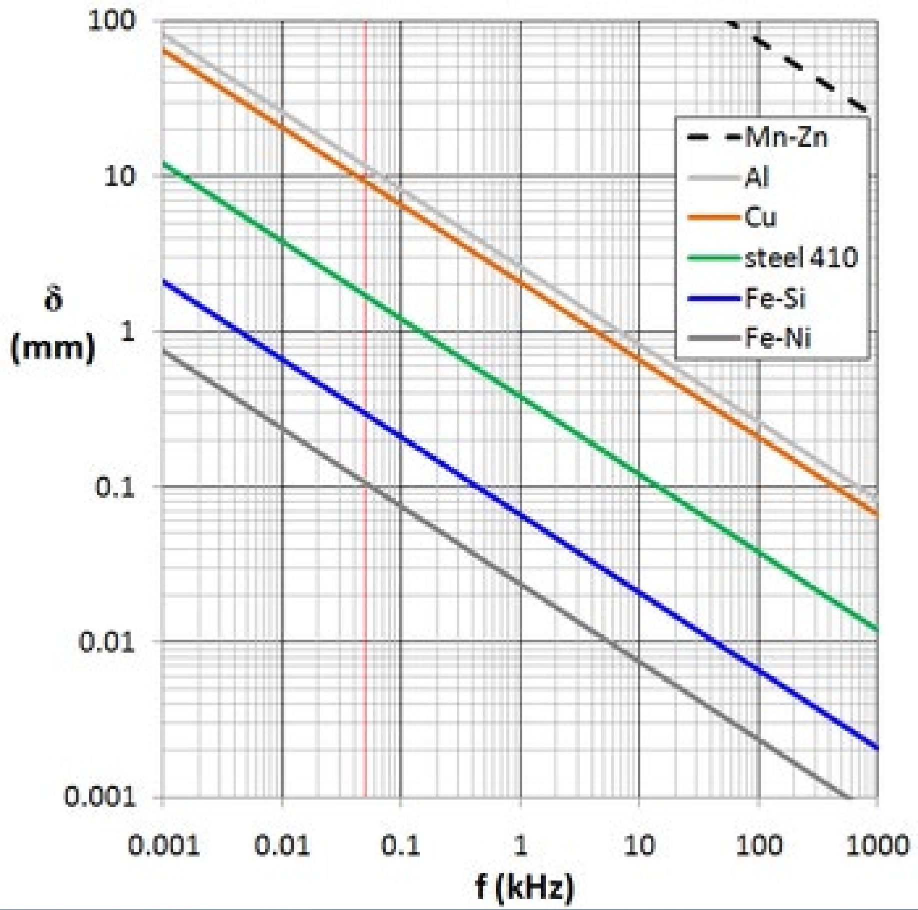


SKIN EFFECT

- Losses due to skin effect
  - Conductor resistance increases with frequency
- Non-ferrous hardware
- Selection of internal connections
  - Wider
  - Litz wire
  - Stranded wire

SKIN EFFECT VARIOUS METALS

Skin depth in (mm)

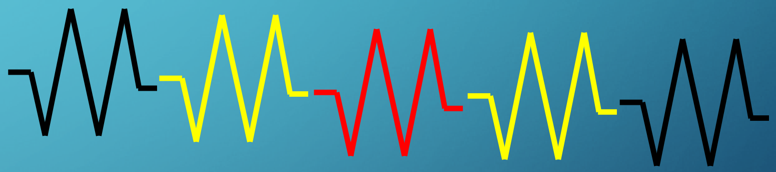


HIGH FREQUENCY CAPACITORS CAREFULLY CONSIDER OHMIC LOSSES

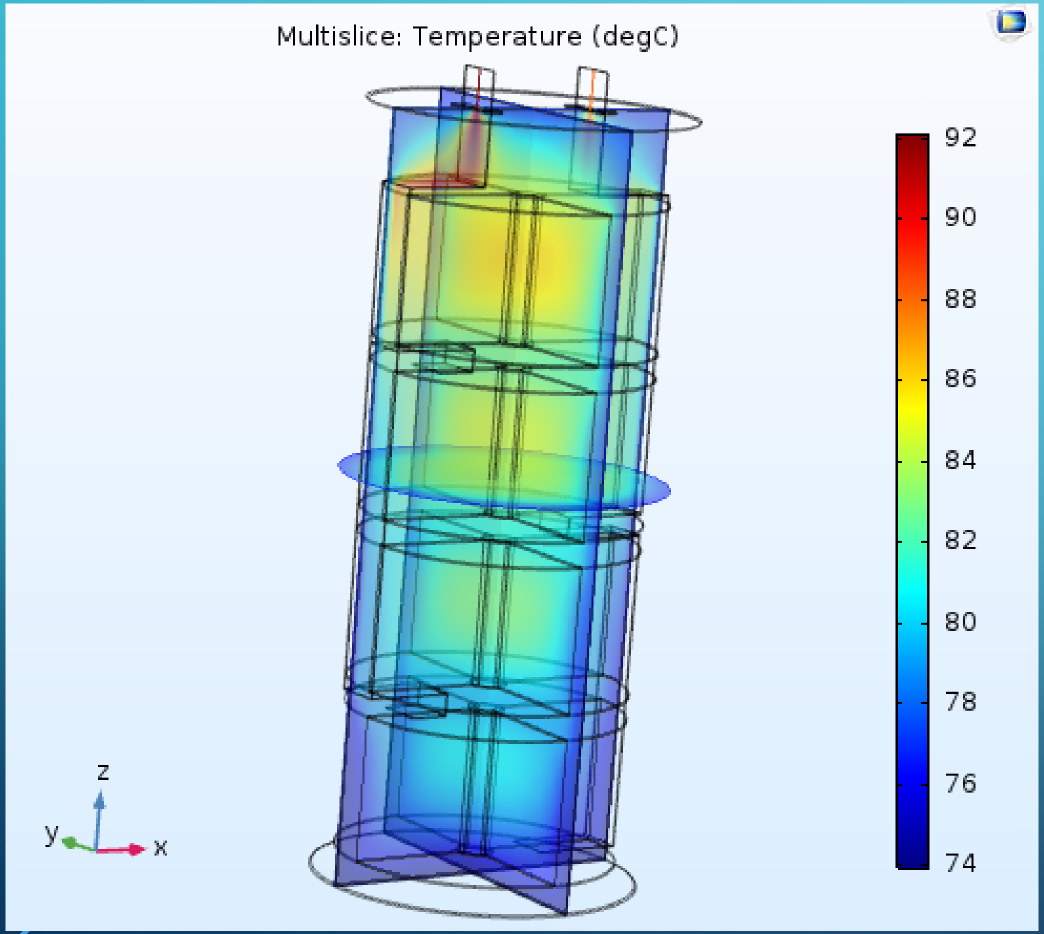
- Reduction of metallic resistance throughout all connections
  - Metallization
  - optimal end spray connection
  - lead attach
  - lead cross sectional area
  - lead geometry
- Non ferrous material throughout
- COMSOL model

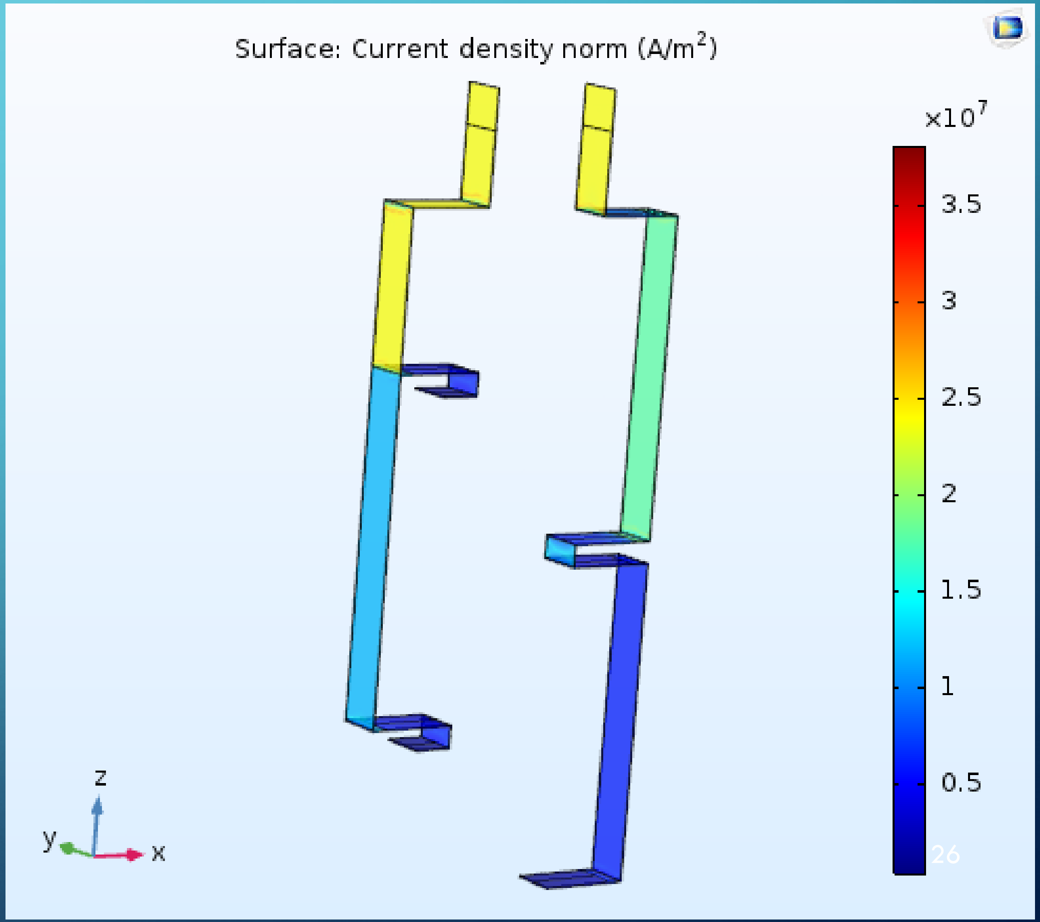
Total

Ohmic losses



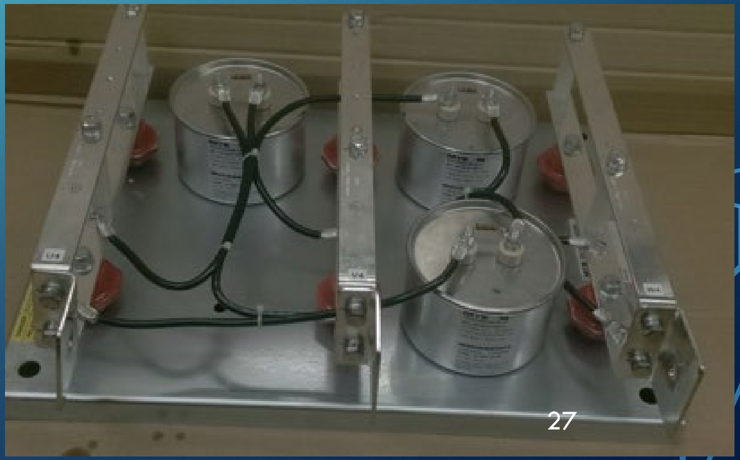
HIGH FREQUENCY CAPACITORS
CAREFULLY CONSIDER OHMIC LOSSES THERMAL MODEL





MISAPPLICATION

- Use standard frequency rated capacitors in high frequency applications
- Thermal overheating of ferrous terminations due to skin effect
- Overheating due to excessive watts lost
  - Increased temperature = reduced life
- Forced to use larger and de-rated capacitors in series parallel configuration
- Fewer high frequency capacitors needed



HIGH FREQUENCY CAPACITOR CONSIDERATIONS

- Keep Rs as low as possible
- Fast Fourier Transform of harmonic content for power loss analysis
  - Shows designer what the harmonic frequencies are and amplitudes
- Power calculation critical at higher frequencies
  - Fundamental frequency drives dielectric losses
  - Harmonic frequencies drive resistive losses
- Voltage and current waveforms
- Application temperature

RECAP

- Higher frequency power film ac capacitors market driven
  - Higher switching speed semiconductors
  - The move to permanent magnet motors
  - Efficiencies, overall costs, and smaller foot prints
- Capacitor
  - FFT of waveform to be filtered
  - Non-ferrous hardware
  - Keep generated power losses safely below power handling capability

FUTURE TRENDS
HIGHER FREQUENCY CAPACITORS

- Lower inductance necessary for higher switching frequency
  - Capacitor methods for cancelling parasitic inductance
  - Bus bar mounting system reducing inductance
- Smaller, more compact capacitors
  - Less capacitance required at the higher frequencies
- Higher temperature
  - Compactness brings capacitor closer to high temperature power electronics
  - Newer high temperature dielectrics required to perform in AC circuits under development

$$V = L \, di / dt$$

Thank you for your attention