Motors & VFDs: How They Work, When They Don't, What You Can do

Presentation at

Elyria Wastewater Workshop Webinar
Operator Training Committee of Ohio

Wednesday, April 21, 2021

Electric Certificate – Ohio PUCO 15-960E

SES
SUSTAINABLE
Energy Services

Natural Gas Certificate – Ohio PUCO 15-427G

A Certified Woman-Owned Business

Sustainable Energy Services
Company Overview

Sustainable Energy Services was founded as one of the first energy consulting firms to combine energy purchasing and energy efficiency services. As a nationally certified woman-owned company, SES acts as an owner's advocate in all energy matters for customers in diverse industries, from manufacturing and retail to healthcare and education, as well as cities and public entities.

The energy specialists at SES are experts in executing customizable solutions to complex energy problems, drawing on 40+ years of energy consulting and engineering experience. The managing partners have shared their expertise as regular speakers at national and regional conferences including the AEE World Energy Conference, AEE East/West Conference, and the Ohio Energy Conference. SES is a registered Trade Ally to all major utilities in Ohio.

The SES managing partners are certified by the PUCO for Electric and Natural Gas, by the Association of Energy Engineers and the Compressed Air & Gas Institute:

- C.E.M. (Certified Energy Manager)
- C.E.A. (Certified Energy Auditor)
- C.E.P. (Certified Energy Procurement Professional)
- C.D.S.M. (Certified Demand Side Manager)
- C.C.A.S.S. (Certified Compressed Air System Specialist)

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An older but reliable motor…

Gets hooked up to a new VFD

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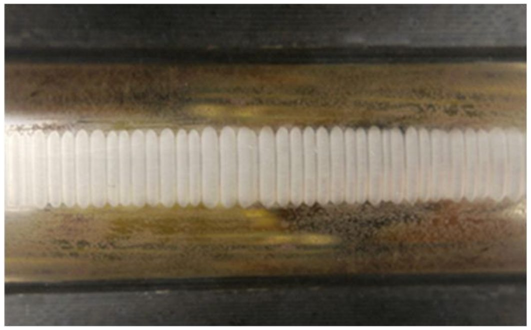

And fails unexpectedly

At least 14 reasons why motors fail unexpectedly!

Unexpected Motor Failure

1. Transient voltages
2. Voltage imbalance
3. Harmonic distortion
4. VFD reflected waves
5. Sigma currents
6. Overloading
7. Misalignment
8. Shaft imbalance
9. Shaft looseness
10. Bearing wear
11. Soft footing
12. Pipe strain
13. Shaft voltage
14. Loose connections

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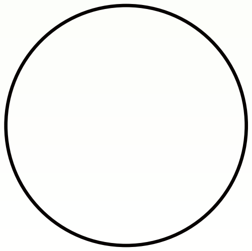
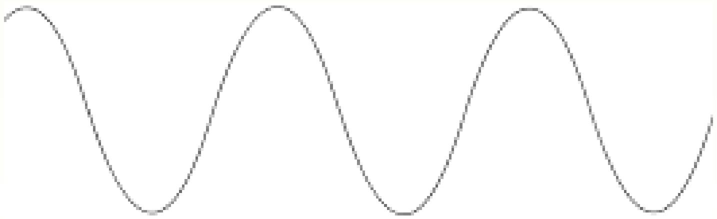
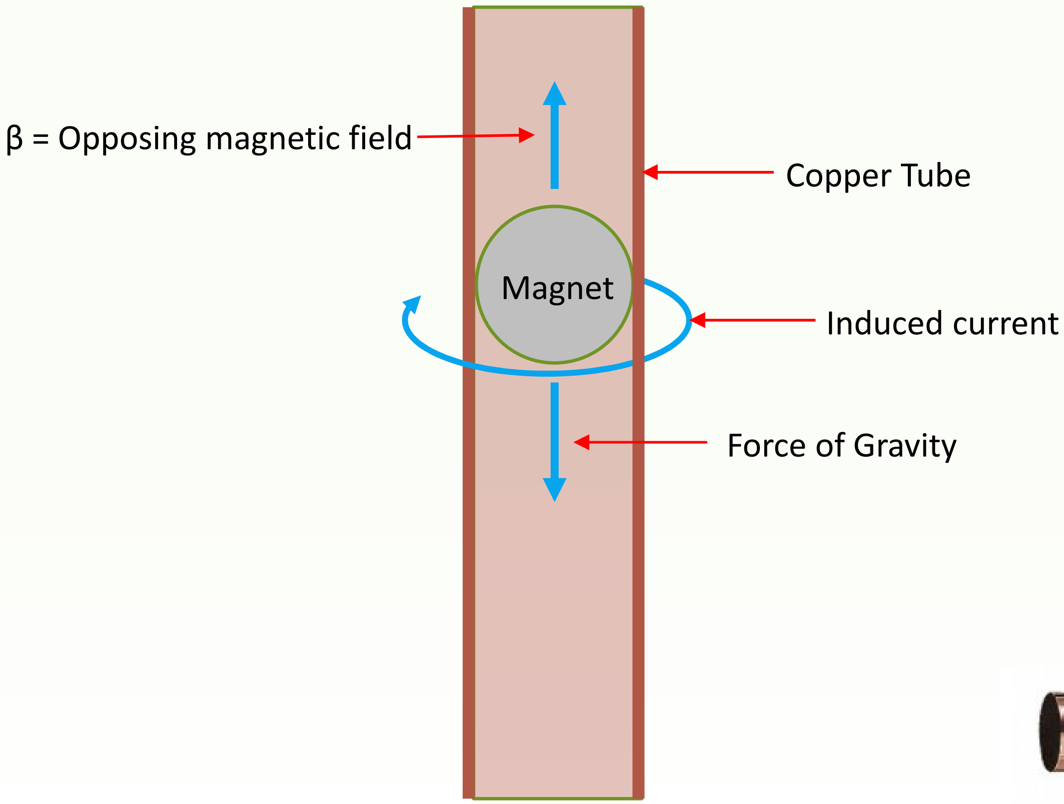
Motor Basics

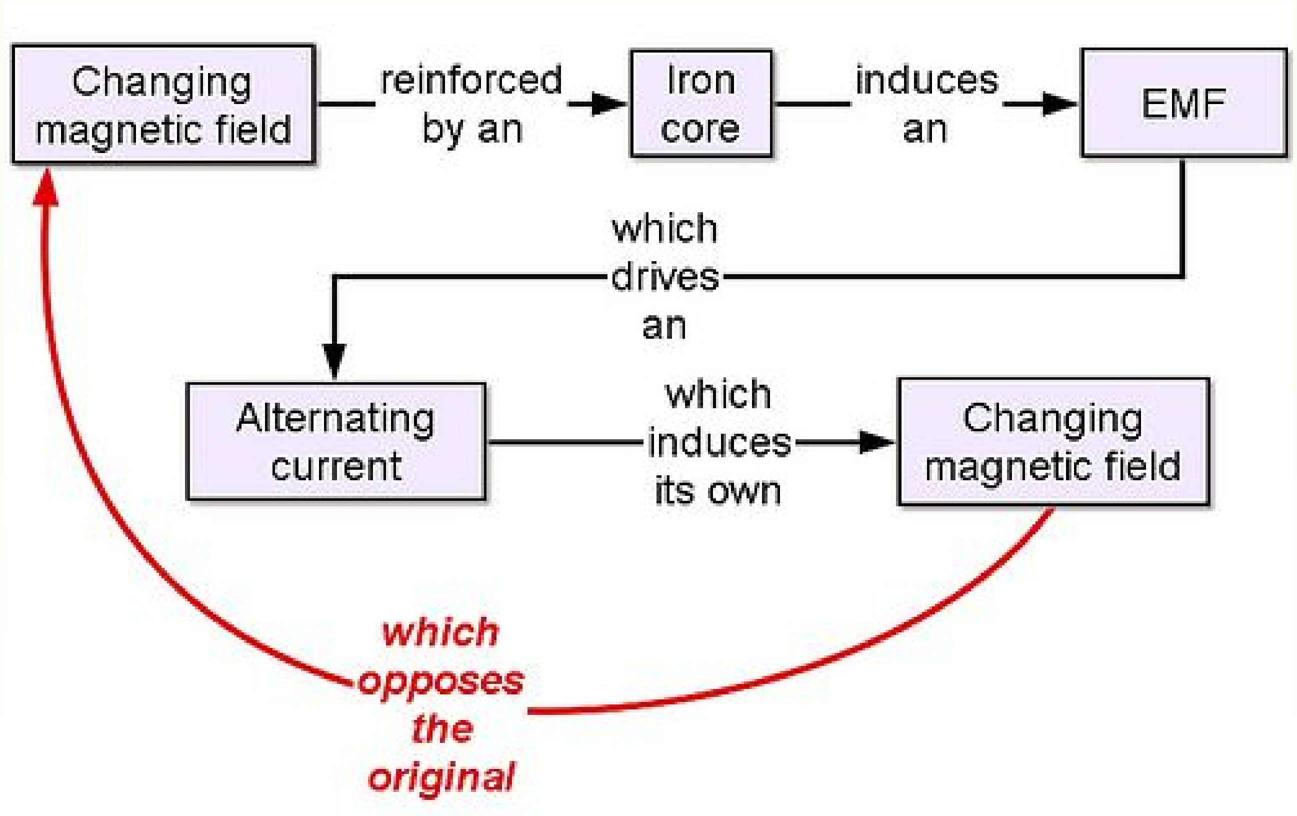
Rotational space and time






β = Opposing magnetic field
Copper Tube
Magnet
Induced current
Force of Gravity

Faraday - Lenz' Law



Faraday – Lenz Law

$$\nabla \times E = -\mu \, \partial H / \partial t$$

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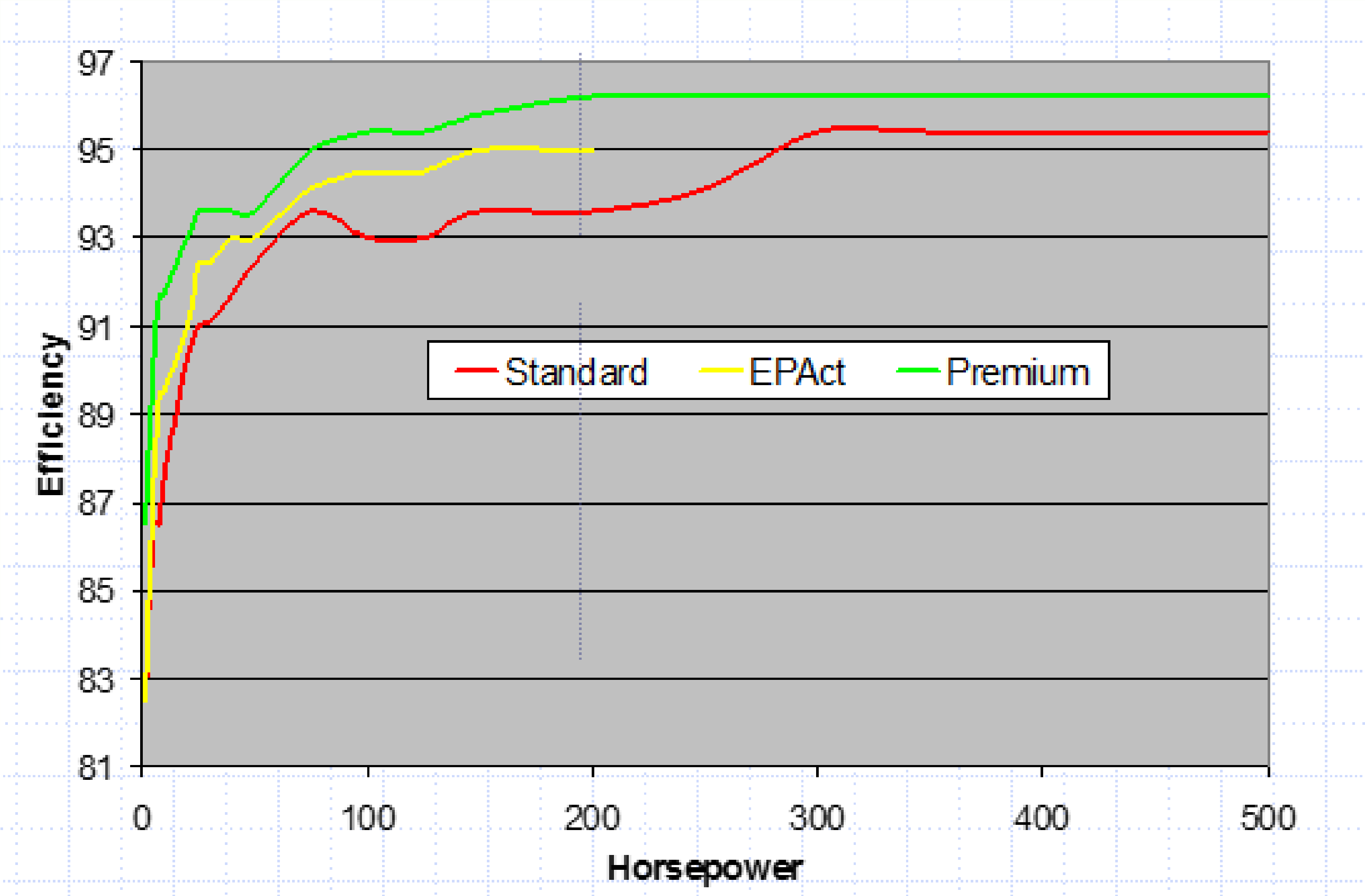
A Few Motor Facts

- Standard Efficiency
  - Most motors today were installed before 1997
  - Typical efficiency is 83% to 90%
- EPAct Motors
  - Energy Policy Act of 1992
  - Effective October 1997
  - Typical efficiency is 87% to 92%
- NEMA Premium Motors
  - Energy Independence and Security Act 2007
  - Effective December 2010
  - Typical efficiency is 91% to 95%
- DOE Extending Range for Premium Efficiency Motors with Effectivity June 2016
  - New rule adds NEMA - A, B, C and IEC - N, H plus specials in 1HP to 500HP
  - Applies to 5 million units vs 1.6 – 2 million units currently
  - Current rule affects 18 million connected HP; new rule affects 50 million HP

Evolution of Motor Efficiency



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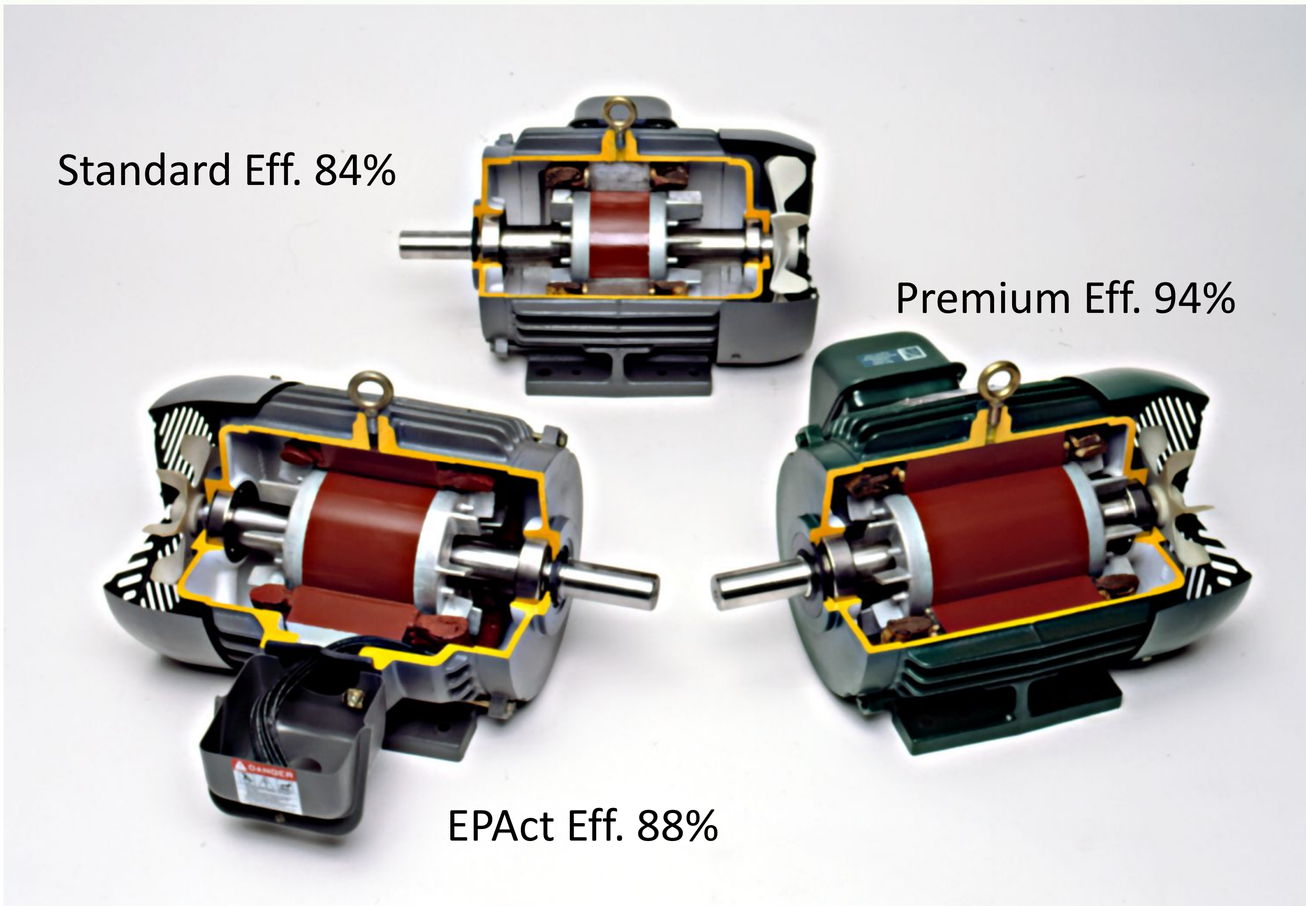
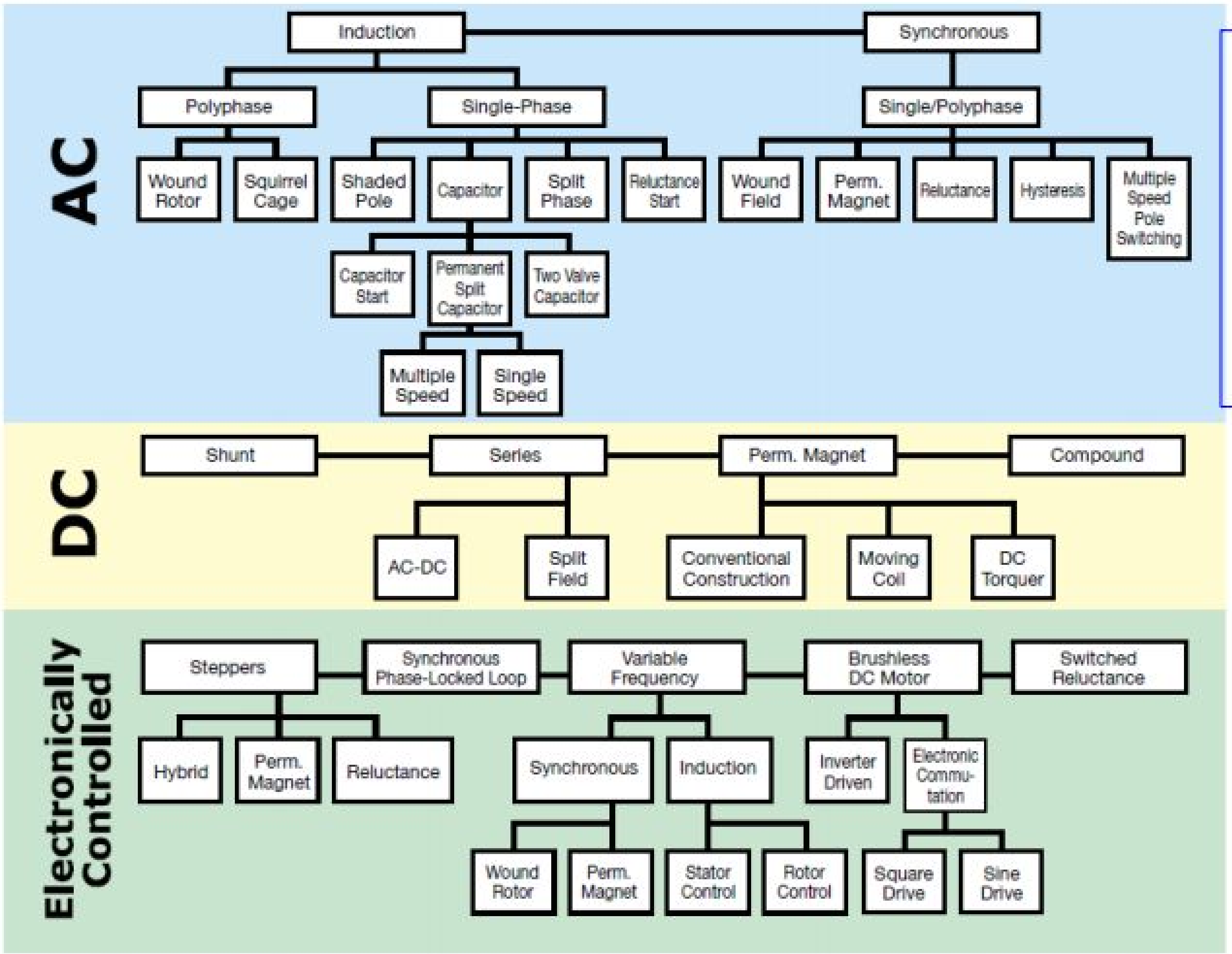
Differences in Motor Construction

10 HP, 1200 RPM



There are Many Motor Types



Differences:

- ***Phase Number***
- ***Rotor Construction***
- ***Starting Method***
- ***Speeds Built In***
- ***Rotor Excitation***
- ***Controller Type***
- ***Current Shape***

Also, Flux Direction:

- ***Radial***
- ***Axial***
- ***Linear***
- ***Tubular***
- ***Transverse***

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	Induction motor	Synchronous motor	PM motor	SyncRel motor	SR motor
Rotor and stator	cage rotor or wound rotor	Would-field rotor, round or salient rotor, damper winding	Magnet, surface PM or IPM, damper winding	Laminated rotor, normal winding for stator	Laminated rotor, concentrate winding for stator
Speed	Must run less than synchronous speed; varies with load	Synchronous speed, need damper winding for line start	Synchronous speed, need induction cage for line start	Synchronous speed	Half speed of synchronous speed
Efficiency	Degraded efficiency at low load operation	Higher efficiency than induction motor	High efficiency than induction motor and synchronous motor	Similar efficiency with induction; better at partial load	Similar efficiency with induction or synchronous motors
Reliability	More heat degrade insulation and life time, many years of proven performance	Brushes or slip ring are issues for long life operating, regular maintenance in fewer years	Lower temperature reduce maintenance, trouble-free operation for years.	Good reliability due to simple rotor	Higher reliability than others due to very simple rotor
Power density	Induction field & rotor iron limits power density	Higher power density than induction motor	Higher than induction and synchronous motors	Power density similar to induction motor and lower than PM motor	Higher power density than induction motor and lower than PM motor
Cost	Simple design and high manufacture quantities lower price, but high operating cost	Higher price than induction, but above 10kW, high efficiency brings low operating cost	Higher cost, but higher efficiency gives low operating cost	Lower material cost , but low quantities. Mfr assembly difficult. Need a VFD controller	Lower material cost , but low quantities. Needs a special controller
Application	Many areas, any power, general drive	Many areas, high power, synchronous speed	Many areas, small to high power, high efficiency	Newly available; target is Induction motor applications	Some good examples, mostly for home application; noisy

Inverter Grade Motors

NEMA Premium Efficiency features plus

Beginning and ending of windings are separated

Extra insulation to protect against voltage spikes

Wound with inverter grade magnet wire (for voltage spikes)

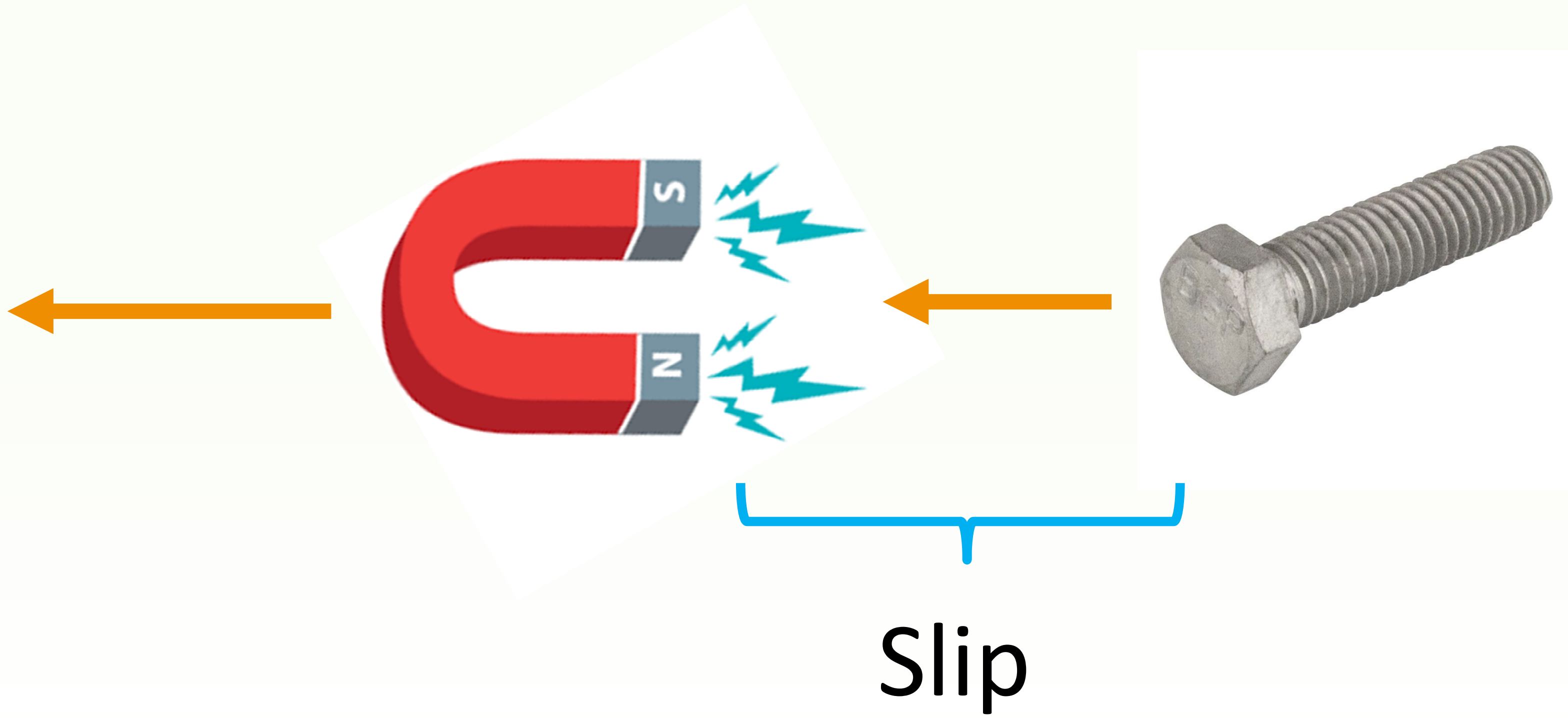
Designed to handle higher frequency components

Either rated for higher temperatures or constant speed cooling fan on auxiliary power for low speeds

Will provide full-rated torque at zero speed and well past base speed

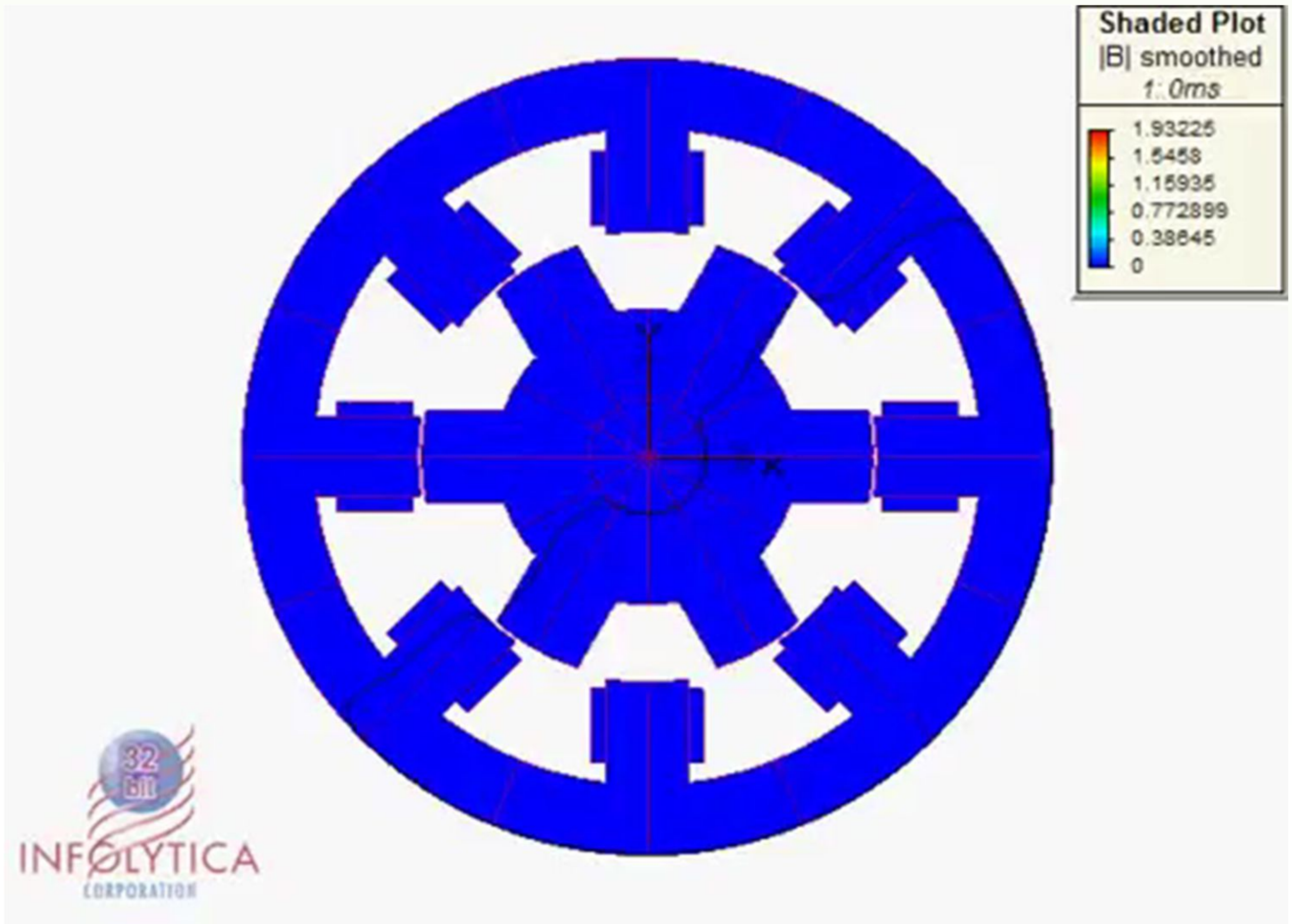
Motor Efficiency vs. Load

Motors Need "Slip" to Operate



Switched Reluctance Motor

Requires VFD to Operate



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True Load - Slip

Speed (RPM) = (60 Hz X 60 sec/min) / Number of pole pairs

RPM = 3600, 1800, 1200, 900, 720..... no other choices

NLRPM = No Load RPM = 3600, 1800, 1200, 900, 720....

FLRPM = Full Load RPM (this is on nameplate)

Measured RPM (use tach or meas. current and use motor curve)

Design Slip = NLRPM – FLRPM

True Slip = NLRPM – Measured RPM

% Load = True Slip / Design Slip

True Load = % Load X nameplate HP

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True Load Example - Slip

Nameplate

- FLRPM = 3555
- HP = 75

NLRPM = 3600 (obviously!)

Measured RPM = 3576

Design Slip = 3600 – 3555 = 45

True Slip = 3600 – 3576 = 24

% Load = 24 / 45 = 53.3%

True Load = 53.3% X 75 = 40 HP

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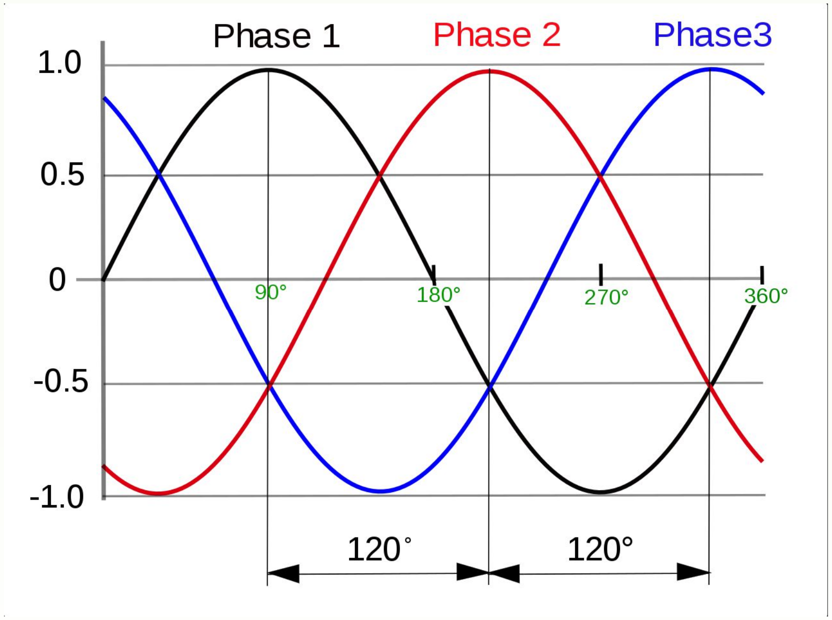
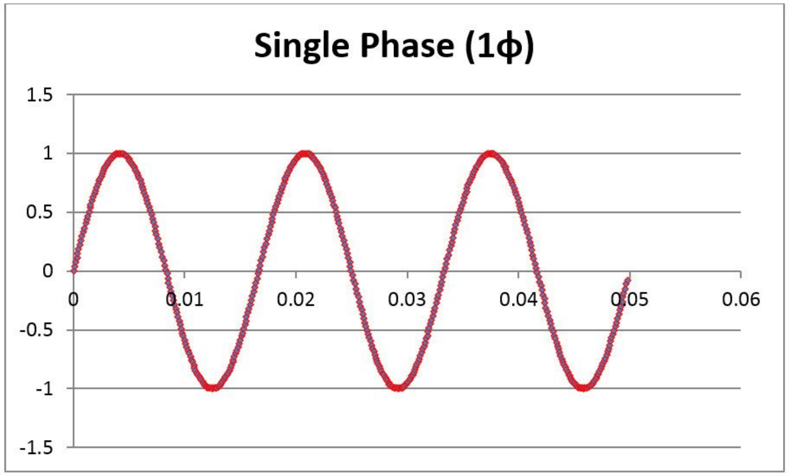
Slip Is Not Naturally Created in Single Phase Motors



3-phase power



1-phase power

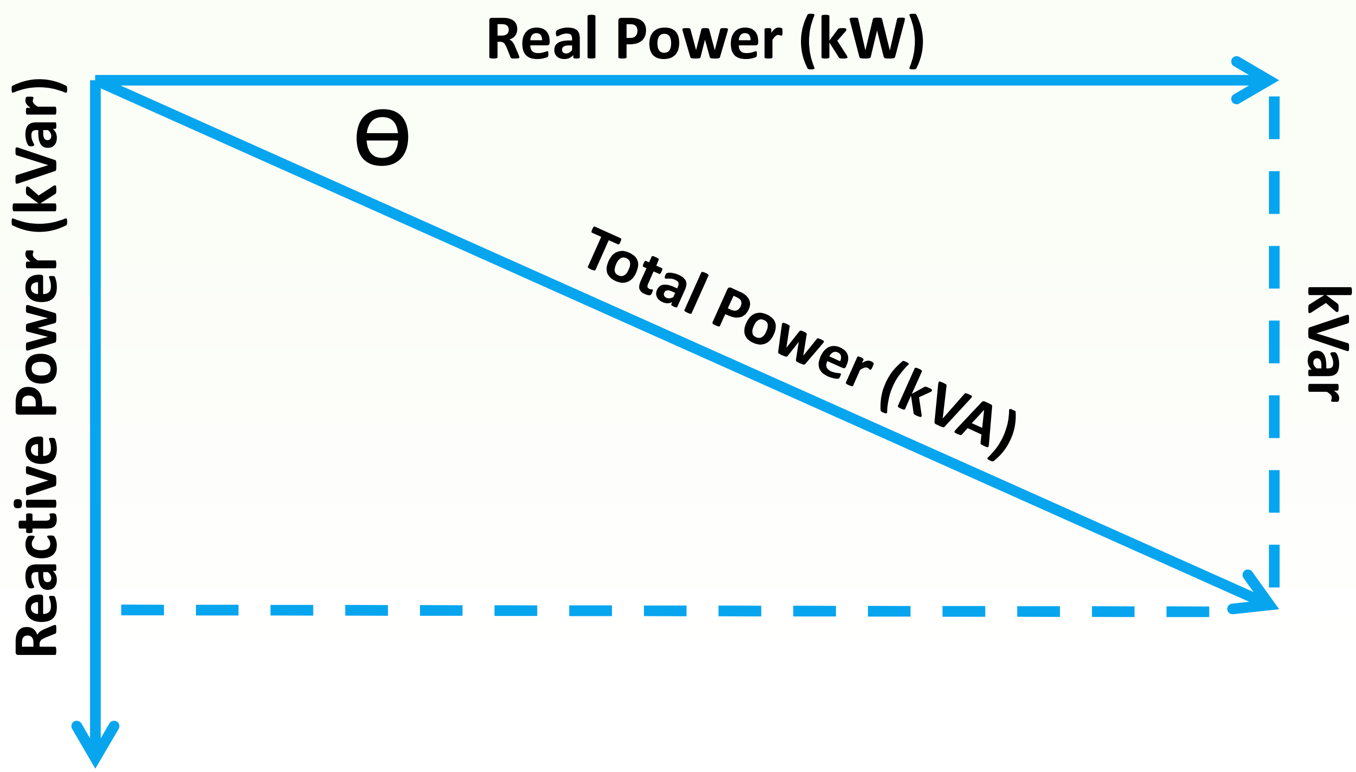
Slip Is Not Naturally Created in Single Phase Motors

3-phase motor

1-phase motor

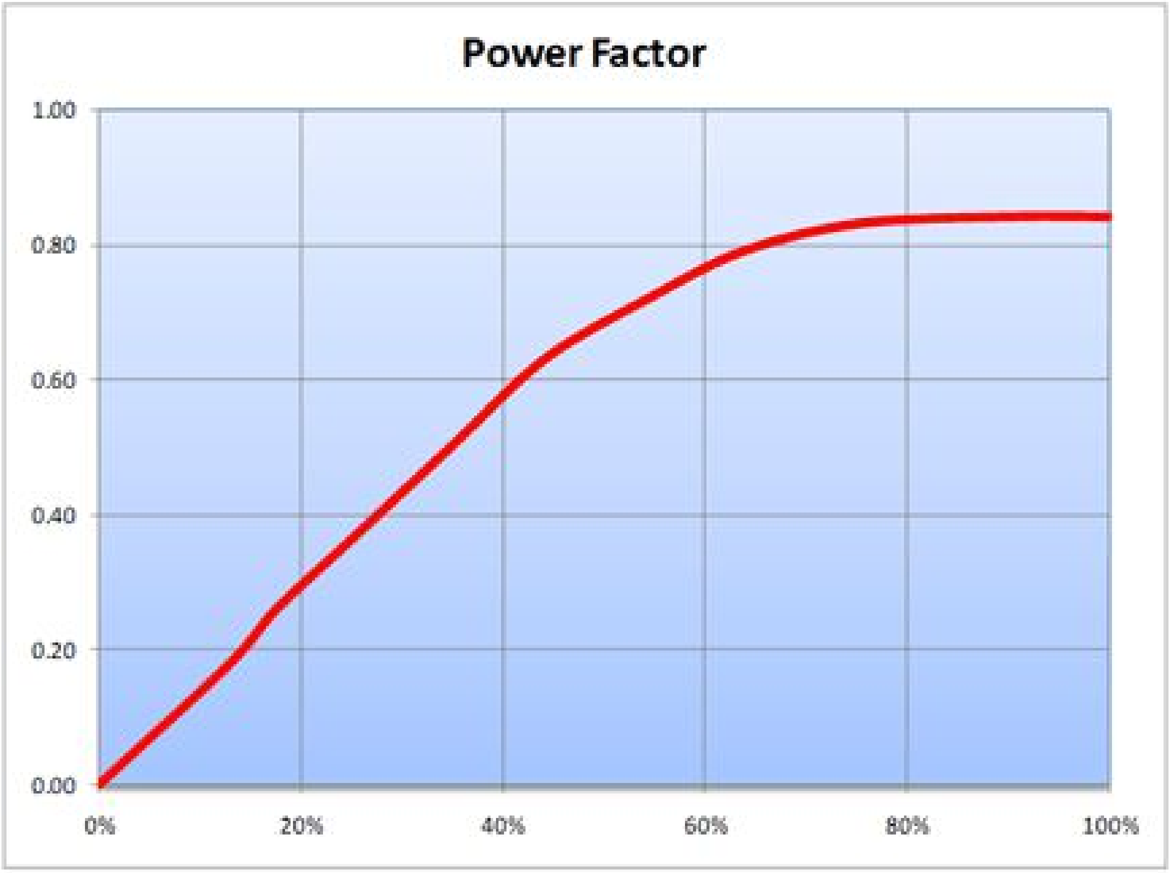
Power Factor

PF = cos ϴ   Motors = 0.85@ Full Load



Power Factor vs. Load

With VFD, PF = 1.0



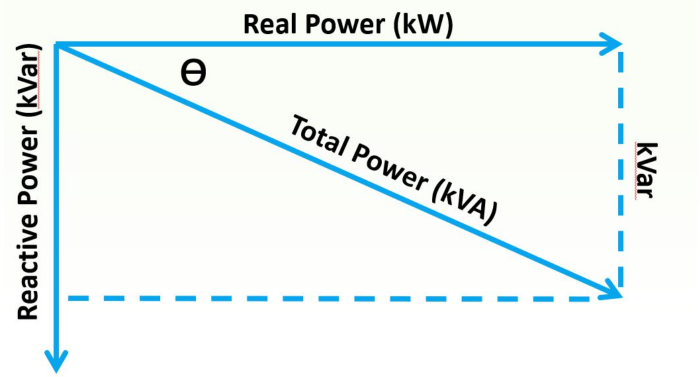
PF

Load

Power Factor

Quick Calc from Electric Bill

$$PF = \cos\left[\tan^{-1}\left(kVar / kW\right)\right]$$



What it Costs to Operate a Motor

If owning a car was like owning a motor?

Purchase price = $30,000

Annual fuel cost = $500,000

What would You be willing to do

to make your car run more efficiently?

Purchasing agents still buy on price

because they probably don't know ?

What it costs to run a motor

Rating = 100HP

Hours of Operation = 7,400

Cost per kWh = $0.09

Demand kW = $11

Purchase Price = $7,000

Load Factor = 70%

Motor Eff. = 94%

$$Annual\ Cost = \overbrace{\frac{100\ x\ 0.746\ x\ 7400\ x\ 0.7\ x\ .09}{.94}}^{\text{kWh}} + \overbrace{\frac{100\ x\ 0.746\ x\ 0.7\ x\ 11\ x\ 12}{.94}}^{\text{kW}}$$

Annual Energy Costs = $36,998 + $7,333 = $44,331

Purchase Price = $7,000

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Is it Worth Switching to a NEMA Premium Efficient Motor?

Using same 100HP motor in previous slide

Annual operating costs = $44,331

Compared to older 87% efficient motor,

which has a cost = $65,030

A difference of $20,699!

A New 100HP NEMA Premium Motor Costs $6,000 to $9,000.

Inverter Grade Motors

NEMA Premium Efficiency features plus

Beginning and ending of windings are separated

Extra insulation to protect against voltage spikes

Wound with inverter grade magnet wire (for voltage spikes)

Designed to handle higher frequency components

Either rated for higher temperatures or constant speed cooling fan on auxiliary power for low speeds

Will provide full-rated torque at zero RPM and well past base nameplate RPM

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VFD Basics

VFD Advantage – Affinity Laws

$$HP_2 = HP_1 / [RPM_1/RPM_2]^3$$

A 50% Drop in RPM = 90% Less HP

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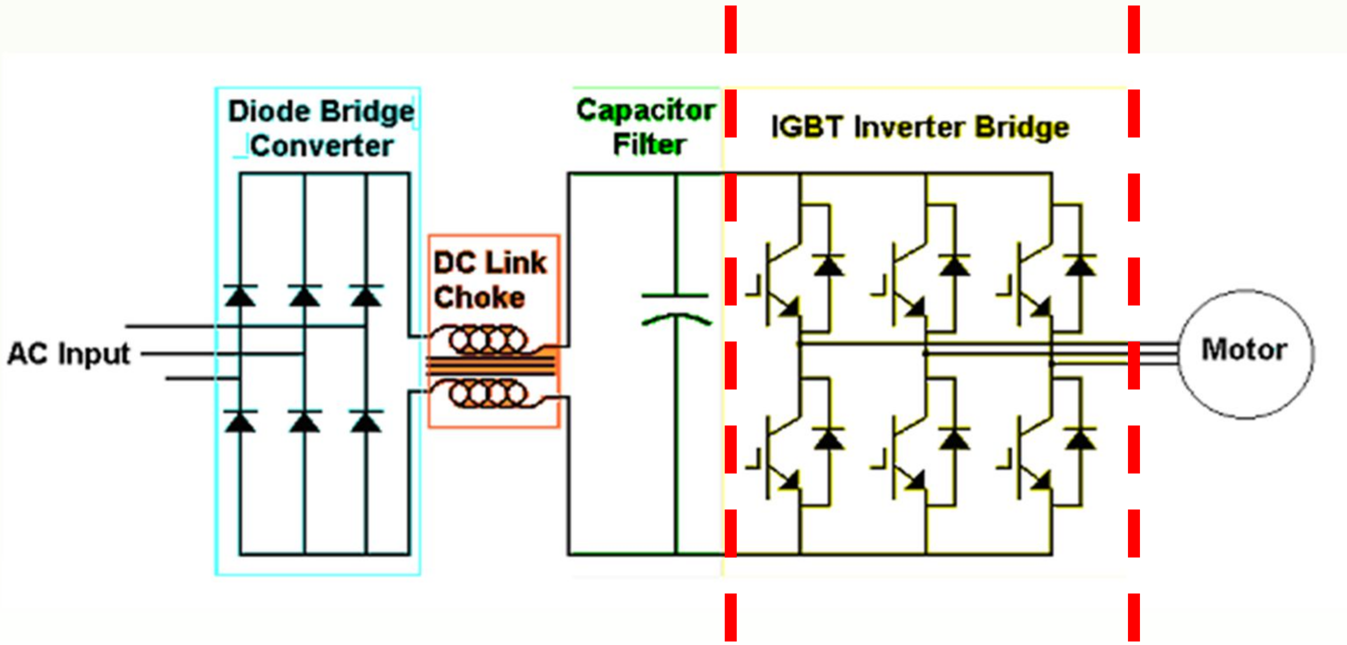
Variable Frequency Drives

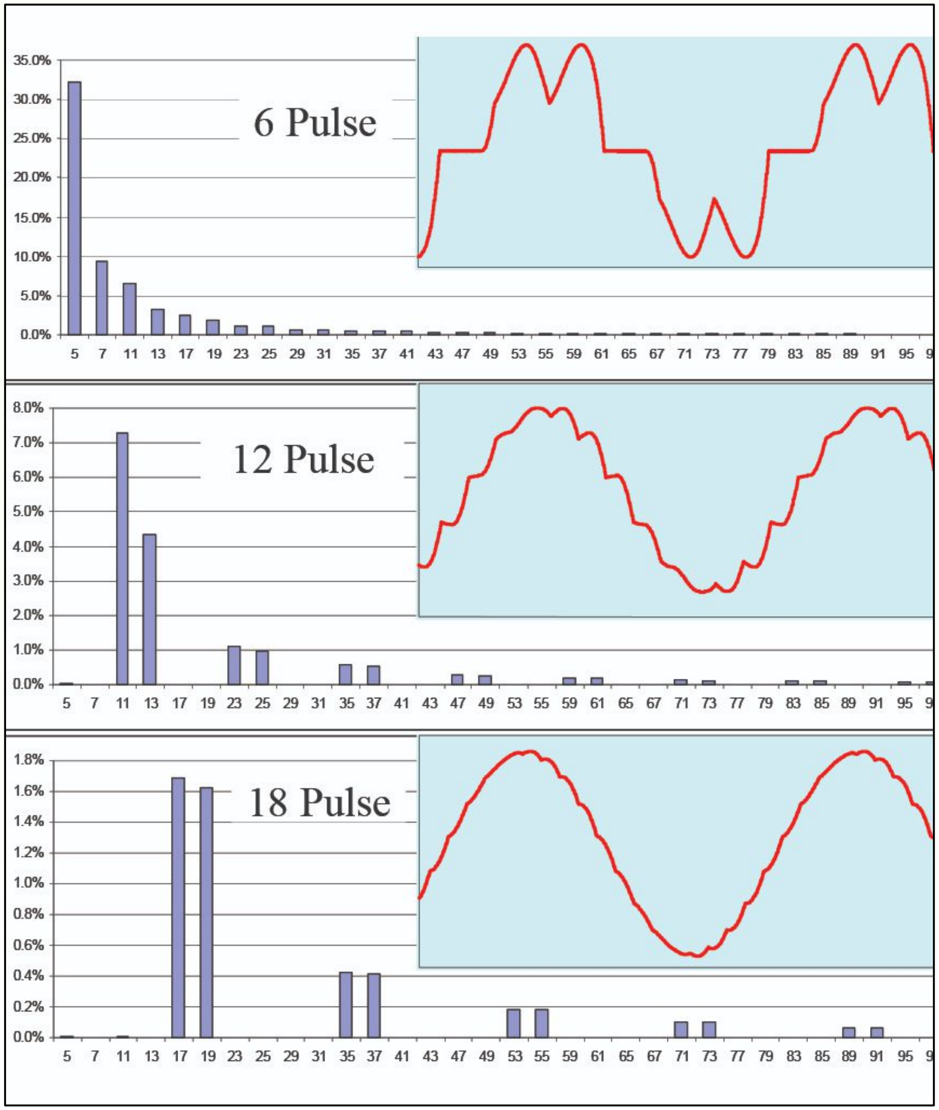
- Ideal for variable load/variable speed application
- Less ideal for constant load/speed applications
- Inherent soft start (extends motor life)
- Unity Power Factor at all loads
- Same variable speed & fast torque of DC motors, but less expensive and much more reliable
- Drive adds heat and stress to motor so inverter grade motors are best
- Drive makes motor less efficient at or near full load when compared to running motor without VFD

VFDs Cover Small HP to Medium & High Voltage

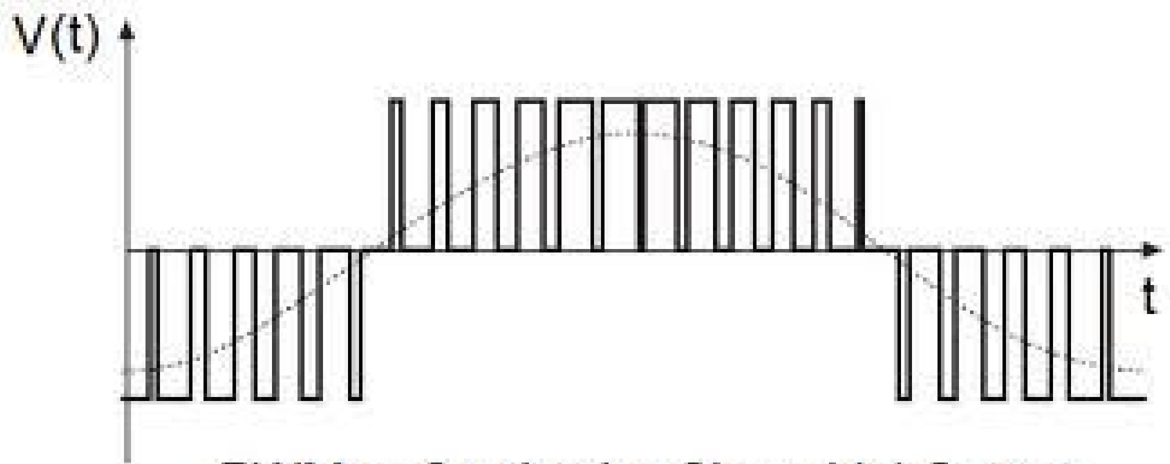
VFD – Envision as 3 Segments



6 v 12 v 18 Pulse Inverter



VFD Output Voltage – PWM



PWM to Synthesize Sinusoidal Output

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VFD & Motor Together

You Need The Right Tools!

Vibration
Analyzer

Oscilloscope

Power
Analyzer

Acoustic/Stethoscope

Data Loggers

Infrared
Camera

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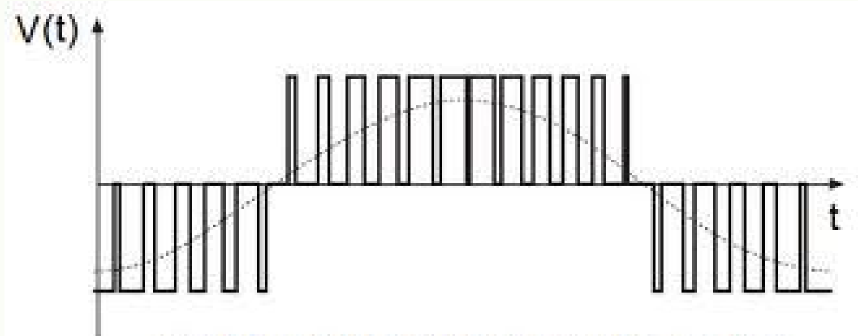
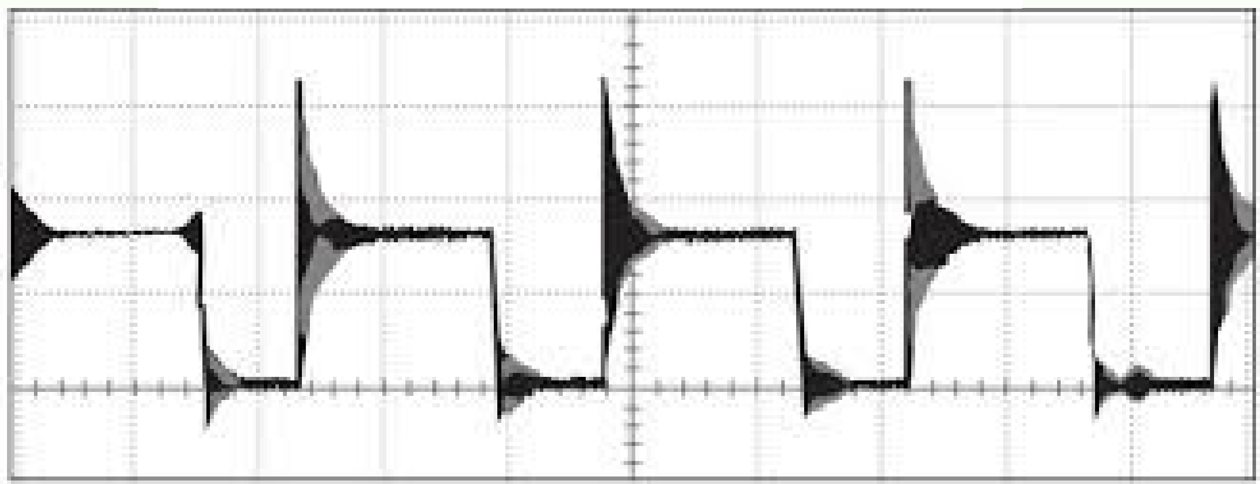
VFD Output Voltage – Reflected Wave

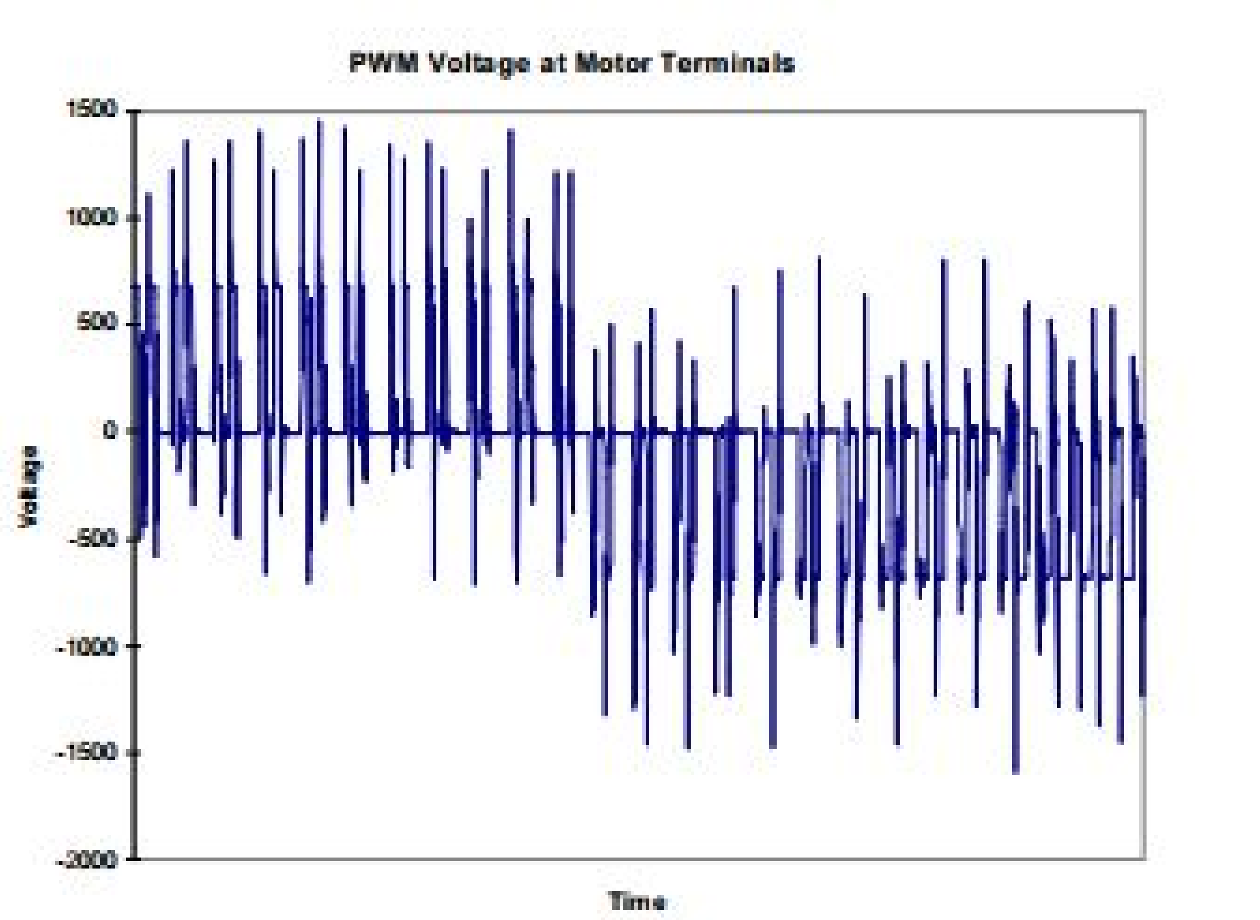


PWM to Synthesize Sinusoidal Output



Rapid dV/dT !!!

Resulting Voltage at Motor Terminals



VFD Output Voltage – Corona Inception Voltage (CIV)

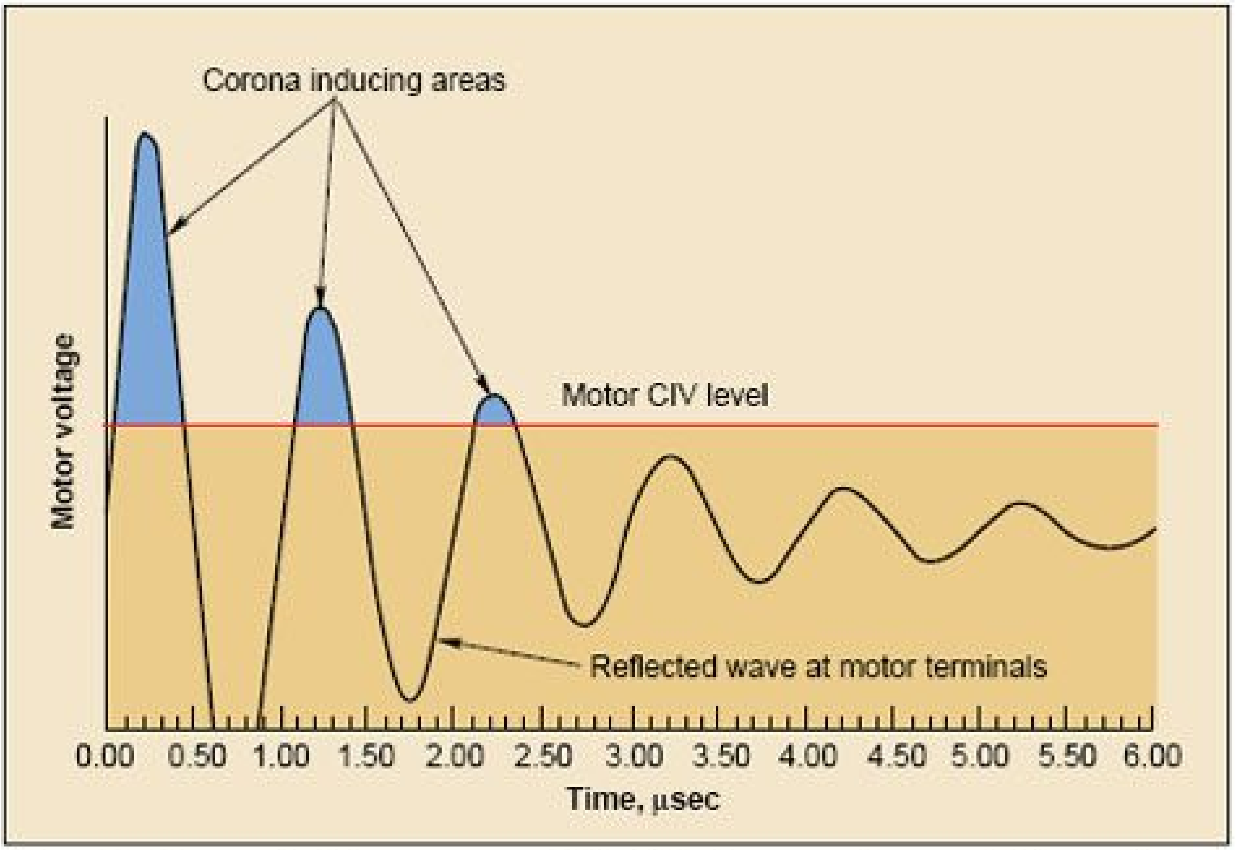


Figure 2 — The peak voltage can exceed the CIV value more than once during a single pulse. For example, any voltage over 1,600 V in a 480-V system will trigger a series of waves over the CIV level.

VFD Output Voltage – Insulation Failure

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Unexpected Failures

Unexpected Motor Failure

1. Transient voltages
2. Voltage imbalance
3. Harmonic distortion
4. VFD reflected waves
5. Sigma currents
6. Overloading
7. Misalignment
8. Shaft imbalance
9. Shaft looseness
10. Bearing wear
11. Soft footing
12. Pipe strain
13. Shaft voltage
14. Loose connections

More than one at a time is common

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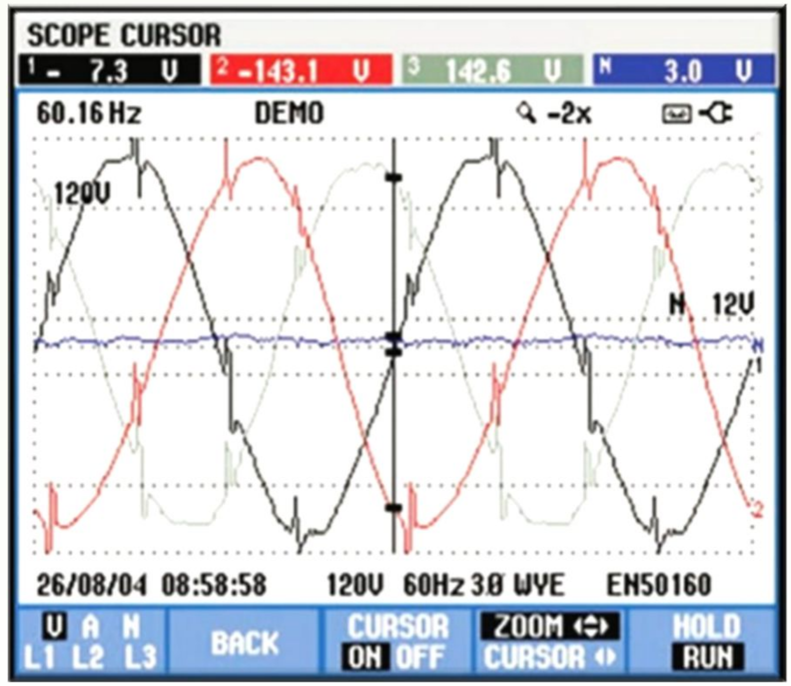
Transient Voltages

- Insulation breakdown
- Caused by abrupt shutoff of reactive loads
- Solution: Transient Voltage Surge Suppression (TVSS)



Voltage Imbalance

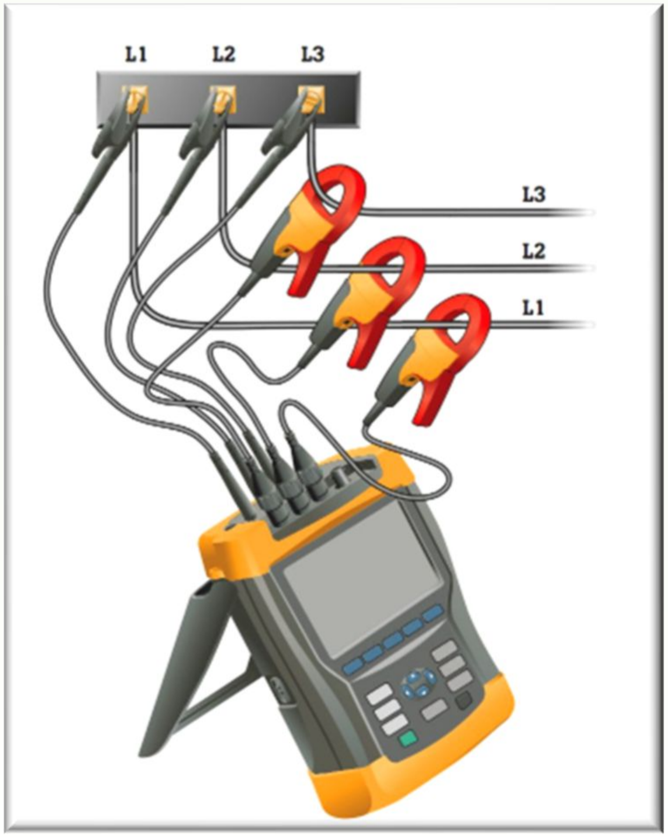
Usually caused by poor planning of single phase loads

Increases current in one or more windings

Can cause overheating

10% is upper limit

Solution: Redistribute loads



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Harmonic Distortion

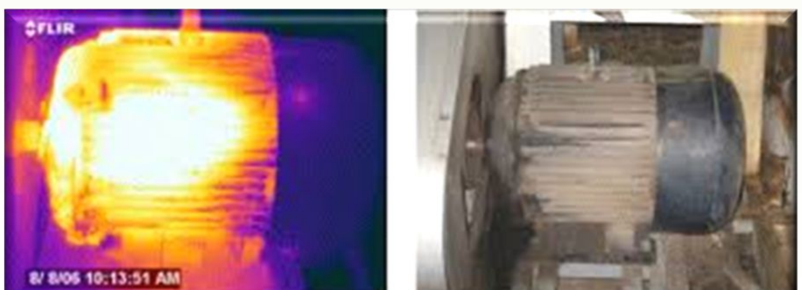
Caused by non-linear loads

Decreases motor efficiency

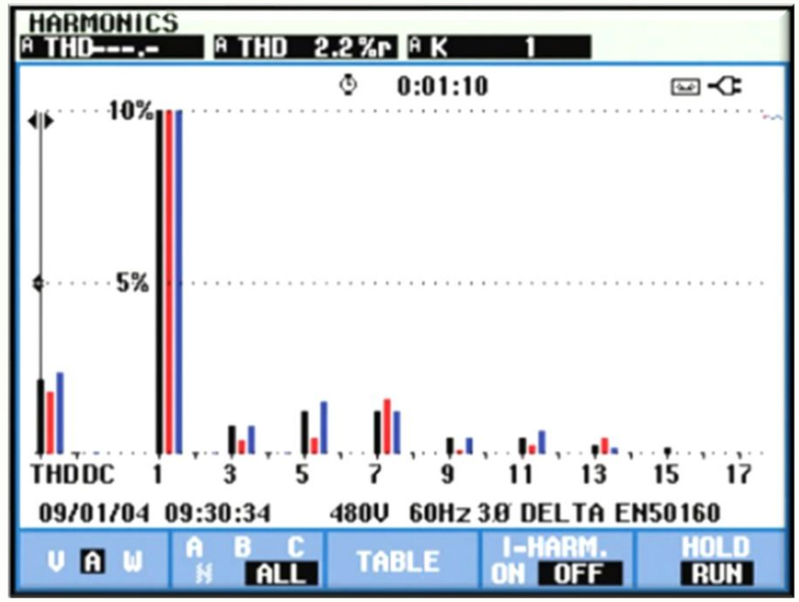
Can cause overheating

5th, 11th, 17th cause a negative torque on motor

Solution: Series trap



Above thermal and daylight images show a three phase motor which has overheated. Power quality analysis proved condition was caused by negative sequence harmonics.



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Harmonic Distortion

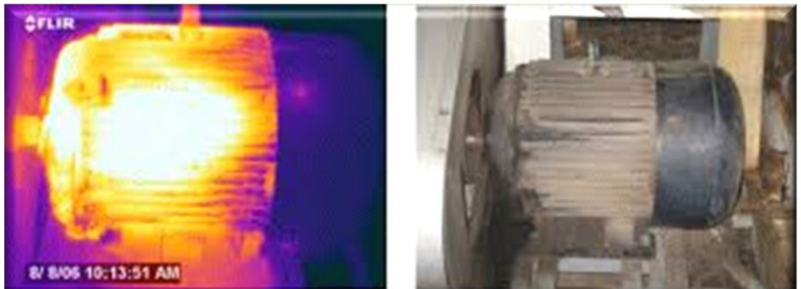
Caused by non-linear loads

Decreases motor efficiency

Can cause overheating

5^{th}, 11^{th}, 17^{th} cause a negative torque on motor

Solution: Series trap; mitigating source



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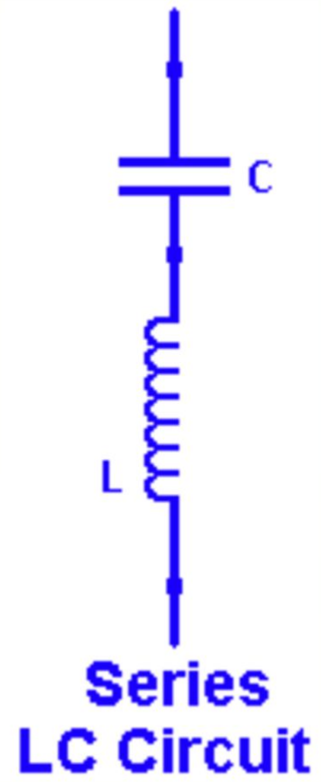

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Harmonic Filters

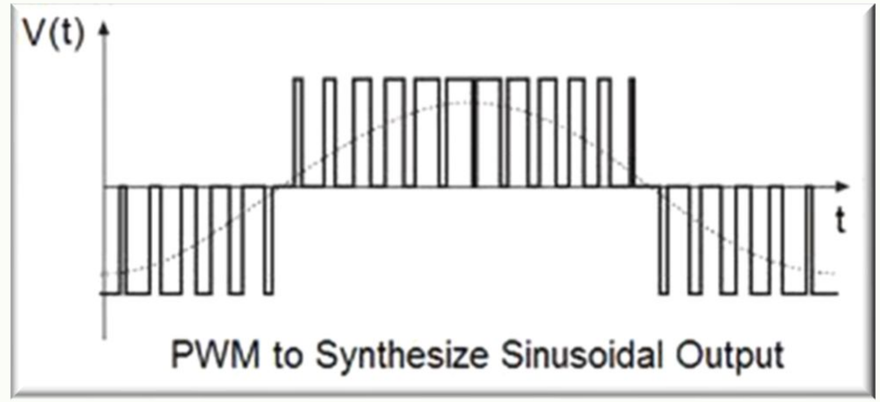
Siemens

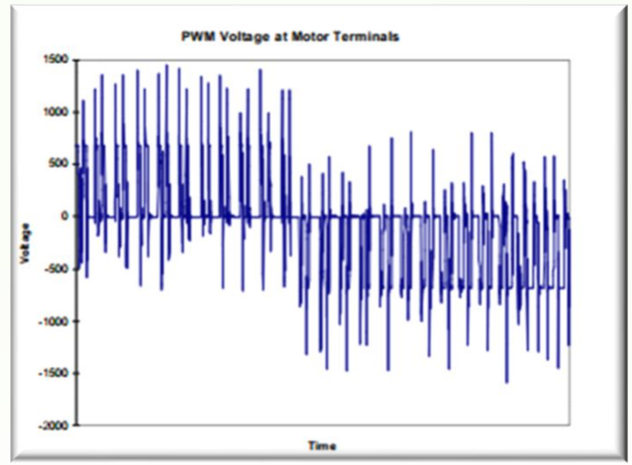
Eaton

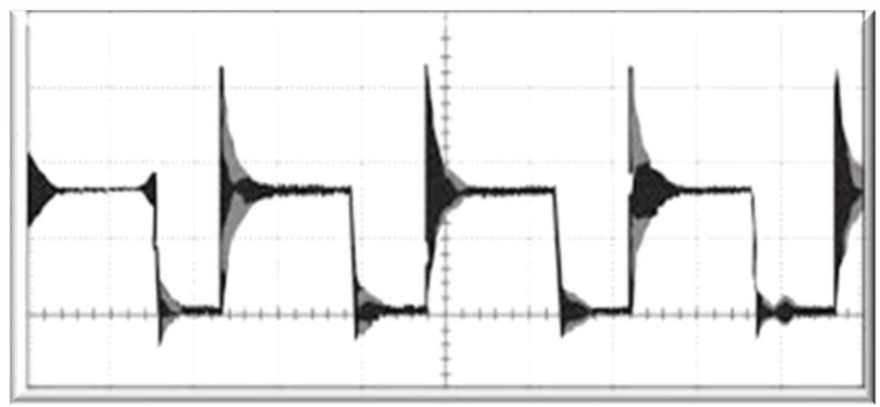
MIRUS

VFD Reflected Waves

- VFD PWM output produces reflections in cable due to mis-matched impedances
- Rapid dV/dT at IGBT trigger
- Resonance in cable can amplify wave
- Can punch through insulation
- Cables over 50ft then measure
- Solution: Shorten distance; use trim capacitors; use VFD cables







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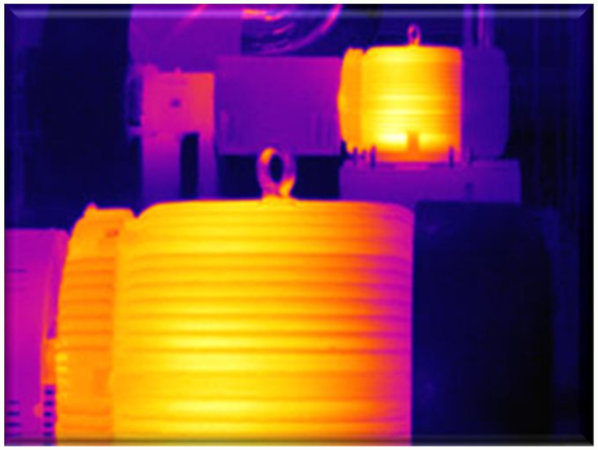
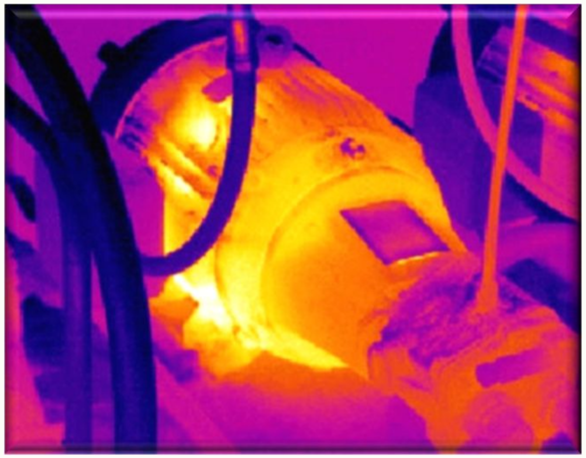
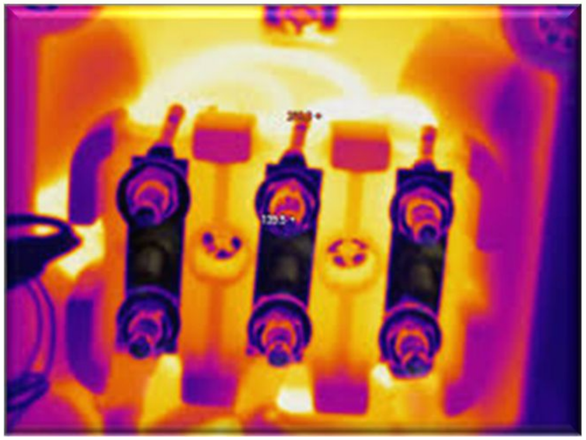
Overloading







30% of all failures

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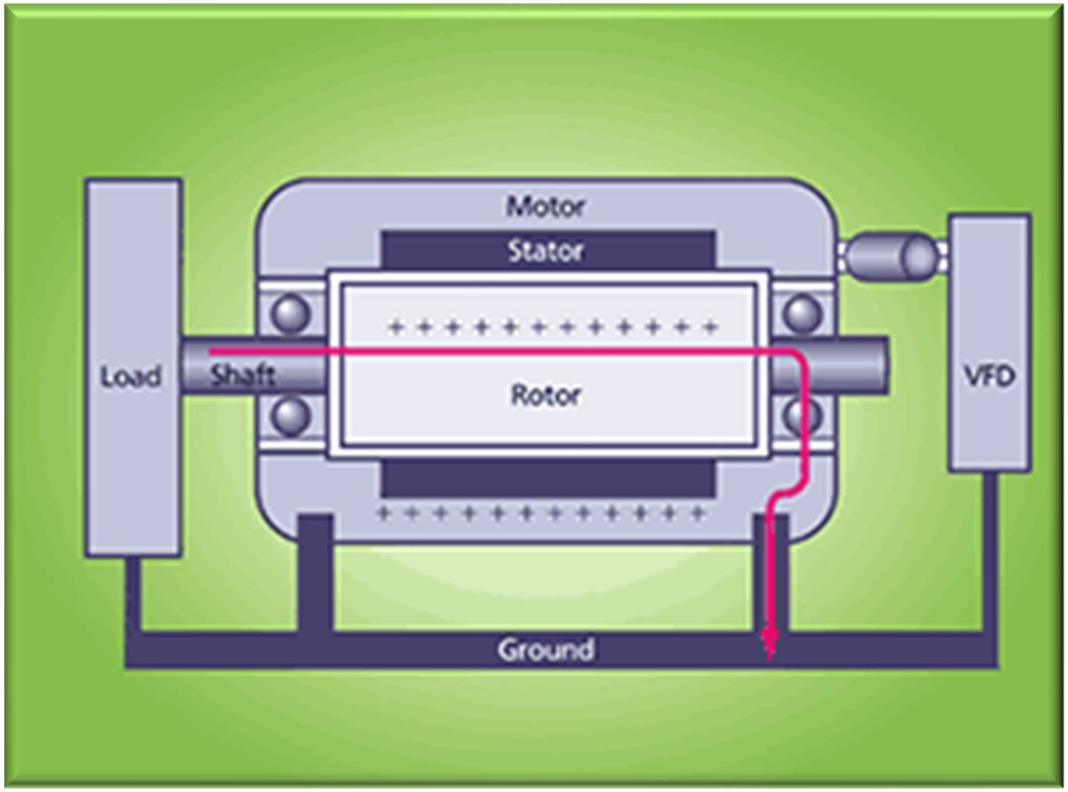
Shaft Voltage

VFD Caused Bearing Wear

- Capacitive coupled leakage current
- Static electricity from load
- Solution: Many! Shaft grounding ring, grounded shaft, insulated bearings, etc.



Marathon: AEGIS Shaft Grounding

Baldor: Shaft Grounding Ring

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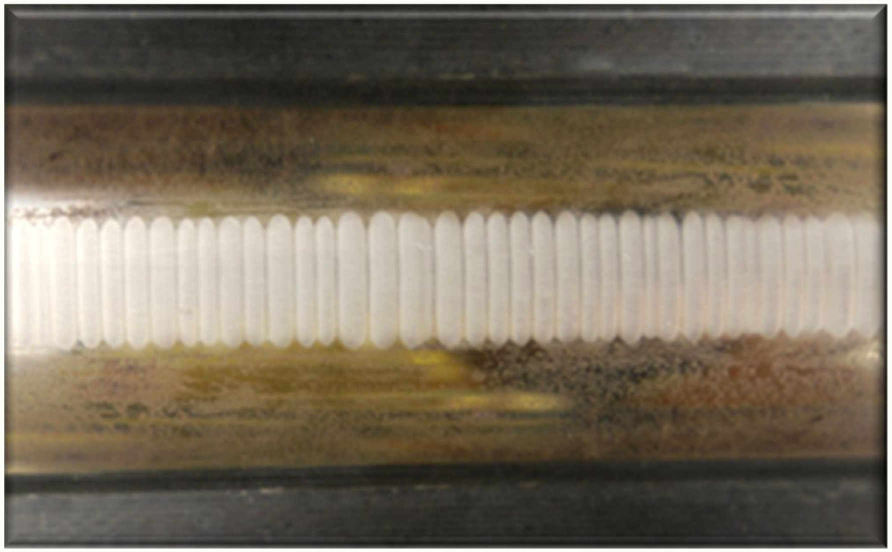
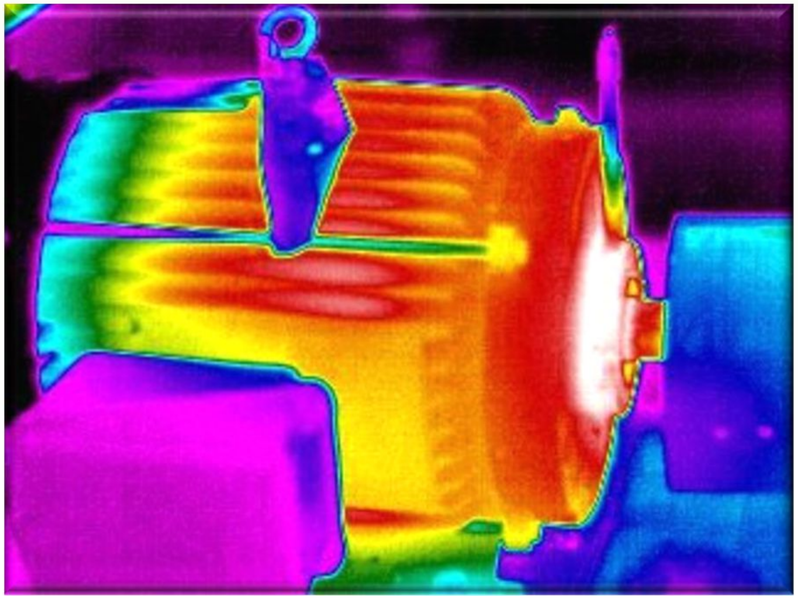
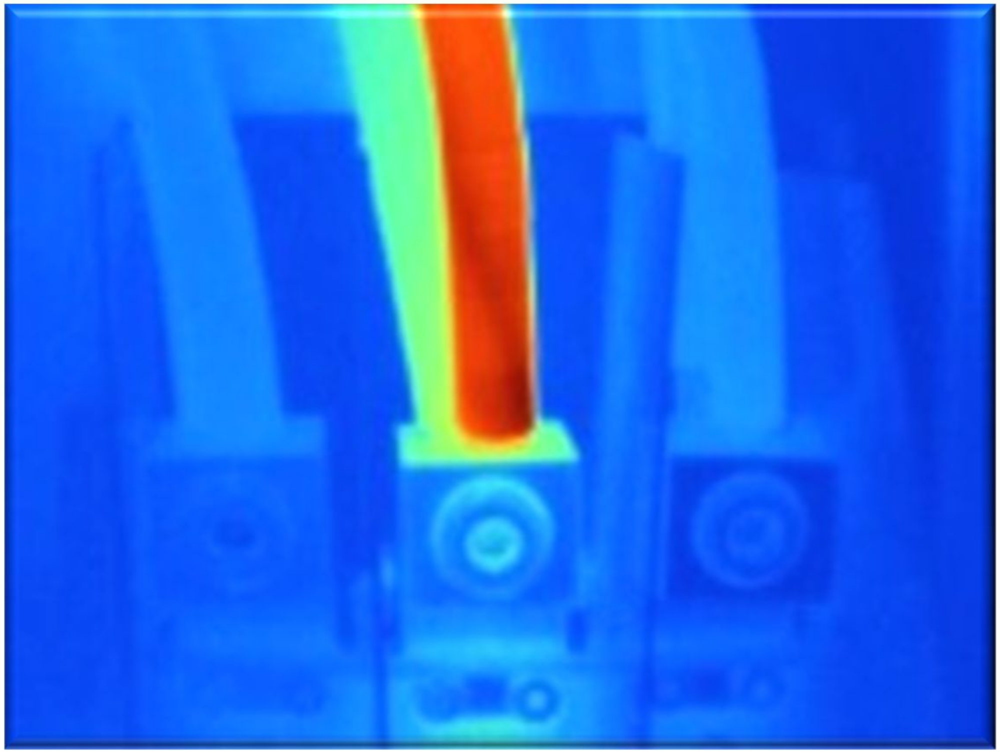
Shaft Voltage Fluting





Loose Connections



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