VFD Basic

Chee Nee Bong

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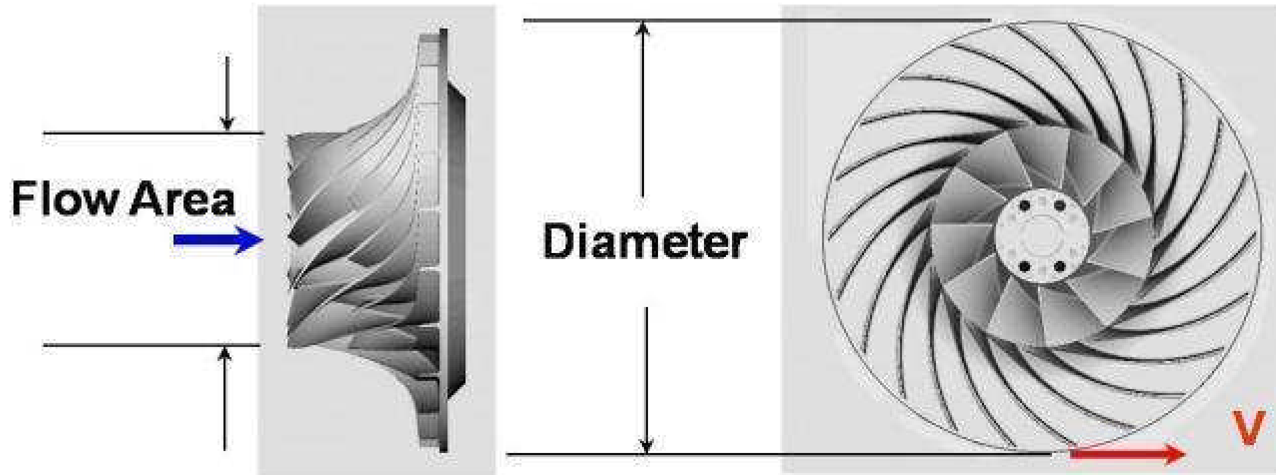
VFD BASIC

Overview

- Fundamentals
  - Centrifugal operation
  - Affinity Laws
  - Tower Reset & ARI
- AC Motor
- Electrical Basic
- VFD Components & Basic Theory
- Formulas

VFD Basics

Fundamentals of Centrifugal Operation



The basic physics are the same for centrifugal pumps, fans and compressors

Flow ~ V

To increase flow, increase flow area or rotor speed

Lift ~ V^2

To increase lift, increase diameter or rotor speed

Power ~ Flow x Lift ~ V^3

With constant flow and reduced lift, reduce speed to reduce power

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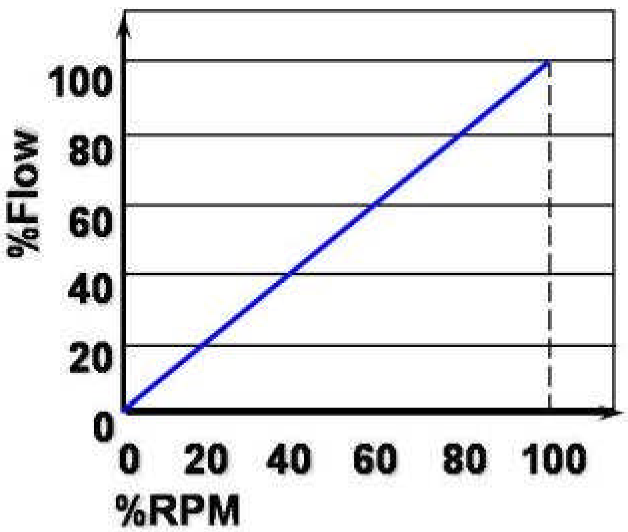
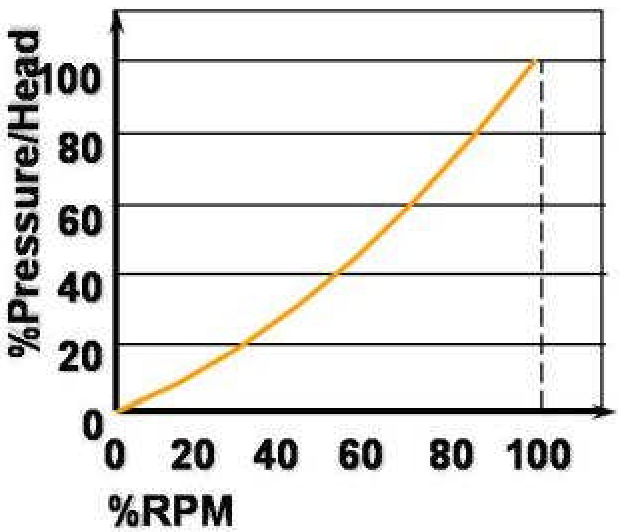
Affinity Laws for Centrifugal Loads [Fans and Pumps (no static head)]

Flow ~ Speed



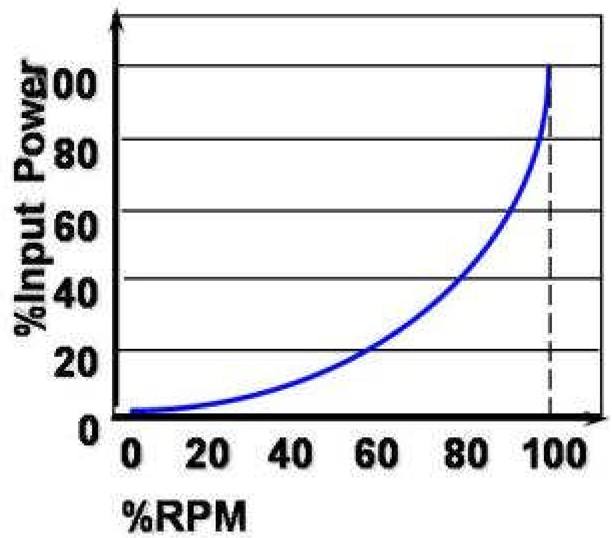
Capacity drops as we slow down the compressor

Lift ~ Speed^2



Lift drops off faster as we slow down the compressor

Power ~ Speed^3



But Power Usage drops even faster!

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The Affinity Laws

Flow is proportional to shaft speed

Head is proportional to square of shaft speed

Power is proportional to cube of shaft speed

VFDs take advantage of the affinity laws which state

“As the speed of a centrifugal load decreases, the horsepower requirement will decrease with the cube of the speed.”

Numeric Description of The Affinity Laws

Speed	Flow	Required Power
100%	100%	100%
90%	90%	73%
80%	80%	50%
70%	70%	34%
60%	60%	22%
50%	50%	13%
40%	40%	6%
30%	30%	3%

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How does speed affect power ?

19XRV is taking advantage of the use of Tower Water Reset (set point for leaving condenser water)

Critical with 19XRV (VFD) chillers

Tower water temperature goes down, compressor speed is reduced

$Speed^3$ = Power
Speed = Flow

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ARI condition: Old vs. New

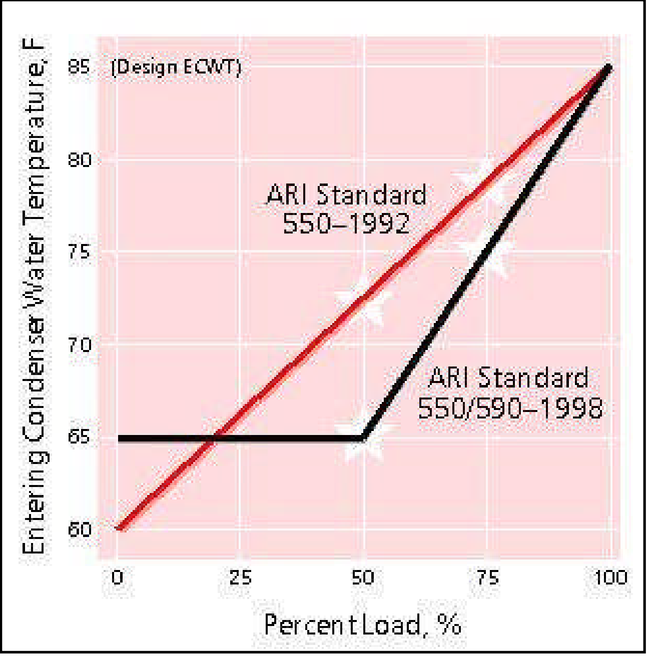
TABLE 3. - ENTERING CONDENSER FLUID TEMPERATURES AT PART LOAD
I-P SYSTEM

% LOAD	1992 STANDARD			1998 STANDARD		
	WC °F ECWT	AC °F EDB	EC °F EWB	WC °F ECWT	AC °F EDB	EC °F EWB
100%	85	95	75	85	95	75
75%	78.75	85	68.75	75	80	68.75
50%	72.5	75	62.5	65	65	62.5
25%	66.25	65	56.25	65	55	56.25

WC = water-cooled
AC = air-cooled
EC = evaporative cooled

ECWT = entering condenser water temperature
EDB = entering air dry bulb temperature
EWB = entering air wet bulb temperature

New ARI 550/590-1998



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Tower Reset & ARI Condition

100% load, 55~44ºF Chilled Water, 3 GPM @ 85ºF Tower water

For each 10% drop of load, the tower water must drop 4ºF from design. Therefore, at 75% load, the tower water should be @ 75ºF

So…Why Tower Water Reset at Part Load Necessary ?
When mass flow is reduced, the ability to produce lift decreases.
The guide vane angle changes, thereby reducing the lift ability. Compressor will surge

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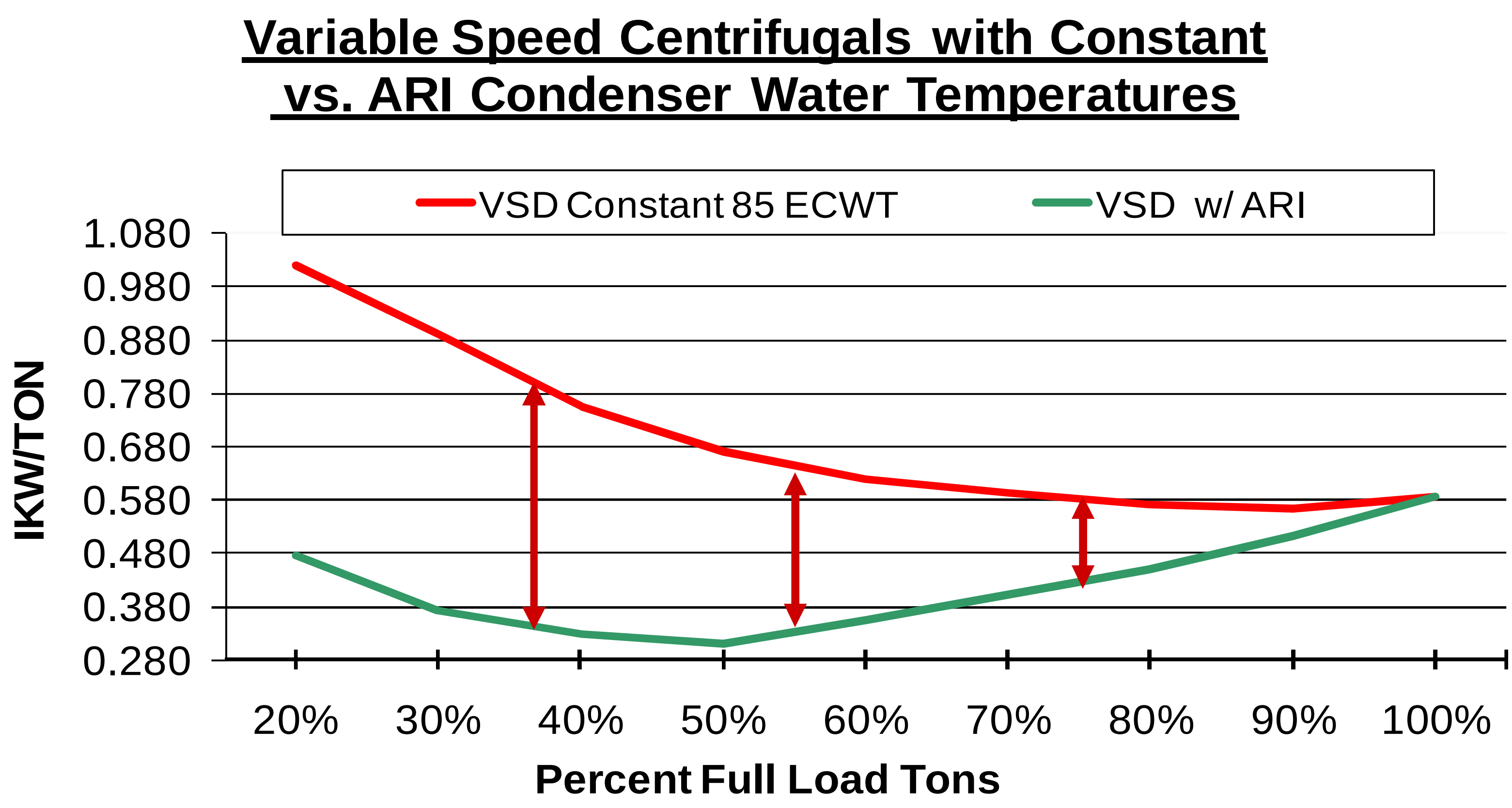
VFD applied savings



A VSD chiller reduces KW-HR consumption

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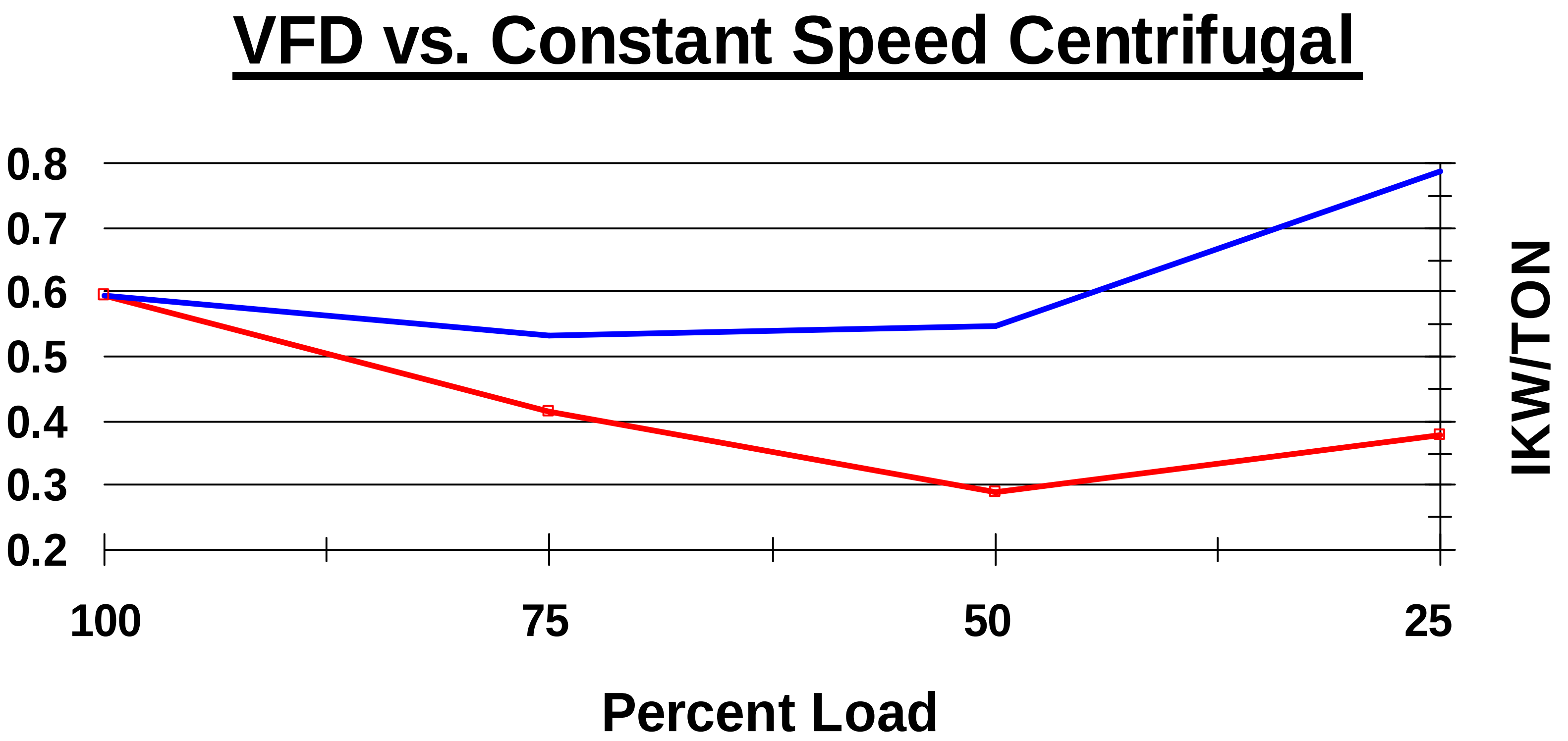
Centrifugal: VFD vs. Constant Speed

Carrier
Turn to the Experts.



Primary function of VFD is to improve part load efficiency

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AC Motor

AC Induction Motor

Power by Electromagnetic Induction

How does this work ?

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AC Motor

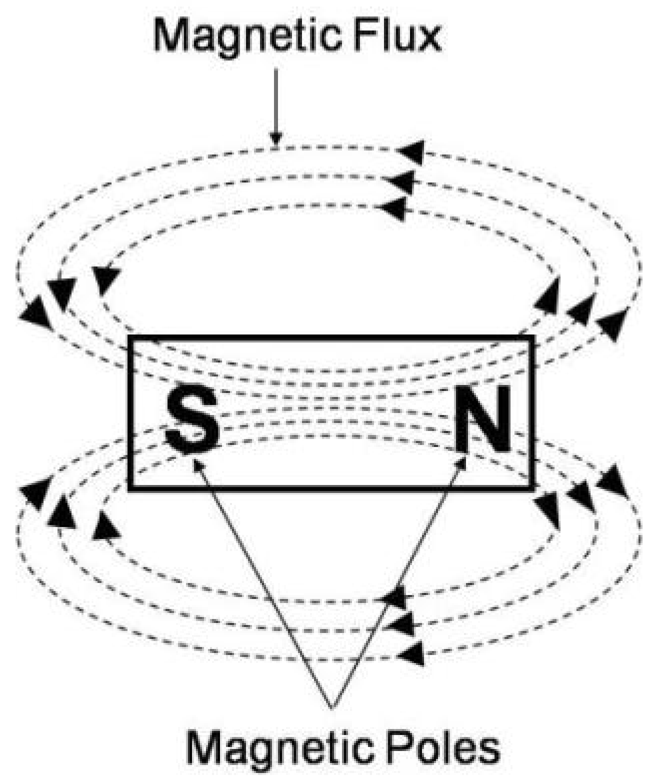
Magnets – material that produces magnetic field. Unlike poles attract, like poles repel

Magnetic field – region around magnet or electric current where there is a magnetic force within the region

Magnetic flux – number of magnetic lines of force leaving or entering the poles of a magnet

Flux Density -- # flux lines per unit area. The Greater flux density, the greater field intensity.

Intensity of magnetic field is related to magnetic force



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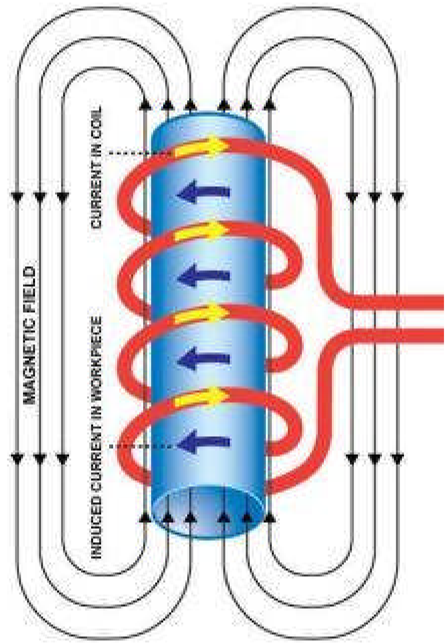
AC Motor

<u>Electricity and Magnetism</u>

Electric current is generated in a wire by moving current through a magnetic field

Electric current produces magnetic field

Electromagnet creates magnetic field from electric current moving through the coils



***The <u>higher</u> the number of turns in a coil, the <u>stronger</u> the magnetic field that is developed around it.*

***With fixed number of coil, magnetic field strength is <u>directly proportional</u> to the amount of current flowing within the coil*

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AC Motor

What are the characteristics of magnetic lines of force ? Magnetic lines of force are

- Continuous & always form closed loops
- Do no cross one another
- Parallel magnetic lines travelling in same direction repel one another
- Parallel magnetic lines travelling in opposite directions unite with each other to form single lines
- Magnetic lines existing between two unlike poles causes the poles to pull together
- Pass through all materials, both magnetic and non-magnetic
- Leave magnetic material at right angles to the surface

VFD BASIC

AC Motor

AC motor operates by creating magnetic field that rotates around rotor

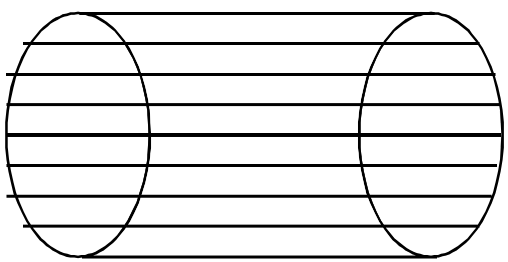
There stator and rotor are **not** directly connected

Energized stator creates rotating magnetic field around rotor bar

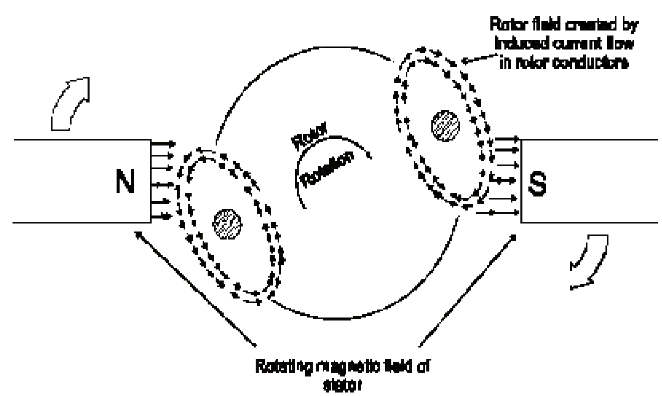
Magnetic field in Rotor bar interact with magnetic field of stator causing both to rotate

Induced voltage causes current flow in rotor bar

Amount of induced voltage depends on flux and speed



Squirrel Cage Rotor (Motor)



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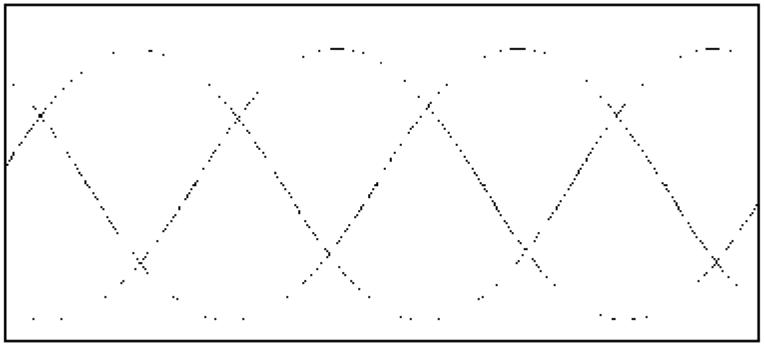
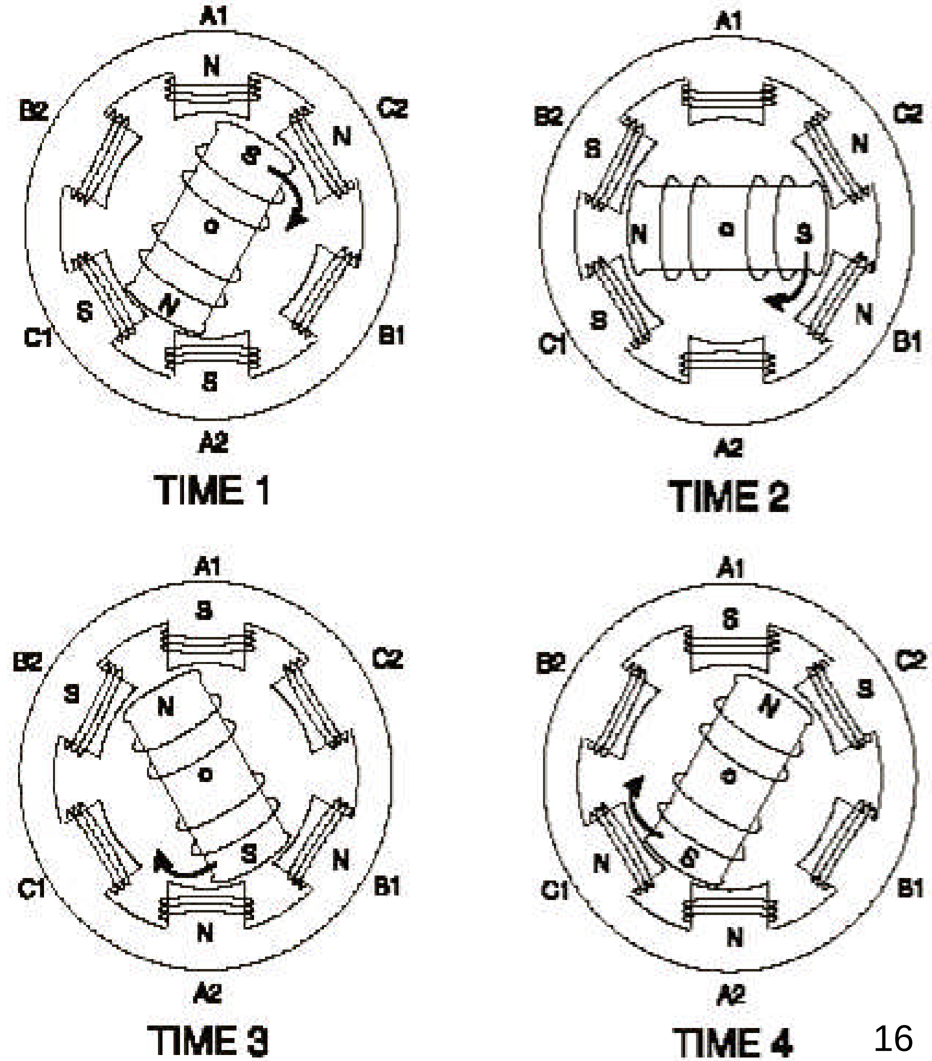
Rotating Magnetic Field





By progressively changing stator pole polarity a rotating magnetic field is created

VFD BASIC

AC Motor

Speed (RPM) – number revolution per unit time frame

Torque (ft.lb) – turning power of motor

Horsepower (hp) – combination of both torque and speed

Slip = Speed of synchronous speed (rotating magnetic field) – Rotor Speed, difference between synchronous speed and actual speed

Motor Base Speed (RPM) = Synchronous Speed - Slip

$$= \frac{120 \times \text{Applied Frequency}}{\text{\# Poles per Phase}} - \text{Slip}$$

Slip is necessary to create torque

Frequency is the variable in the above formula

Thus, we use variable frequency drives (VFD) to control speed of motor

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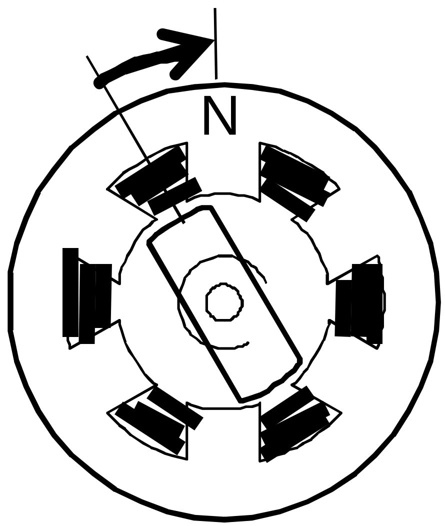
Synchronous Speed



Sync Speed = $\dfrac{\textbf{120 X Applied Frequency}}{\textbf{Number of Poles Per Phase}}$

Example for 2 poles motor:

At 60 Hz: (120 X 60Hz)/2= 3600RPM

At 30 Hz:(120 X 30Hz)/2= 1800RPM

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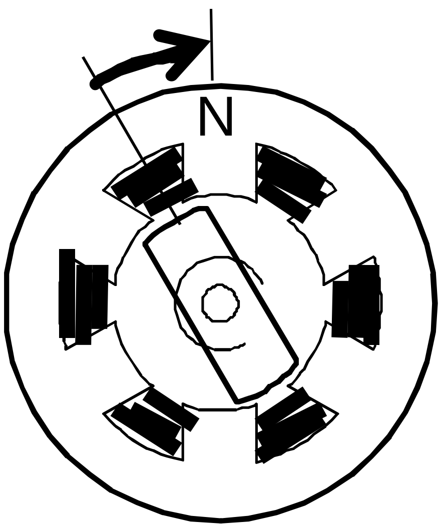
Motor Base Speed (Nameplate Speed)

Motor Base Speed (RPM) = $\dfrac{\textbf{120 X Applied Frequency}}{\textbf{Number of Poles Per Phase}}$ **- Slip**



= $\dfrac{\textbf{120 X 60 Hz}}{\textbf{2}}$ **- Slip**

= 3600 RPM - 40 RPM

= 3560 RPM

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AC Motor

Turn to the Experts.

Rotor

Connected to External device

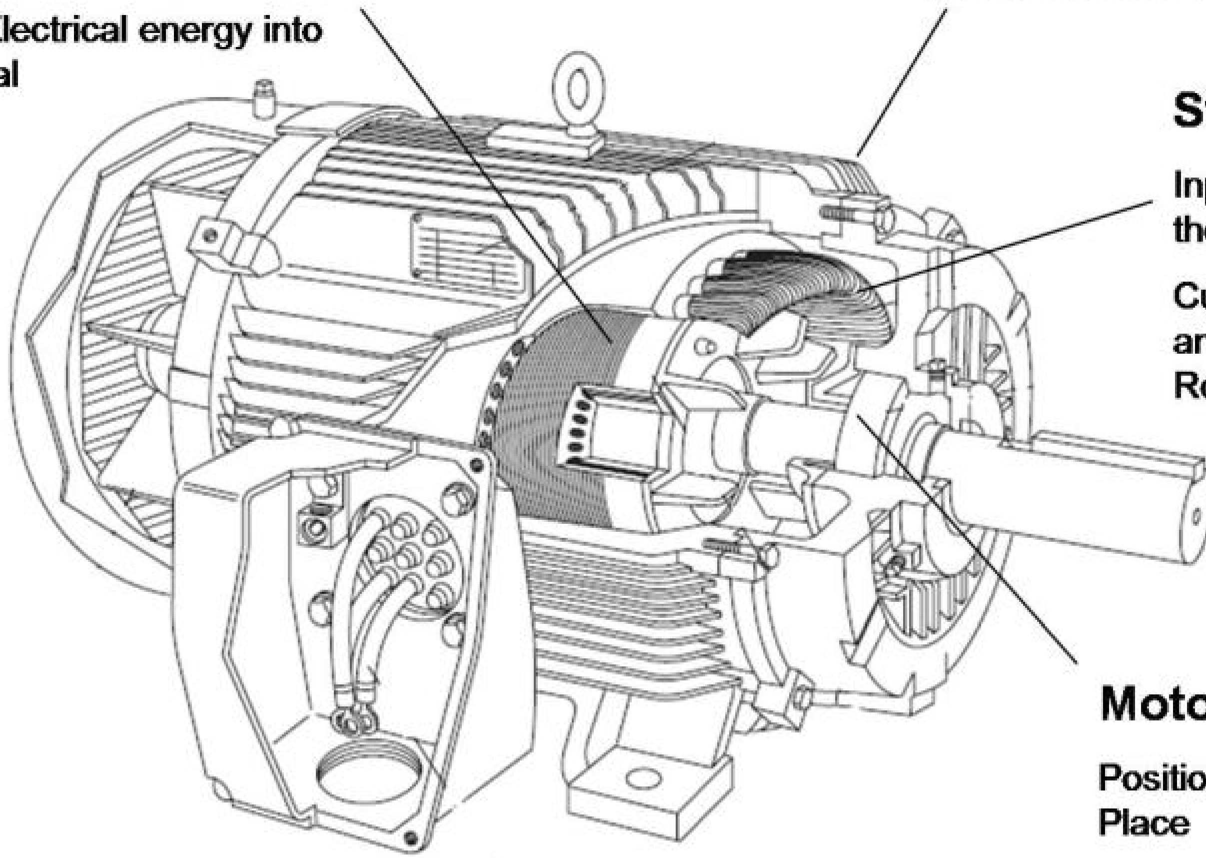
Transfer Electrical energy into mechanical

Motor Housing

Stator Windings

Input connected to these windings

Current flows through and induces voltage on Rotor



Motor Bearing

Position Stator in Place

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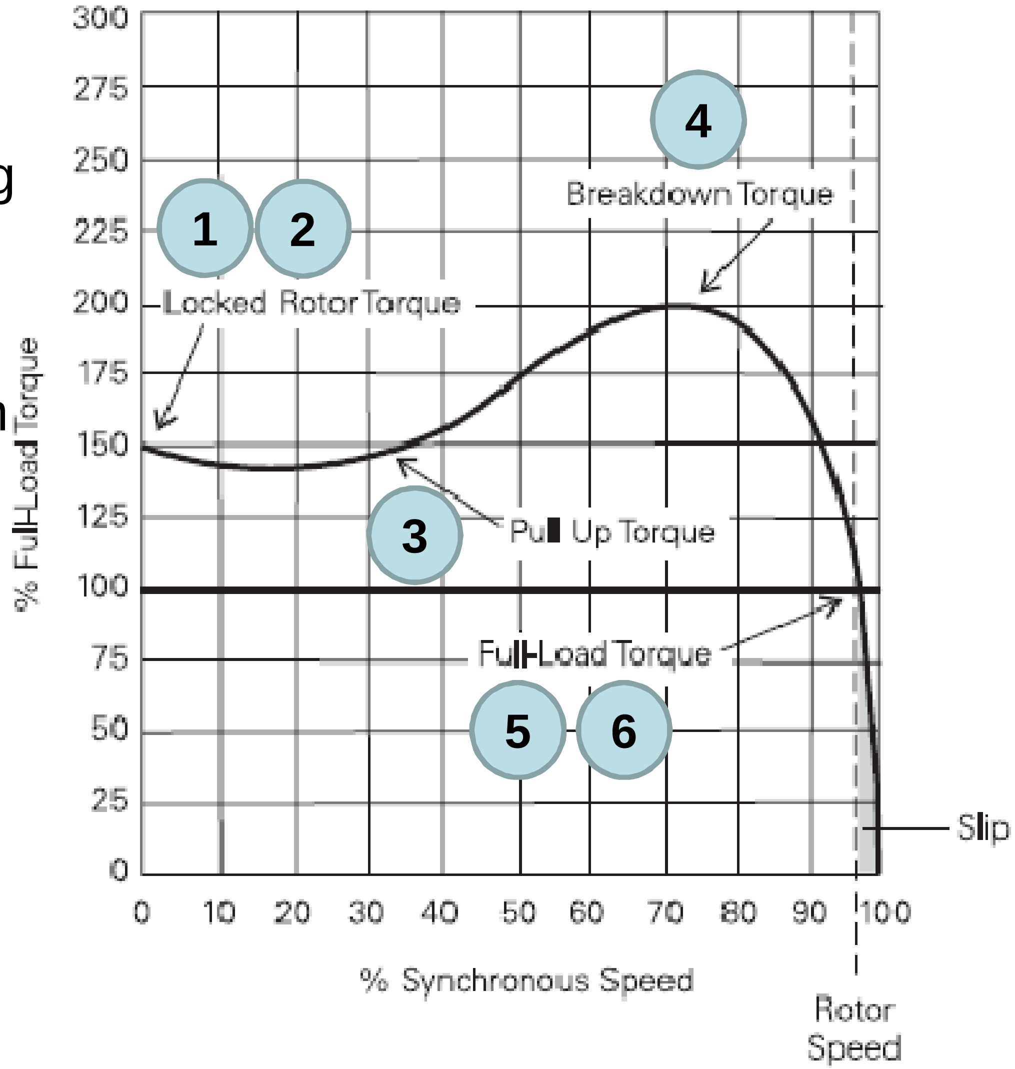
NEMA – Rotor Characteristics

National Electrical Manufacturers Association

1. Locked Rotor Torque – starting torque
2. Locked Rotor Current – starting current
3. Pull Up Torque – acceleration from start to breakdown torque
4. Breakdown Torque – maximum torque without abrupt loss of speed
5. Full Load Torque – motor at rated voltage, frequency, load
6. Full Load Current – supply line current at rated voltage, frequency, load



NEMA – Motor Type Classifications

National Electrical Manufacturers Association

Design A – No Limit on LRA, used at higher LRA for low slip & higher efficiency, unstable at high load condition

Design B -- most common and most suitable for AC drives, applied in variable torque, constant toruqe and constant horsepower, good efficiency, low slip

Design C – high starting torque, higher slip, high pull up torque, no use with VFD

Design D – high impact, high starting torque, high inertia load. High LRT, high slip, low efficiency

Speed & Torque – load change affect slip & torque. When Load increase, slip & torque increase, vise versa

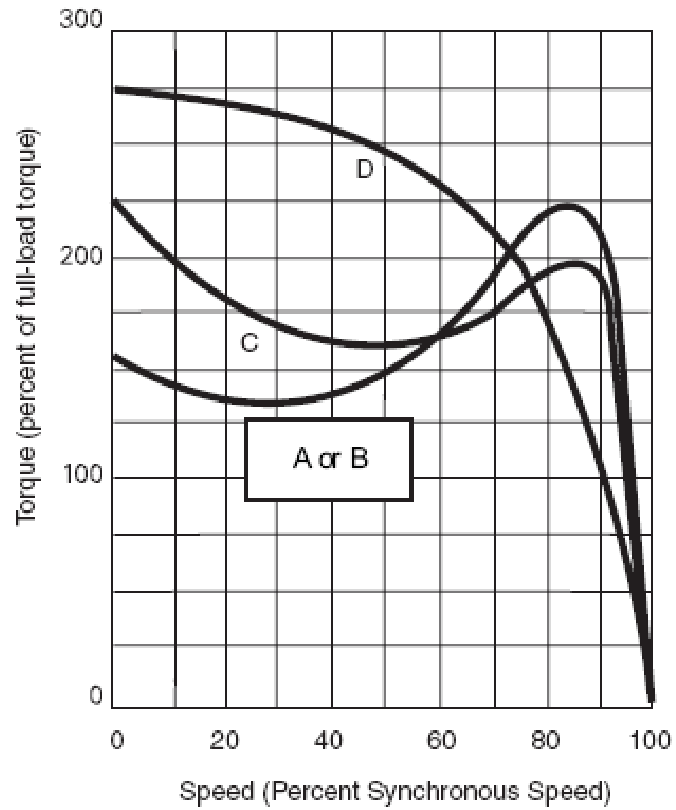


Figure 2-8: Typical Motor Speed Torque Curves

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Electrical Basics

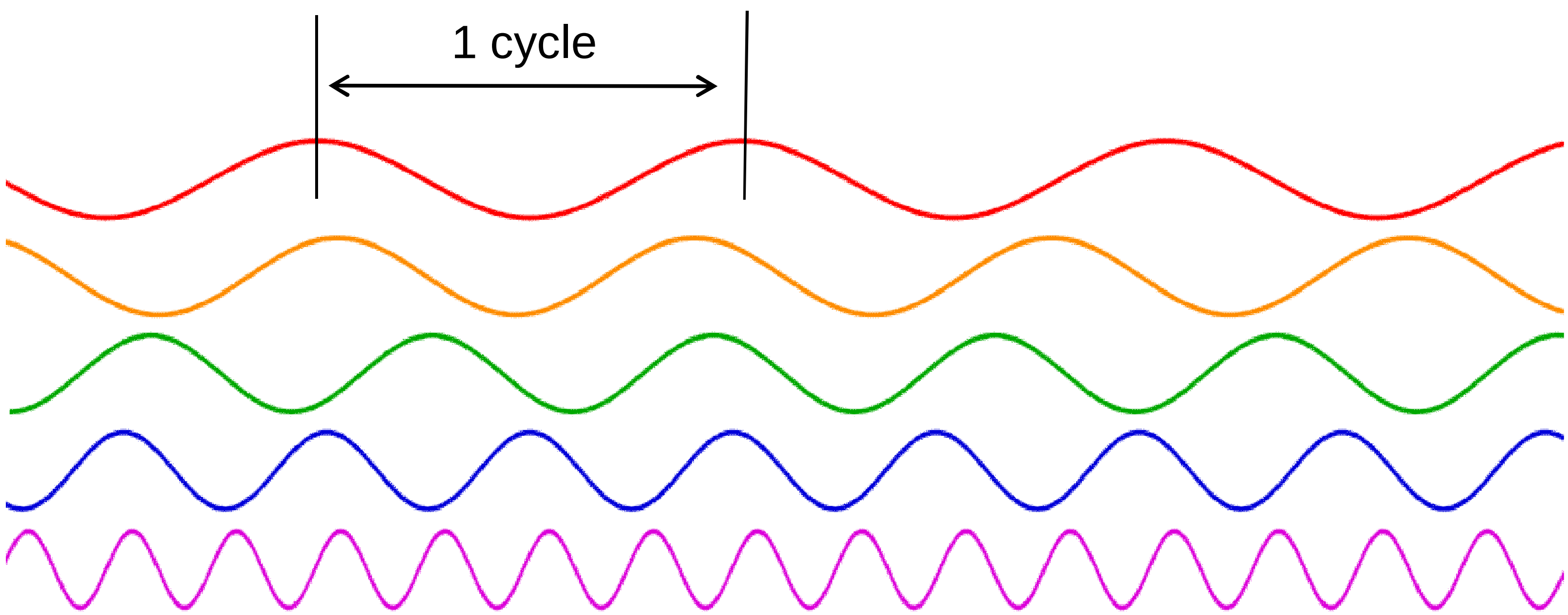
Frequency

of complete cycles of an AC signal per second

Measured in Hertz

60HZ – sixty complete cycles per second

T=1/F=1/60=0.0167 seconds per cycle



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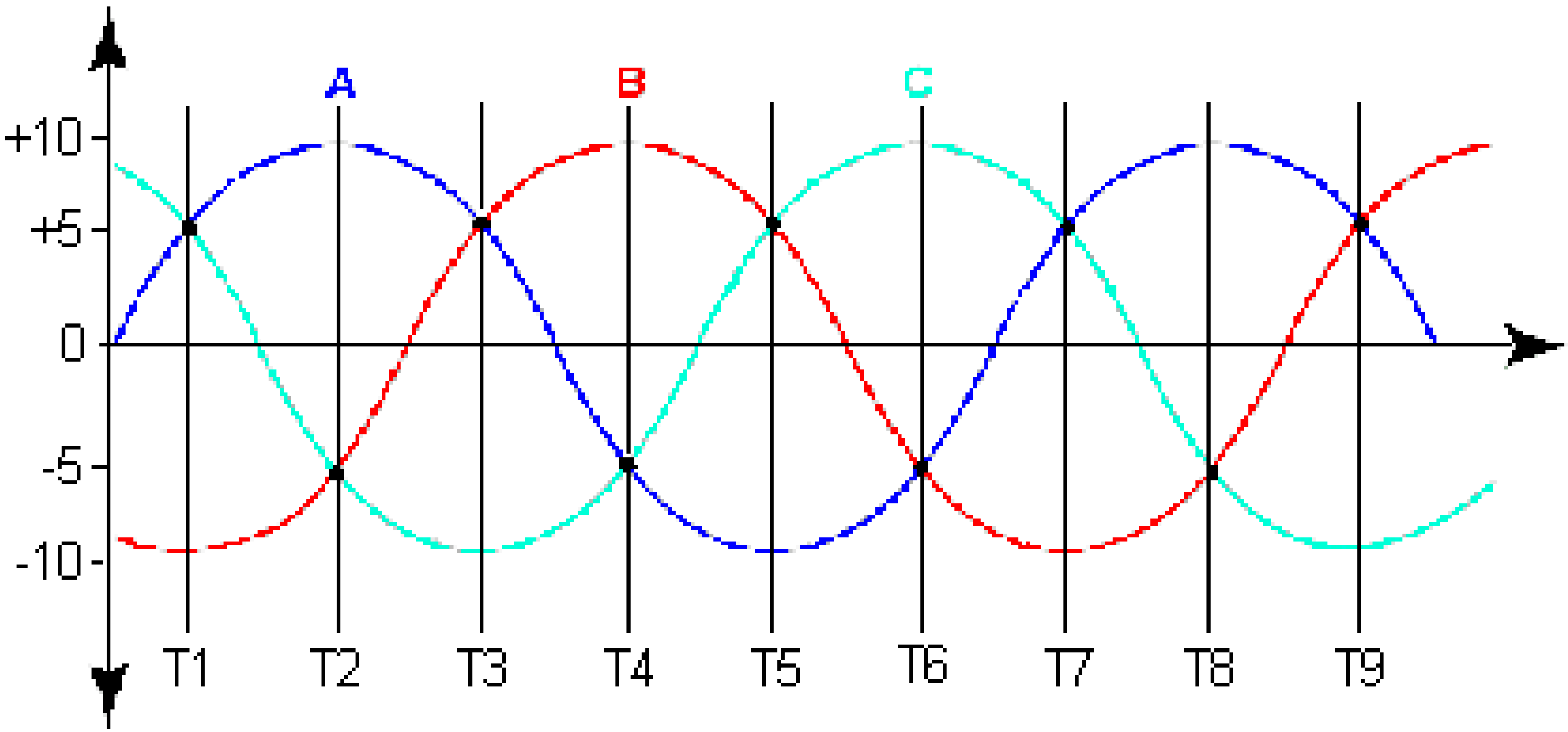
Electrical Basics

A three phase power supply is made up of three separate cycles of power that intersect the other two phases four times every 360 electrical degrees.



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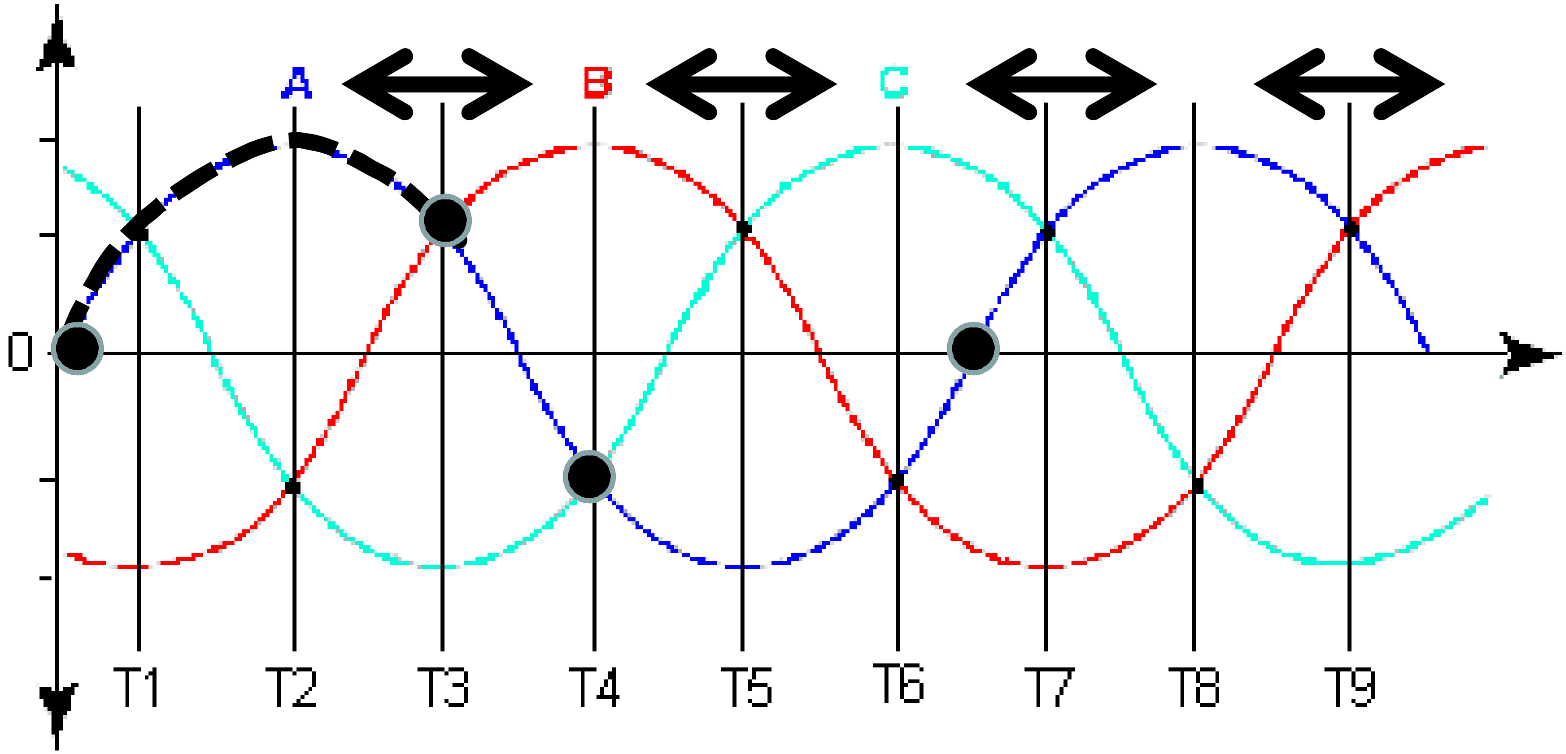
Electrical Basics



Each phase of power is separated by 120 electrical degrees

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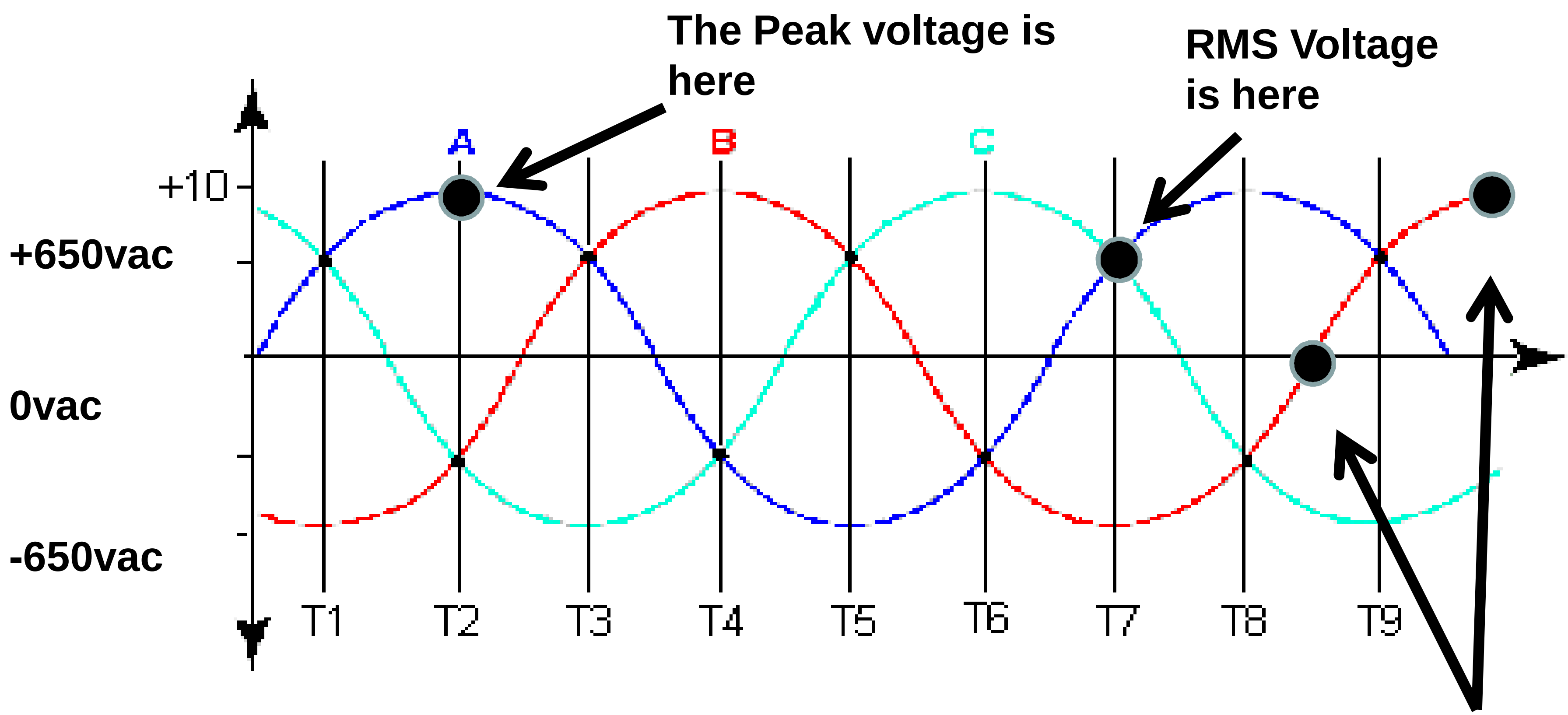
Electrical Basics

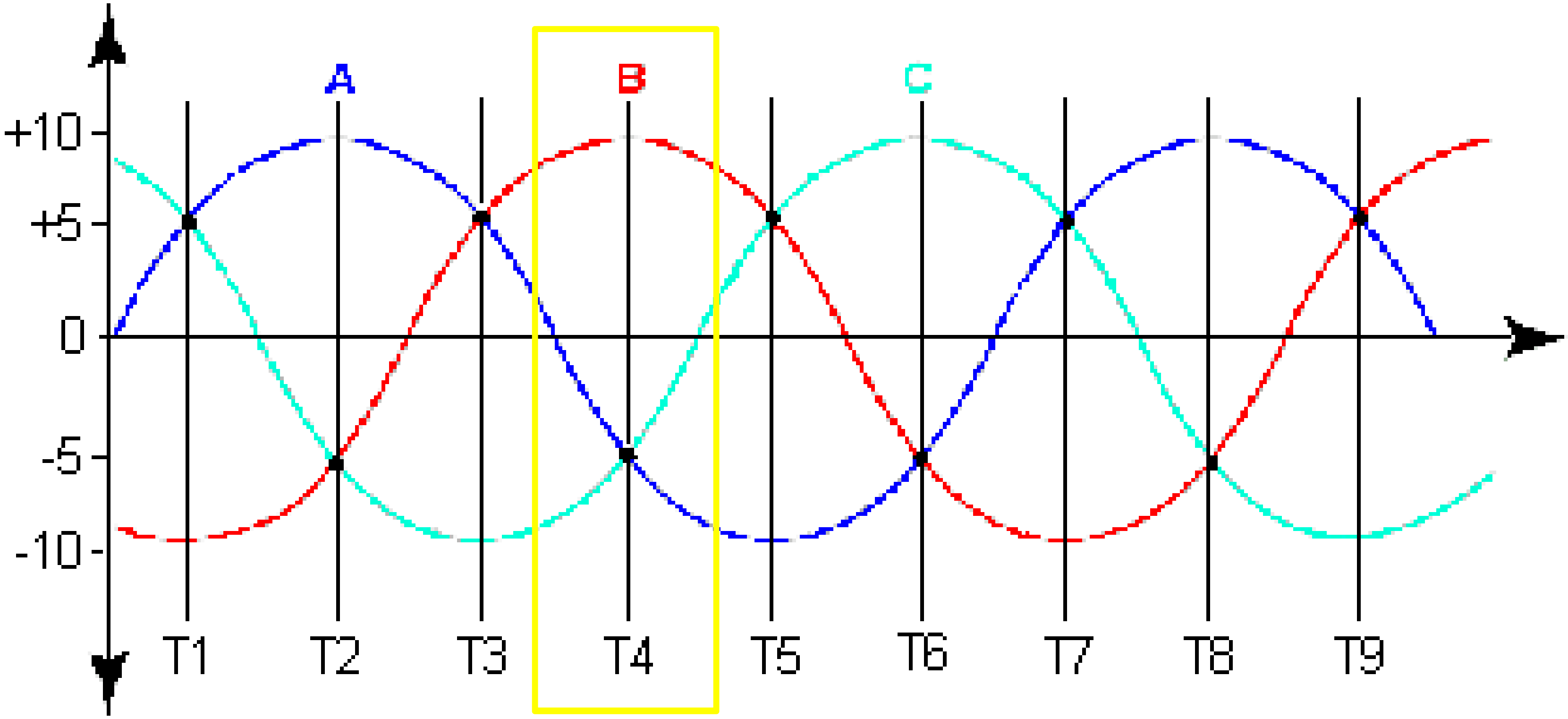


The RMS Voltage is the average of the voltage from the 0 axis to the peak of the sine wave for a particular phase which is the value you will read with your volt meter.

For example: a 460vac RMS measurement will have a peak voltage of 650vac RMS Measurement is X 1.414 = 650vac

VFD BASIC

Electrical Basic: Kirchoff's Current Law

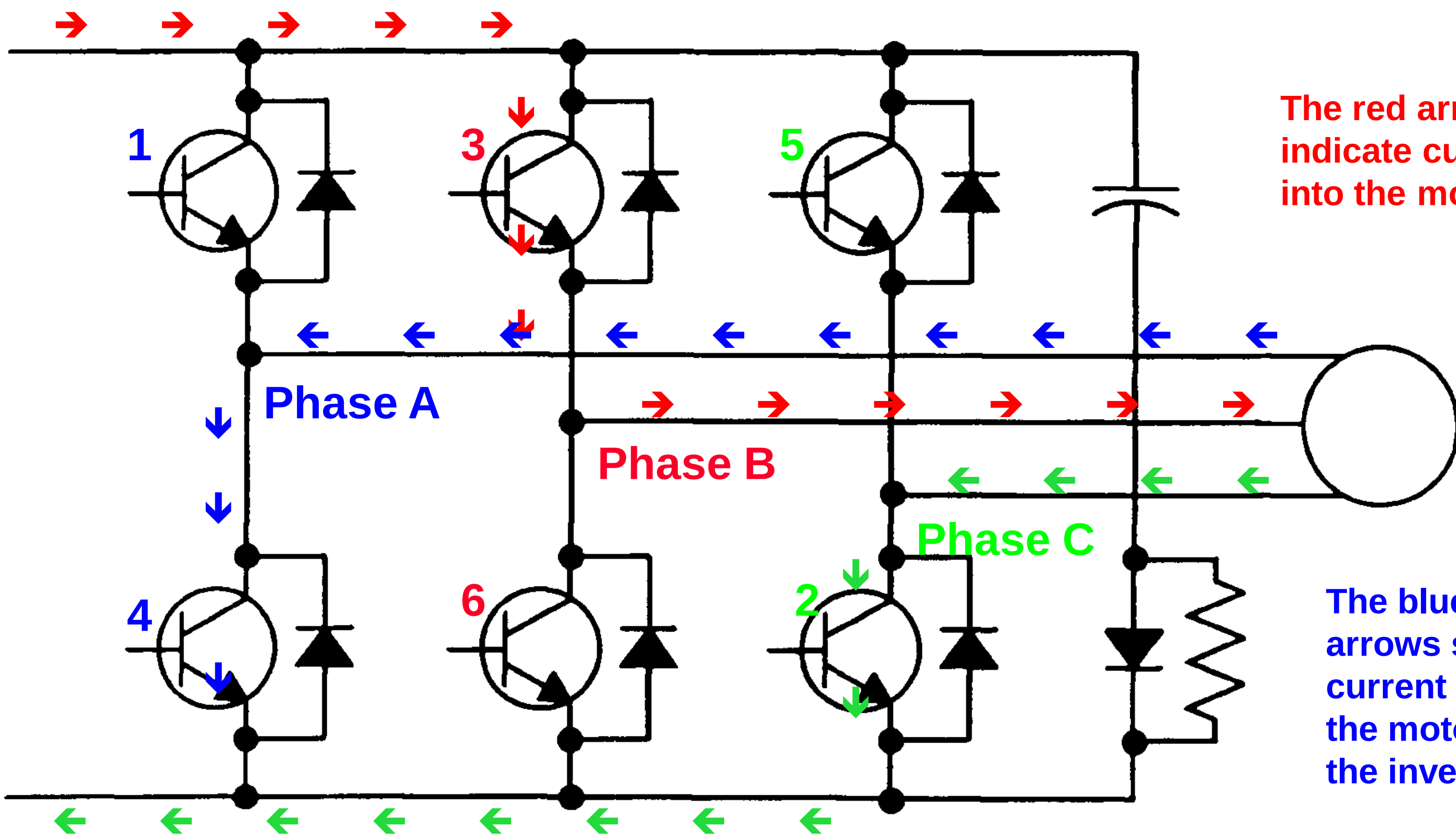


Kirchoff's current law – phase sum of all currents in/out must equal zero

Example:
A= -5; B= 10, C= -5
A + B + C = 0

VFD BASIC

Electrical Basic: Kirchoff's Current Law



The red arrows indicate current flow into the motor leads.

The blue & green arrows show current flow from the motor back into the inverter.

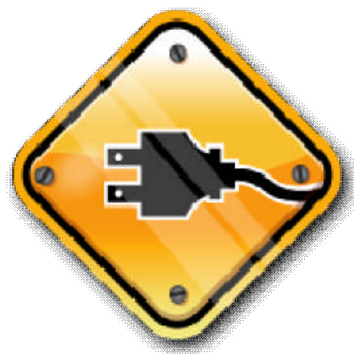
A= -5; B= 10, C= -5

A + B + C = 0

VFD BASIC

Electrical Basics -- Methods of Starting

- Across the line
- Autotransformer Reduced Voltage
- Primary Reactor
- Part Winding
- Wye Delta (Star Delta)
- Solid State Reduced Voltage
- Variable Frequency Drive



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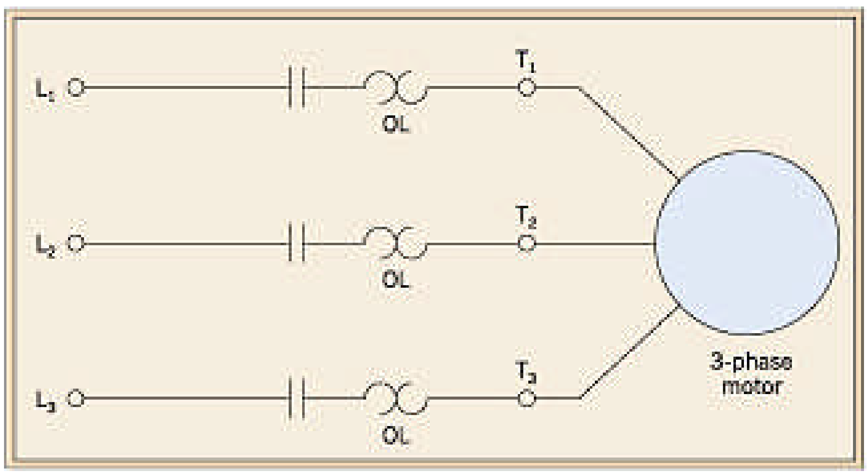
Electrical Basics -- Methods of Starting

Across the line starting

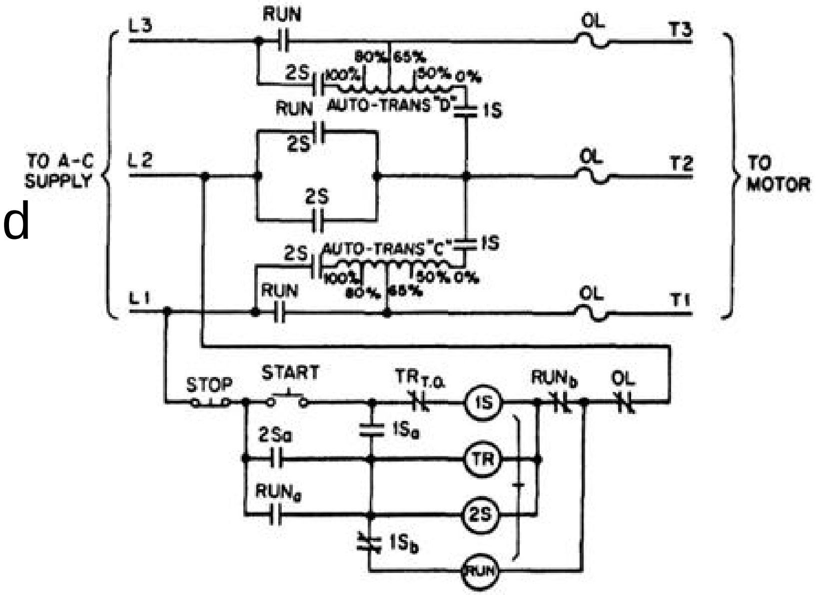
- Simplest and least expensive
- Motor Locked Rotor Amps drawn directly from line
- Inrush can be 6-8 times motor rated FLA
- More suitable for low voltage or medium voltage motor
- On multi compressor chillers, stagger on startup



Electrical Basics -- Methods of Starting

Autotransformer Reduced Voltage Starting

- Reduces inrush line current and motor starting torque by limiting voltage applied to windings
- Transformer within starter allow stepped acceleration
- Considered a soft start
- Start in steps
- Changing line voltage taps in transformer varies current draw from the line, voltage and current, and torque developed by motor



Electrical Basics -- Methods of Starting

Turn to the Experts.

Primary Reactor

- Like an autotransformer, reduces inrush line current and motor starting torque by limiting voltage applied to windings
- Use reactor or resistor instead
- More economical for medium voltage

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Electrical Basics -- Methods of Starting

Turn to the Experts.

Part Winding

- Also produce soft start
- Cost effective
- Can only be used with part winding motors that have two sets of identical windings for parallel operation
- Two step start – energize one winding first
- Not used on centrifugal chillers
- Mostly used on reciprocal compressors

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Electrical Basics -- Methods of Starting

Wye-Delta

Carrier
RediStart MX^3
Low Voltage Wye-Delta Motor Control

- Also called Star-Delta
- Reduce inrush line current and motor starting torque by switching motor windings connections
- Three contactors and timer change winding configuration from 33% current to full
- Low cost compared to reduced voltage type starter
- Most common for use with centrifugal chillers under 600 volts
- Only use in low voltage application

VFD BASIC

Electrical Basics -- Methods of Starting

Turn to the Experts.

Solid State

- Solid state devices used – SCR (silicon controlled recitifier)
- Electronic signal control current flow
- Used for both low voltage and medium voltage applications
- Programmable soft start

RediStart MX3

Low Voltage Solid State Motor Control

VFD BASIC

Electrical Basics – Variable Frequency

Vary motor speed by varying frequency of drive signal

Two basic AC drives

- Current Source Drives
- Voltage Source Drives

Voltage source drives

- Names – VFD, ASD, Inverters
- AC-DC-AC topology
- Same basic components –
  - Rectifier/Converter
  - Filter/Capacitors
  - Inverter

VFD BASIC

Rectifiers/Converter

Converts power from AC to DC using diodes, transistors, or silicon controlled rectifiers (SCR)

VFD using transistor in rectifier is said to have “Active Front End”

One rectifier allows power to pass through when voltage is positive, another allow power to pass through when voltage is negative

3 phase power will have minimum 6 rectifiers

6 pulse means 6 rectifiers

VFD may be 6,12,18, or 24 pulse

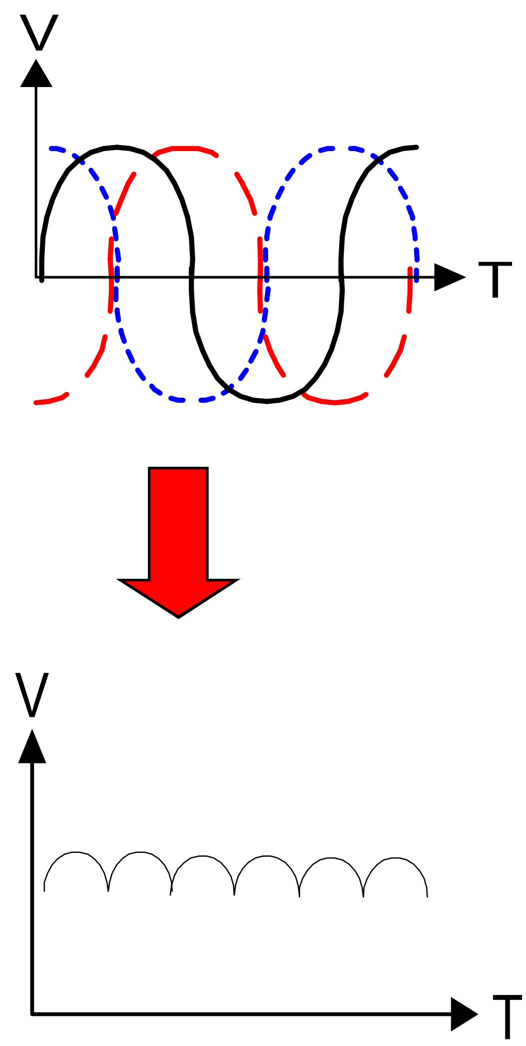
VFD BASIC

Silicon Controlled Rectifiers (SCR)

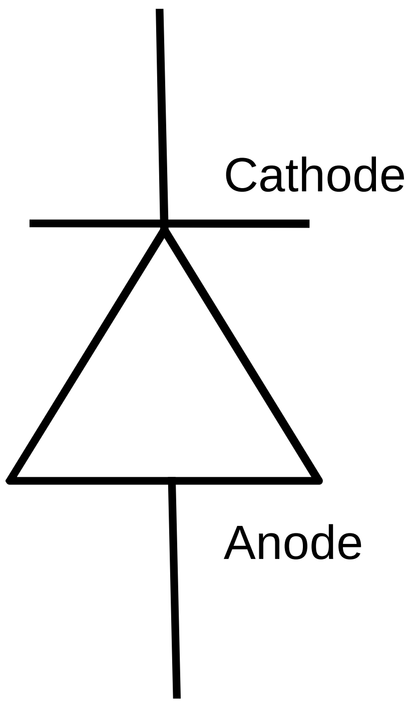
SCR Inverse Parallel Operation

- 1 SCR per ½ sign wave
- 1 negative, 1 positive
- 3 Phase requires 6 SCRs

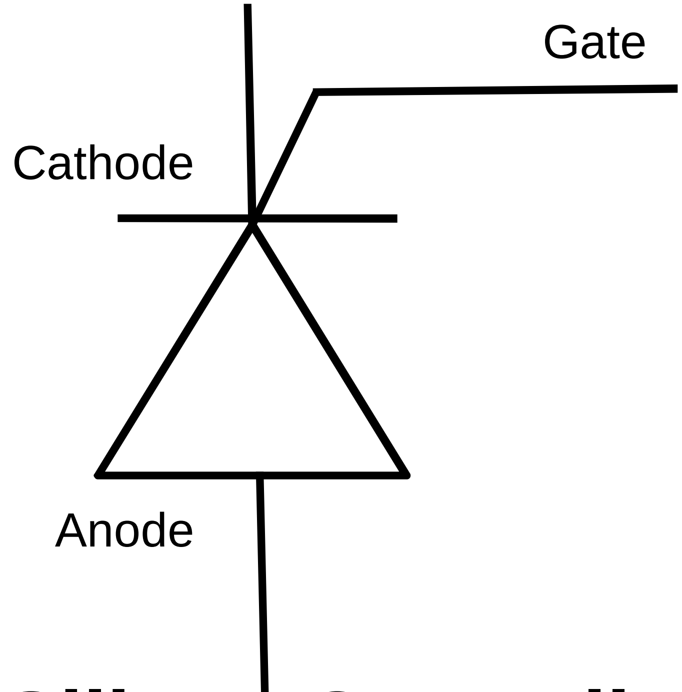
Rockwell utilizes a SCR Bridge consisting of six (6) SCR/ diode sets, 2 per phase.



Diode and SCR

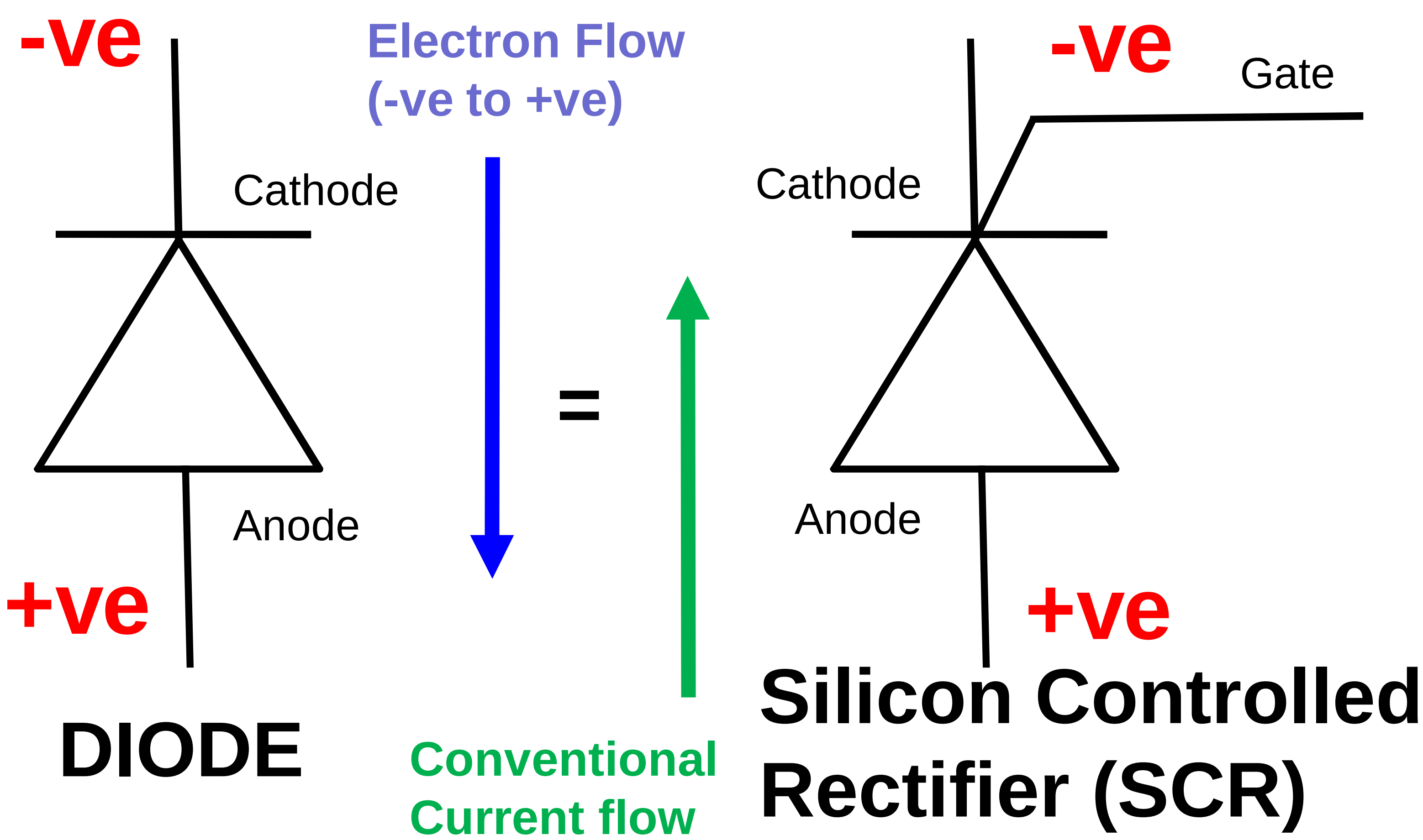


DIODE



Silicon Controlled Rectifier (SCR)

Diode and SCR



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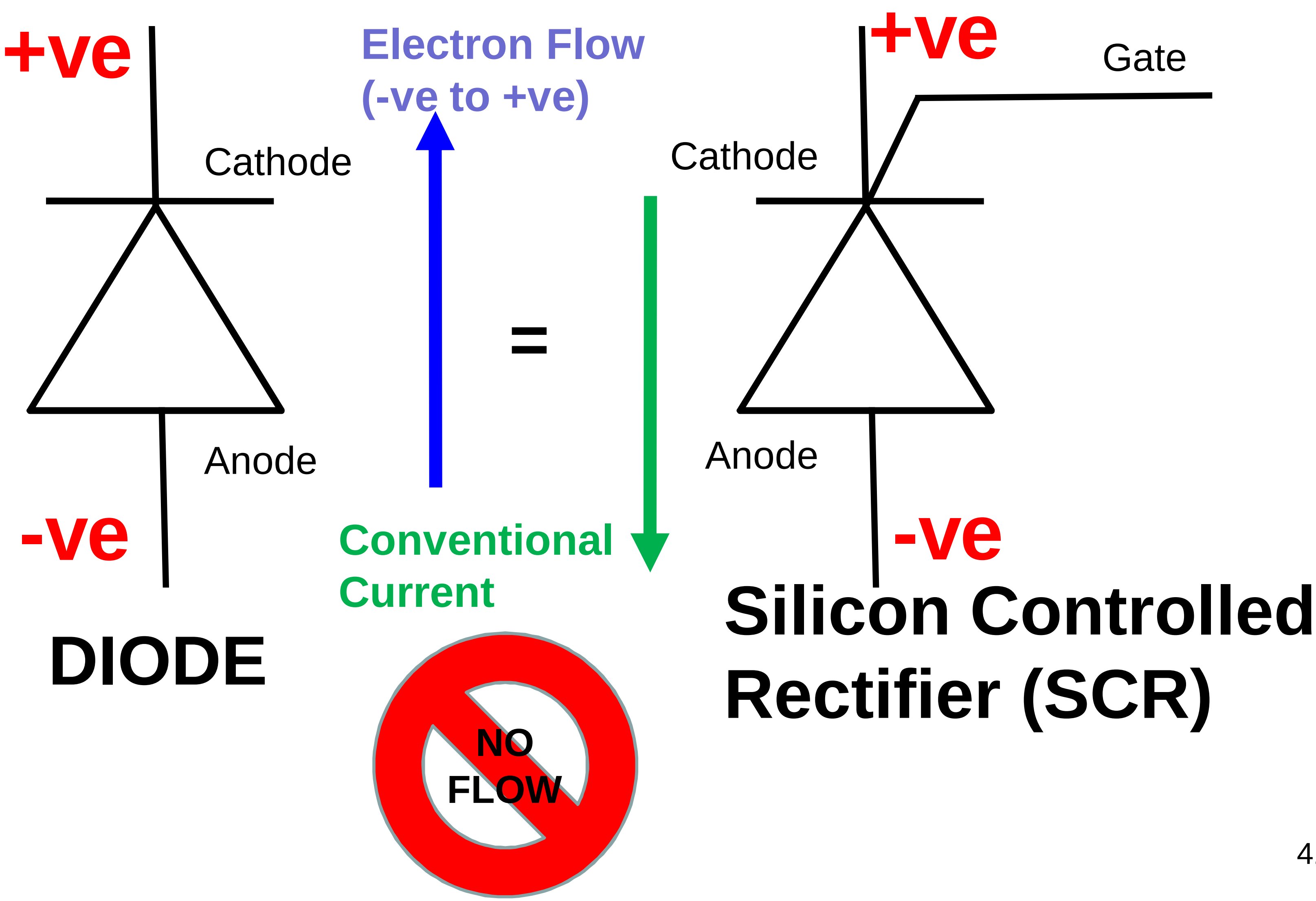
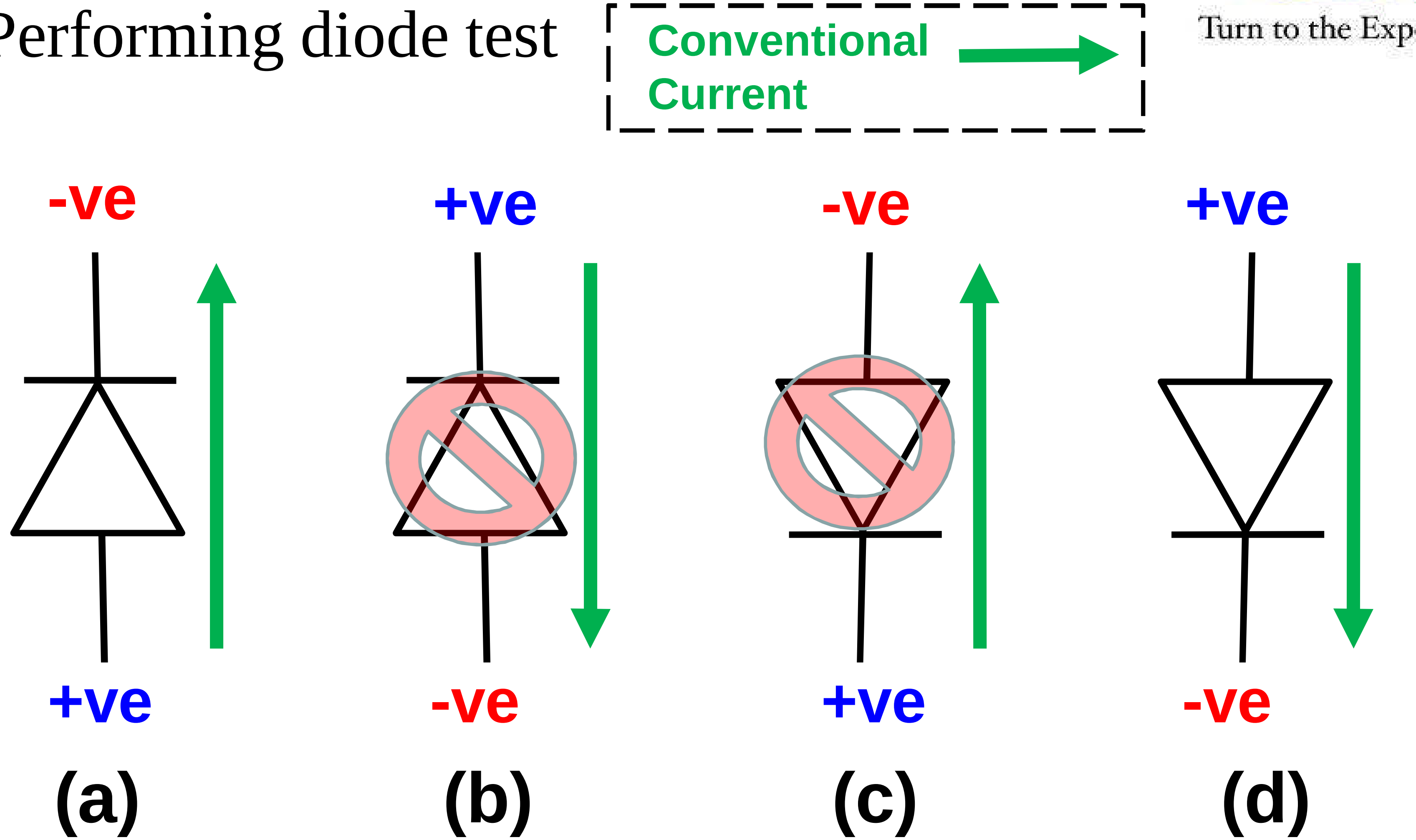
Diode and SCR



VFD BASIC

Performing diode test



When performing diode test on VFD, "-ve" and "+ve" shown above will be the leads on your meter

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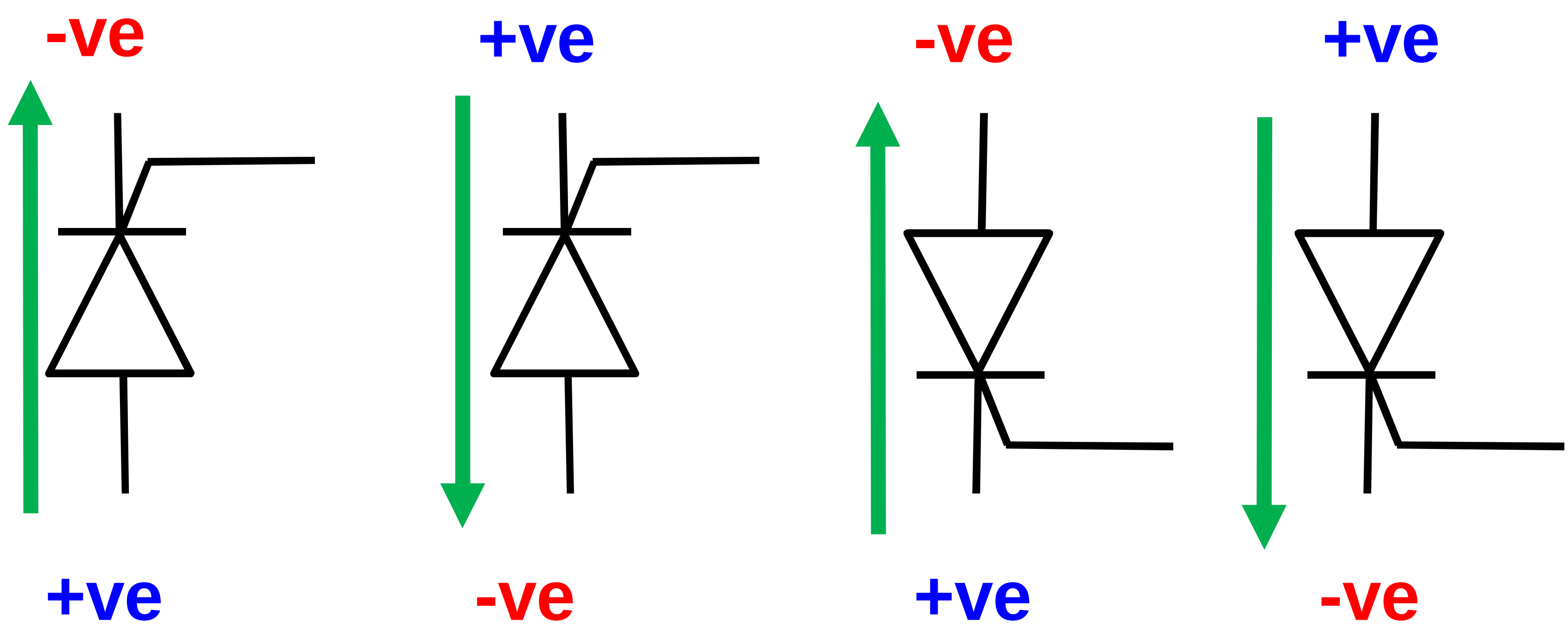
Performing diode test

Conventional Current →



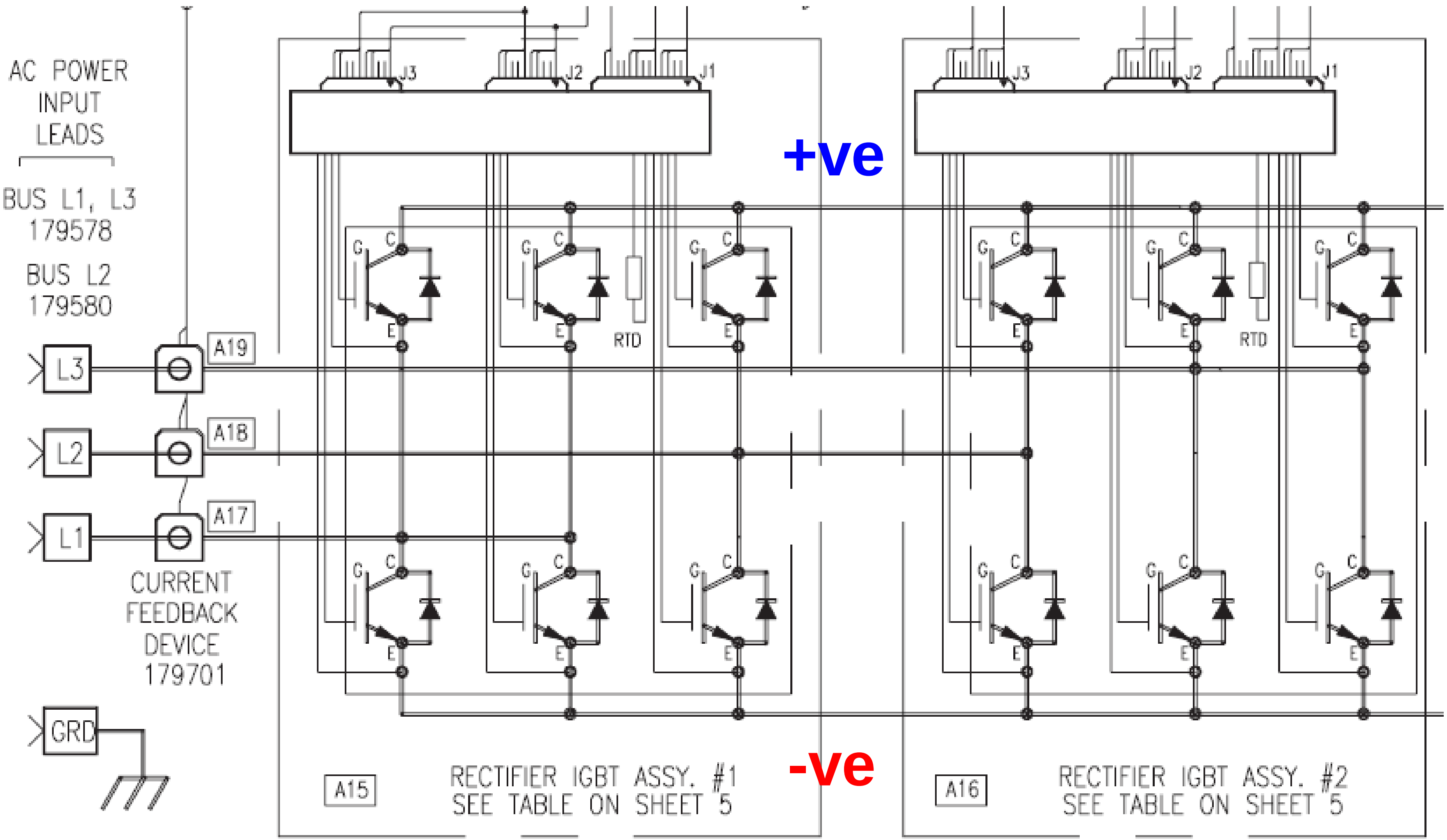
(a) (b) (c) (d)

When performing diode test on VFD, "-ve" and "+ve" shown above will be the leads on your meter

VFD BASIC

Performing diode test

Turn to the Experts.



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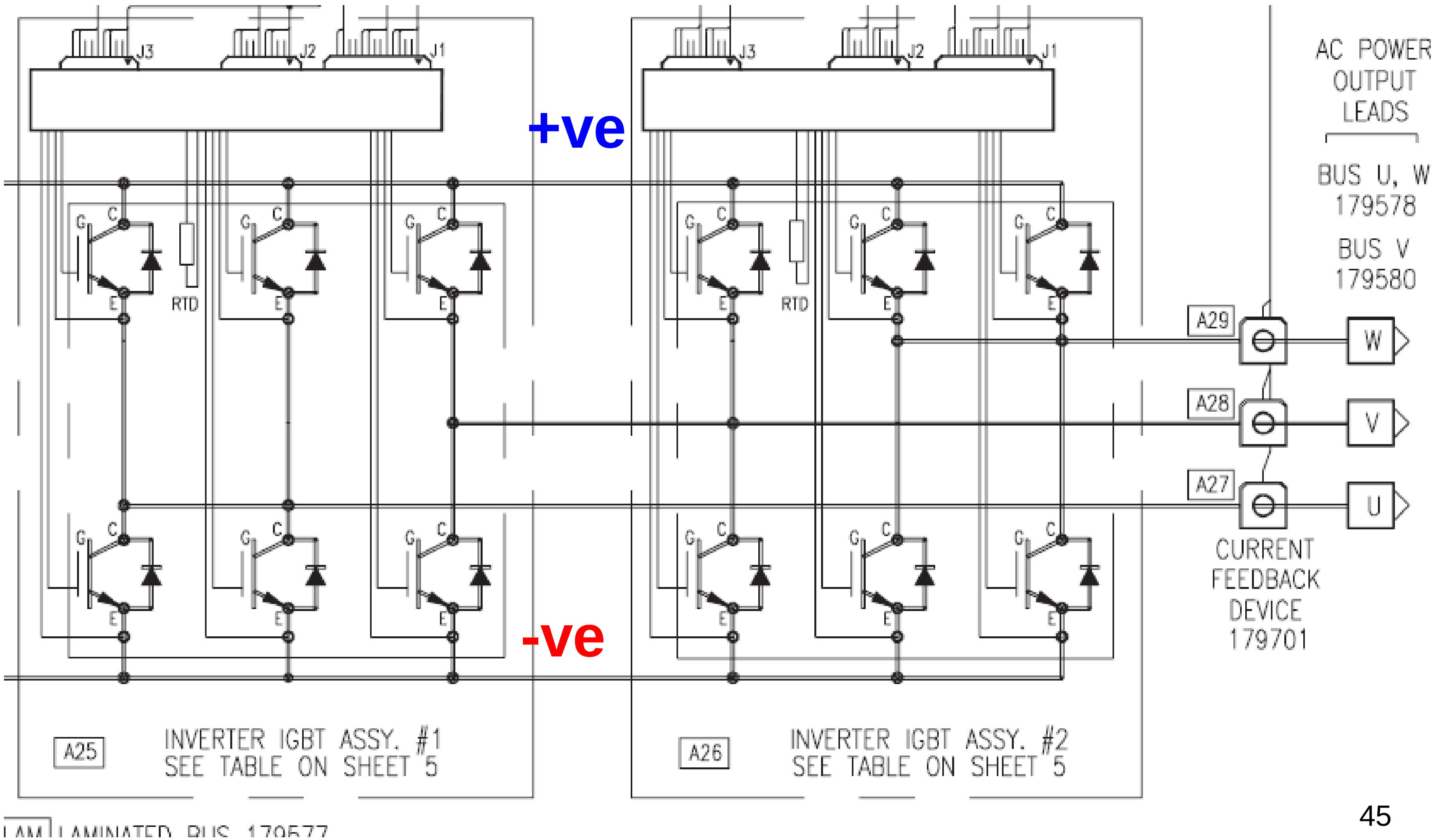
Performing diode test



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Performing diode test

Table 7 — Diode Checks

METER LEAD (+)	METER LEAD (-)	METER READING
R	DC+	0.5 V
S	DC+	0.5 V
T	DC+	0.5 V
R	DC-	infinite (OL)
S	DC-	Infinite (OL)
T	DC-	Infinite (OL)
U	DC+	0.5 V
V	DC+	0.5 V
W	DC+	0.5 V
U	DC-	infinite (OL)
V	DC-	Infinite (OL)
W	DC-	Infinite (OL)
DC+	R	Infinite (OL)
DC+	S	Infinite (OL)
DC+	T	Infinite (OL)
DC-	R	0.5 V
DC-	S	0.5 V
DC-	T	0.5 V
DC+	U	Infinite (OL)
DC+	V	Infinite (OL)
DC+	W	Infinite (OL)
DC-	U	0.5 V
DC-	V	0.5 V
DC-	W	0.5 V

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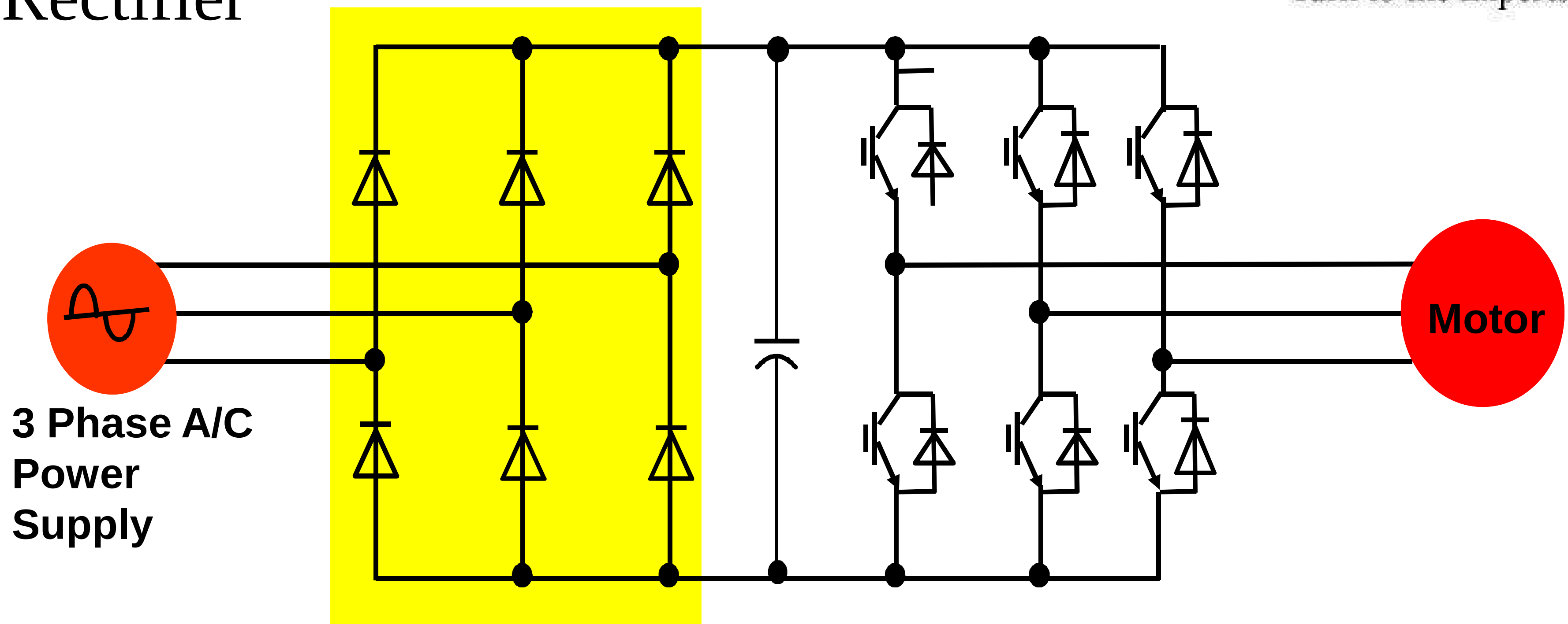
Rectifier



The rectifier section of the drive takes three phase a/c power and converts it to single phase d/c power

One rectifier for positive voltage, one rectifier for negative voltage, 2 rectifiers per phase

3 phase power will required minimum 6 rectifiers (6 pulses)

May contain diodes, SCR, or transistors

VFD BASIC

DC Bus Capacitor

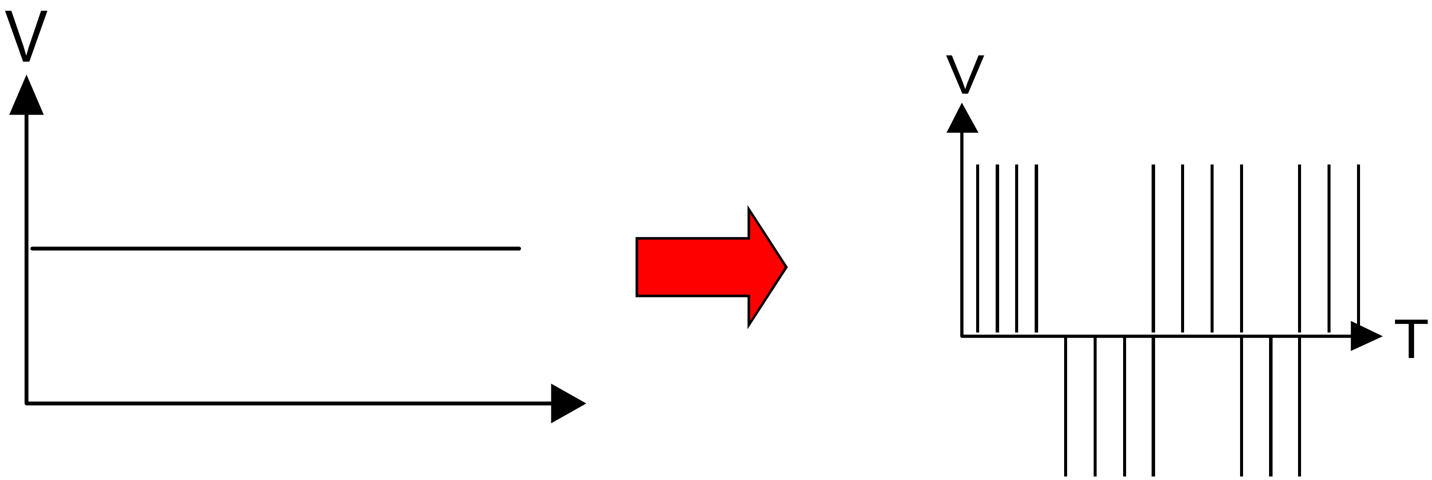
Turn to the Experts.

- Filter ("Smoothes out") the DC Voltage ripple
- Capacitor resists an abrupt change in voltage
- Stores energy when a voltage appears across it
- When rectifier output drops off, the capacitor will take over and furnish the load
- May contain inductors, dc links, chokes etc to smooth out incoming power to DC bus
- Change out power module if capacitor leaks

VFD BASIC

Inverter

- Change DC waveform back to AC
- Create sine wave to motor using pulse width modulation (PWM)
- IGBT – Insulated Gate Bipolar Transistor



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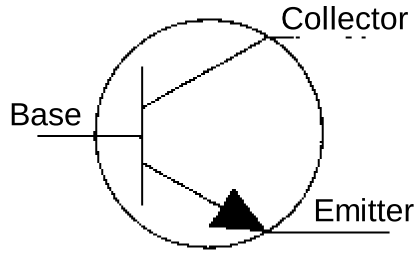
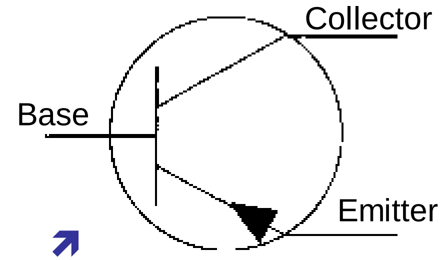
Transistor

A transistor is a solid-state device using the element silicon or germanium.

NPN Transistors

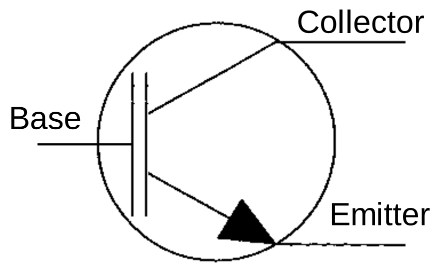


PNP Transistors

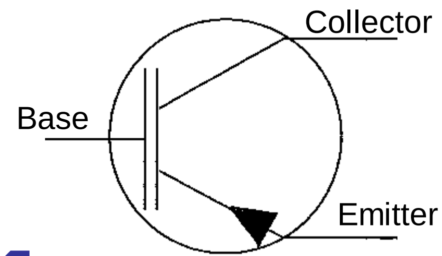


Standard Transistors

NPN IGBT



PNP IGBT



IGBT Transistors

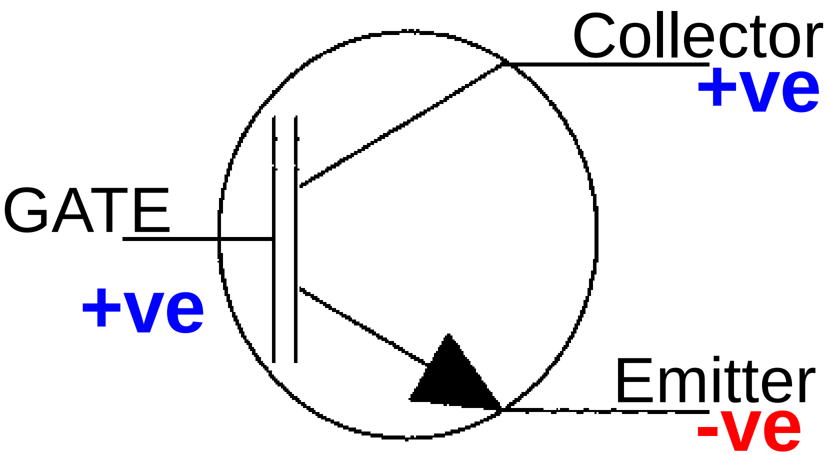
Double line on base if IGBT transistors

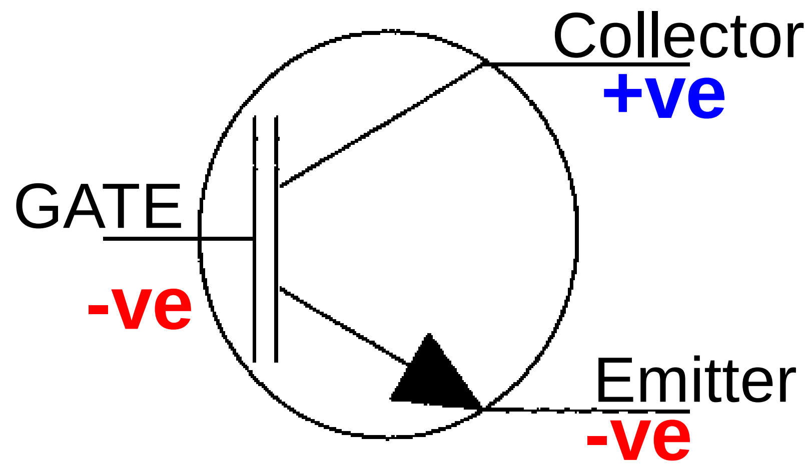
Insulated gate bipolar transistor – separate base from other transistors to prevent leakage current through base of emitter/collector

IGBT insures 100% current flows through emitter & collector

VFD BASIC

Insulated Gate Bipolar Transistor (IGBT)





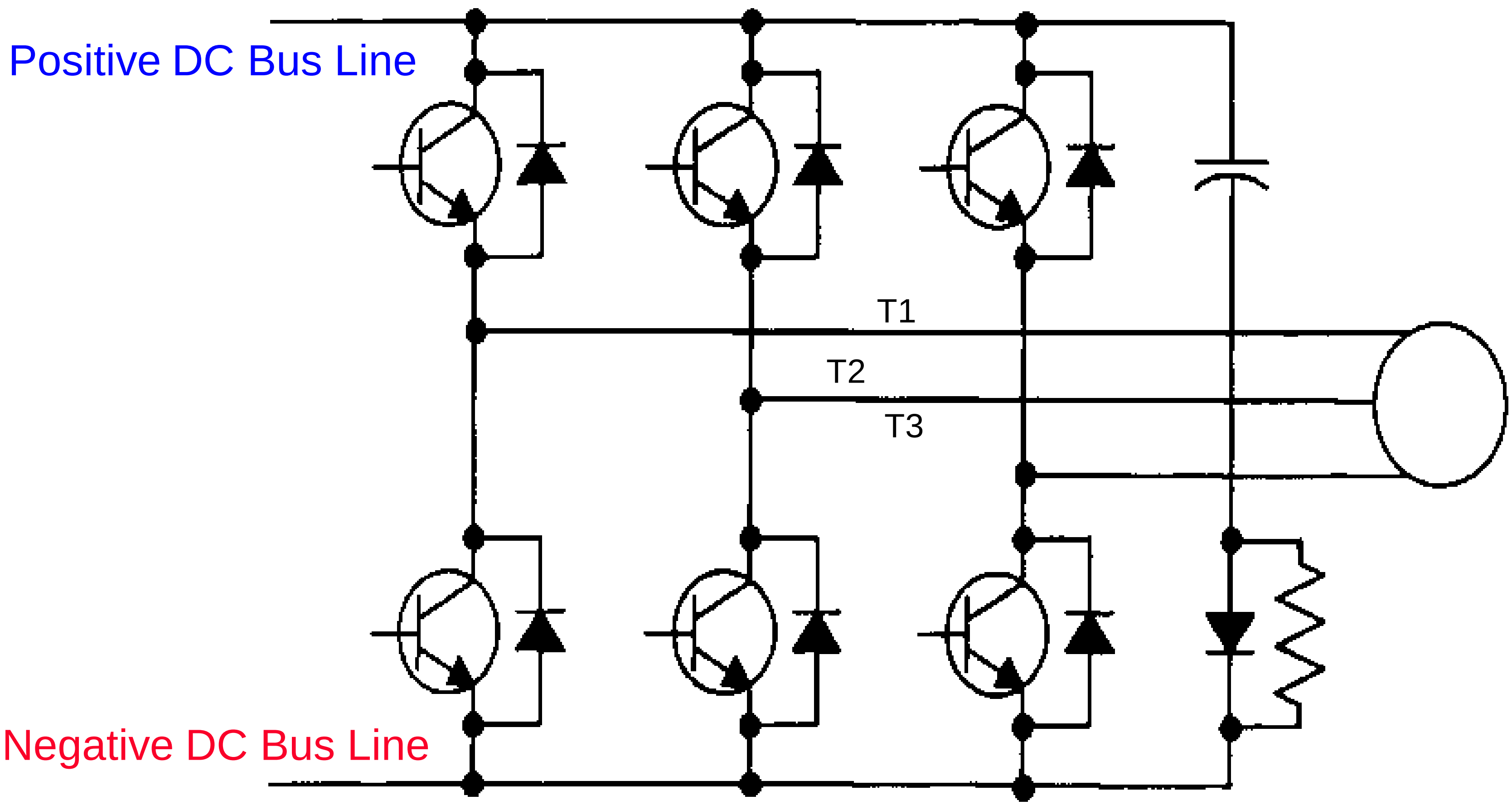
Flow

High switching capabilities

IGBT can switch on/off several thousand times per second

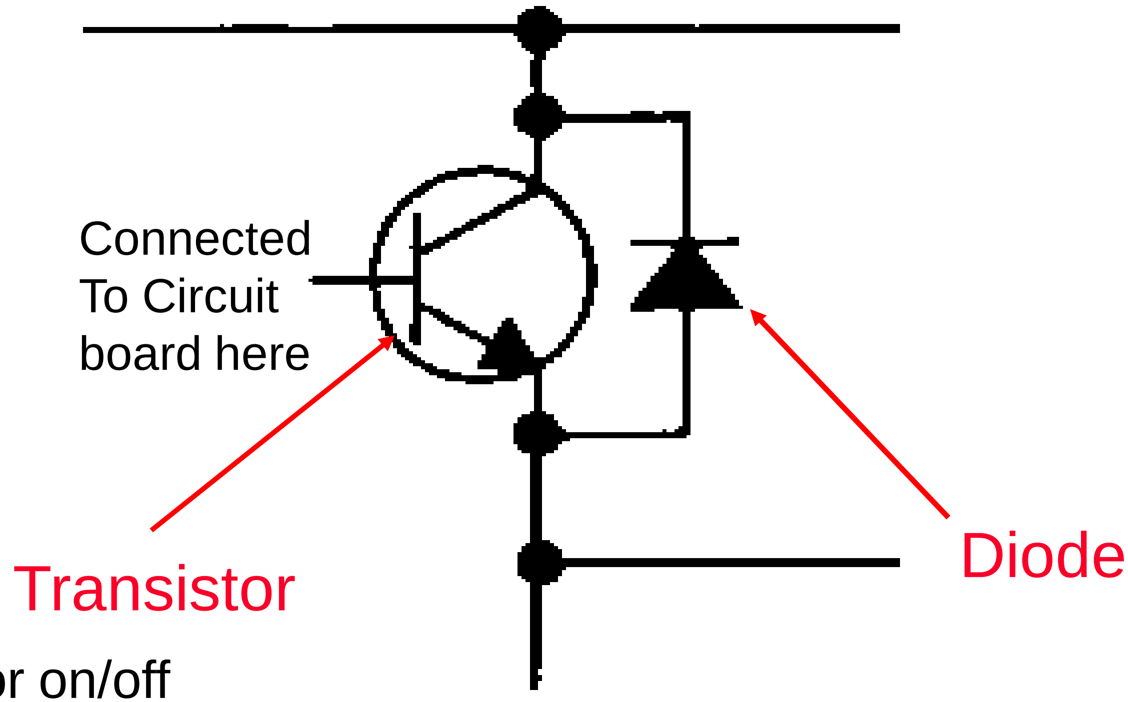
VFD BASIC

Inverter



VFD BASIC

Transistor & Diode



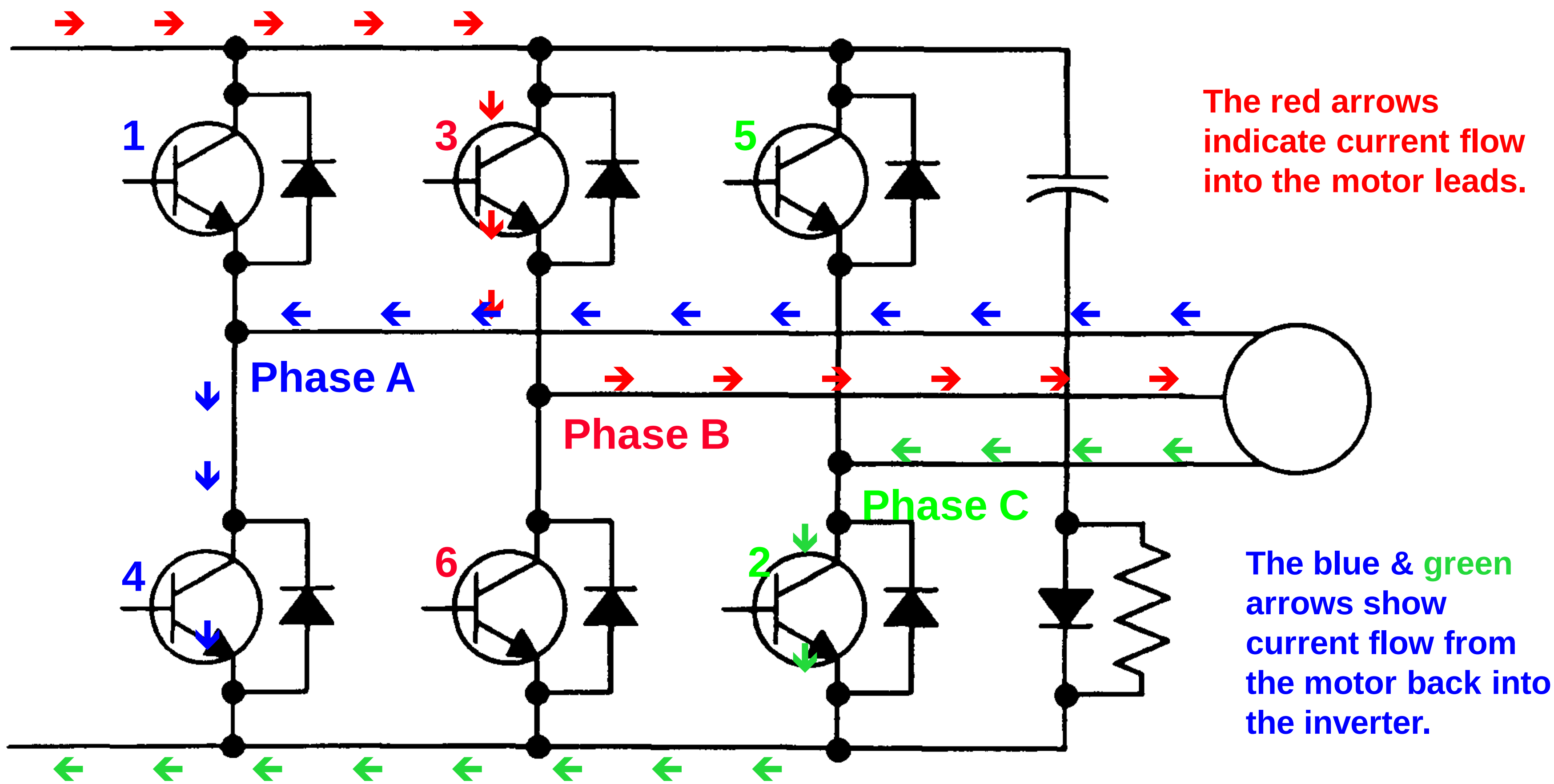
Transistor on/off

- Longer ON Pulses – higher voltage
- Longer OFF Pulses – lower voltage
- Switching frequency – Speed pulses On/Off
- 2KHZ – 2000 times per second

The duration and speed of pulses combined is what is known as Pulse width modulation (PWM)

Higher frequency – smoother waveform, more heat

Electrical Basic: Kirchoff's Current Law



Notice that phase "A" transistor #1 is turned off & transistor #4 turned on, phase "C" transistor #2 & phase "B" transistor #3 remained on.

VFD BASIC

Pulse Width Modulation (PWM)

Simulated sine wave at desired frequency

$$\textbf{Speed} = \frac{\textbf{120 X (Frequency)Hz}}{\textbf{Number of Poles Per Phase}}$$

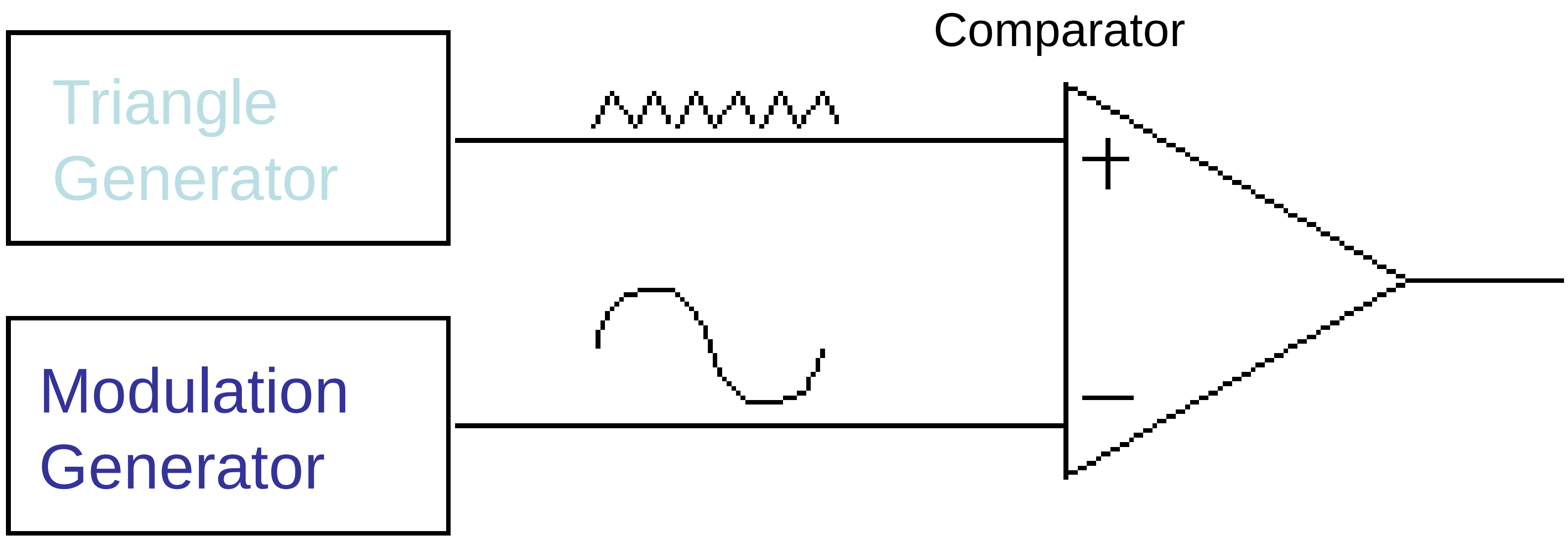
Electronically control a series of pulses creating a signal that closely resembles a sine wave

Drive controls when IGBT is switched on/off, and how long it is held on (width)

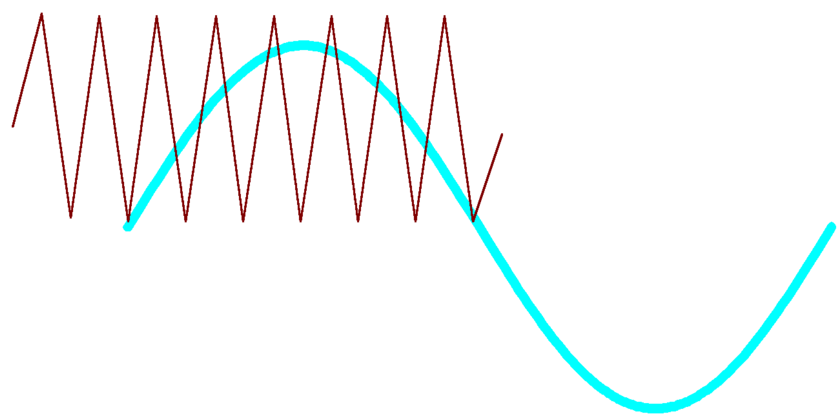
Wide pulses=high voltage, narrow pulse=low voltage

VFD BASIC

VFD -- Rockwell Drives

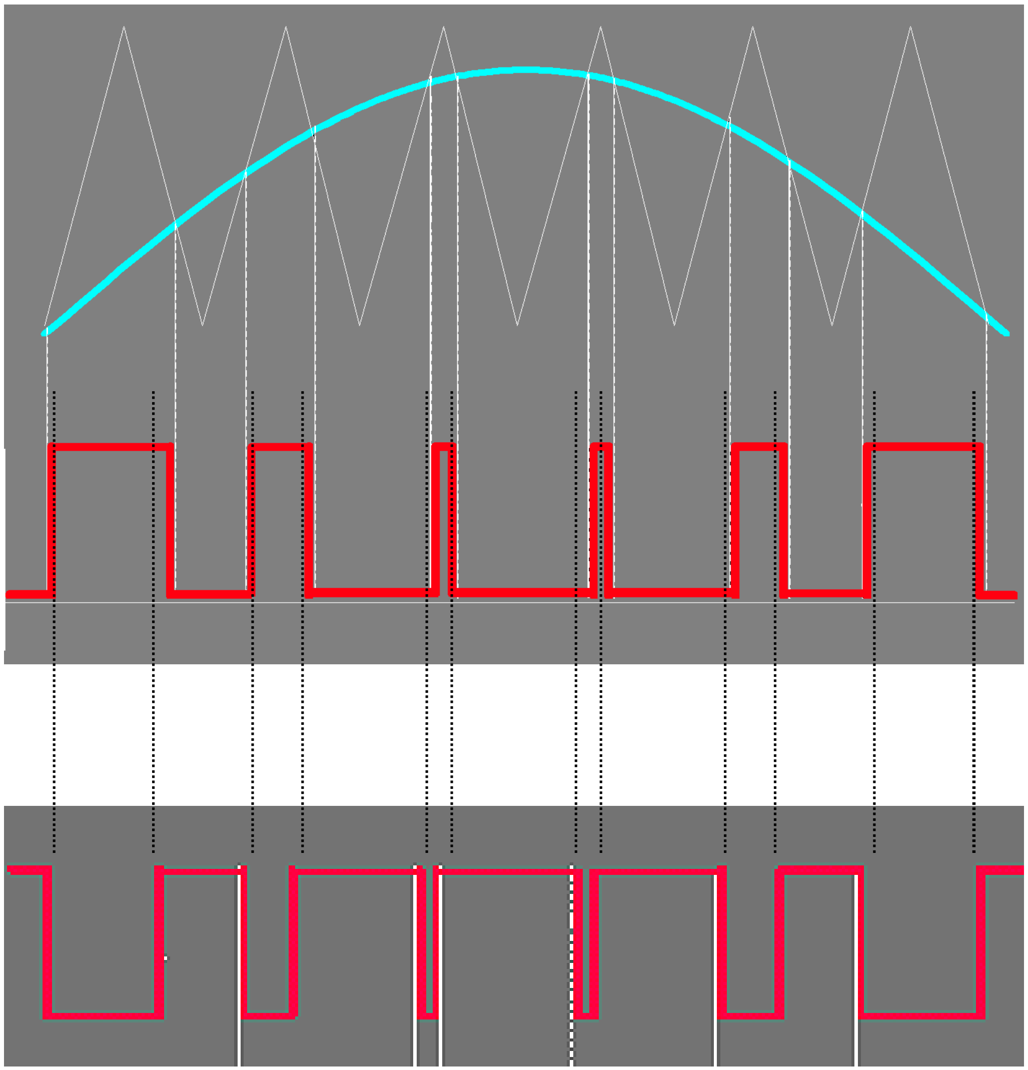


Combination of Triangular signal and sine wave



VFD BASIC

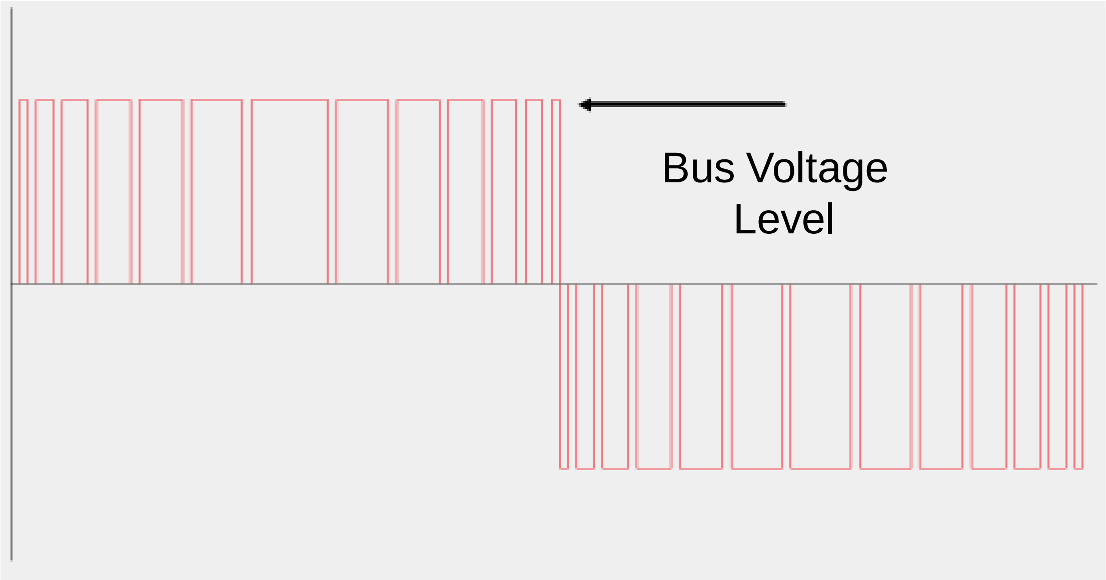
VFD -- Rockwell Drives



Different widths are formed based on the weighing of sine wave

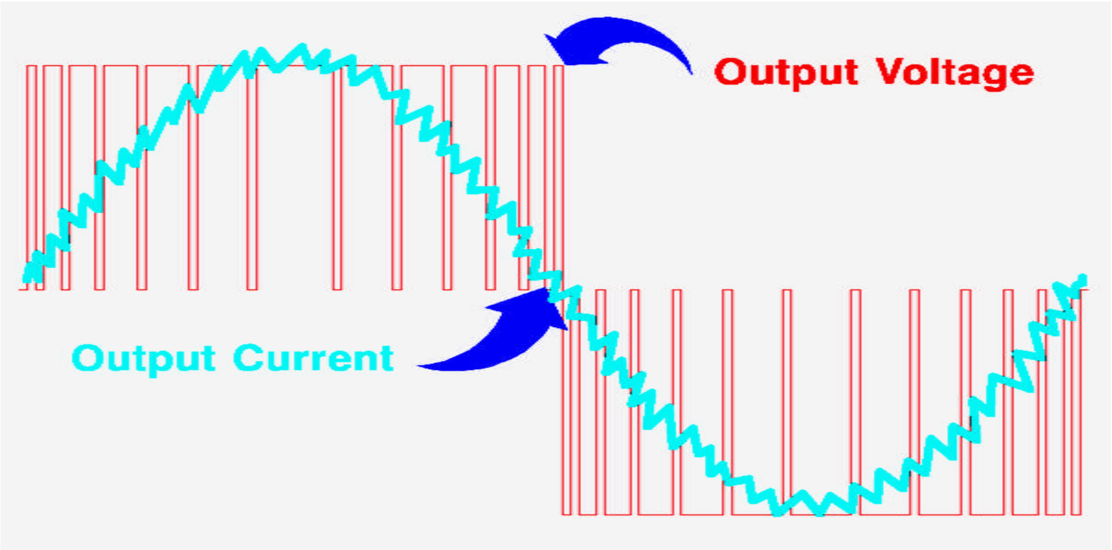
VFD BASIC

VFD -- Rockwell Drives



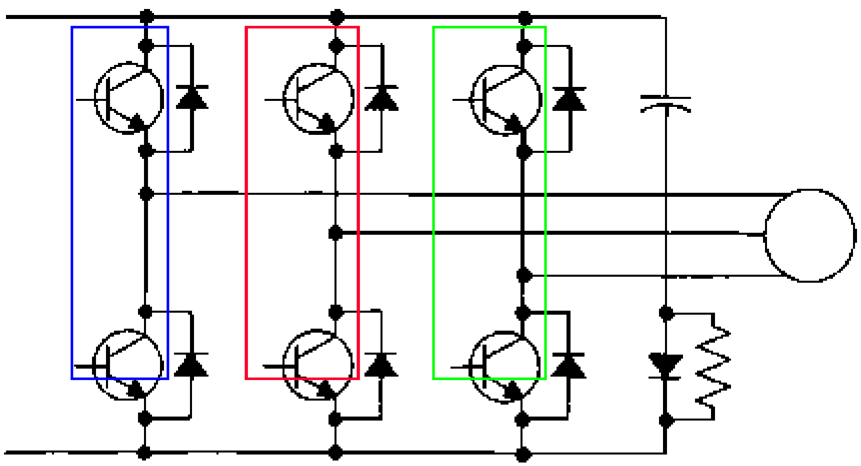
Varying pulse width will vary RMS voltage to motor

Combination of Triangular signal and sine wave

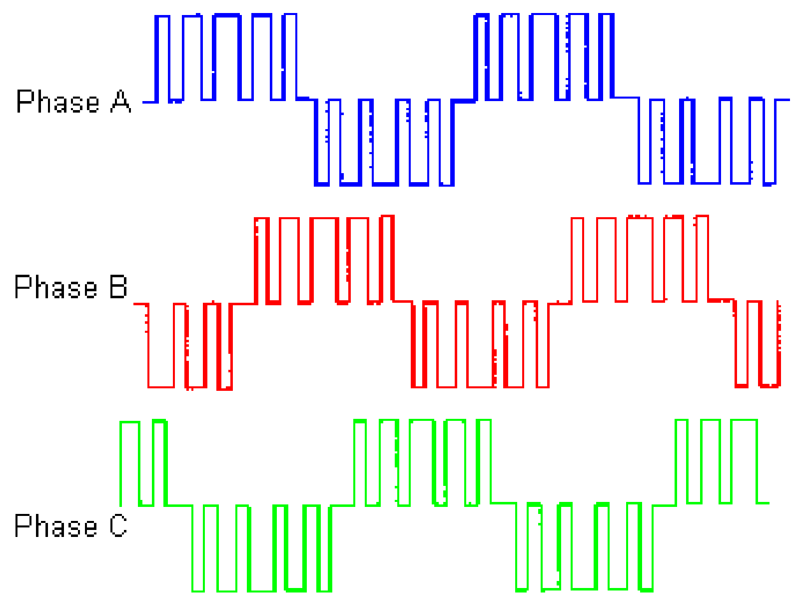


VFD BASIC

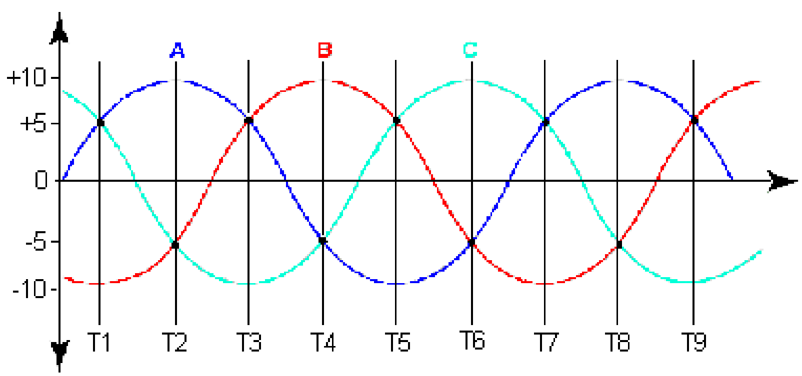
VFD -- Rockwell Drives



The six transistors are turned on and off in a certain order to form three phase pulse width modulated waveforms.



The PWM waveform actually is a Square wave DC voltage. This voltage is applied directly to the AC motor terminals.



Although DC voltage is applied to the motor, the current waveform resembles an AC sine wave and is used to control speed of the AC squirrel cage induction motor.

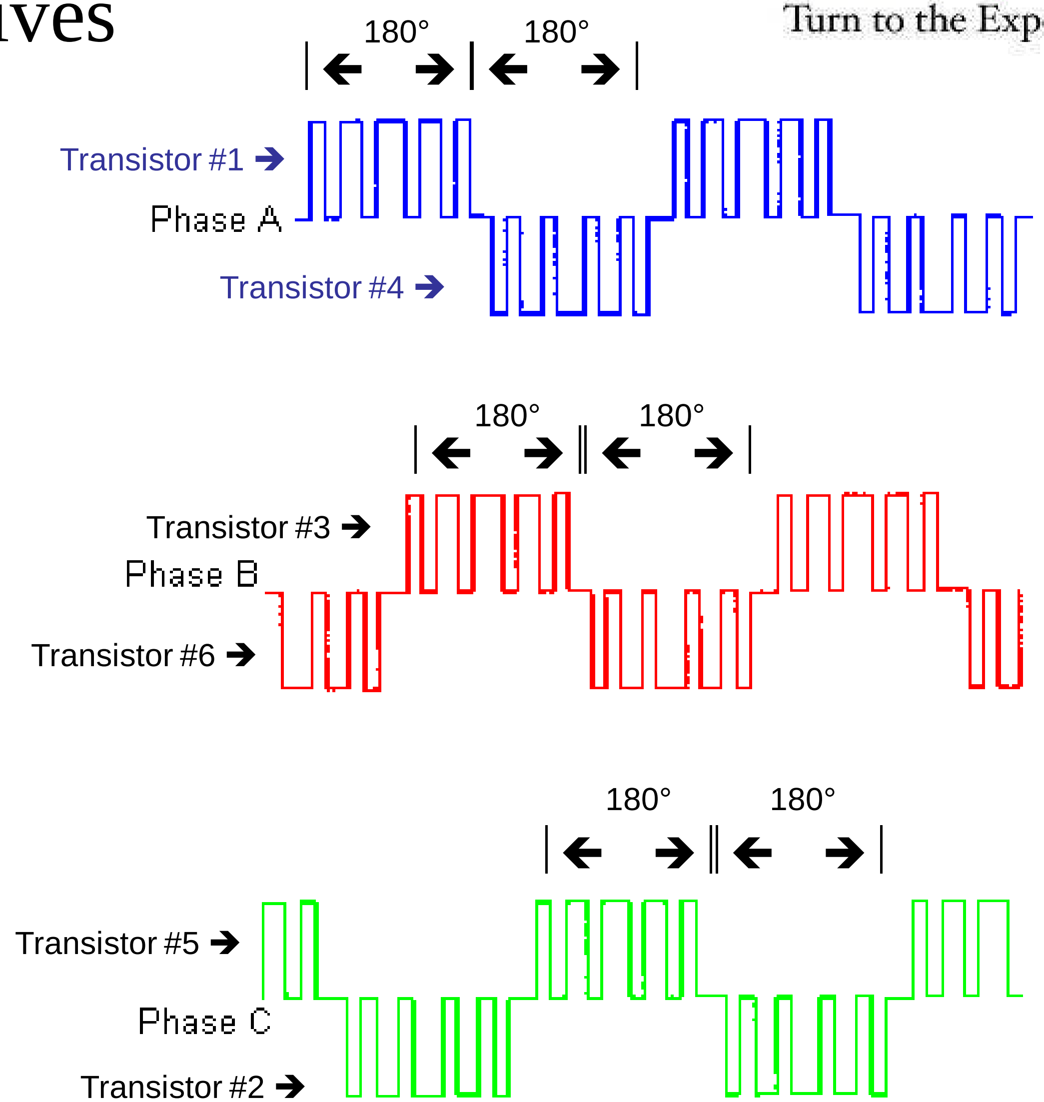
VFD BASIC

VFD -- Rockwell Drives

Example:

Phase A
Transistor 1 turn on/off on positive ½ cycle; Transistor 4 turn on/off on negative ½ cycle

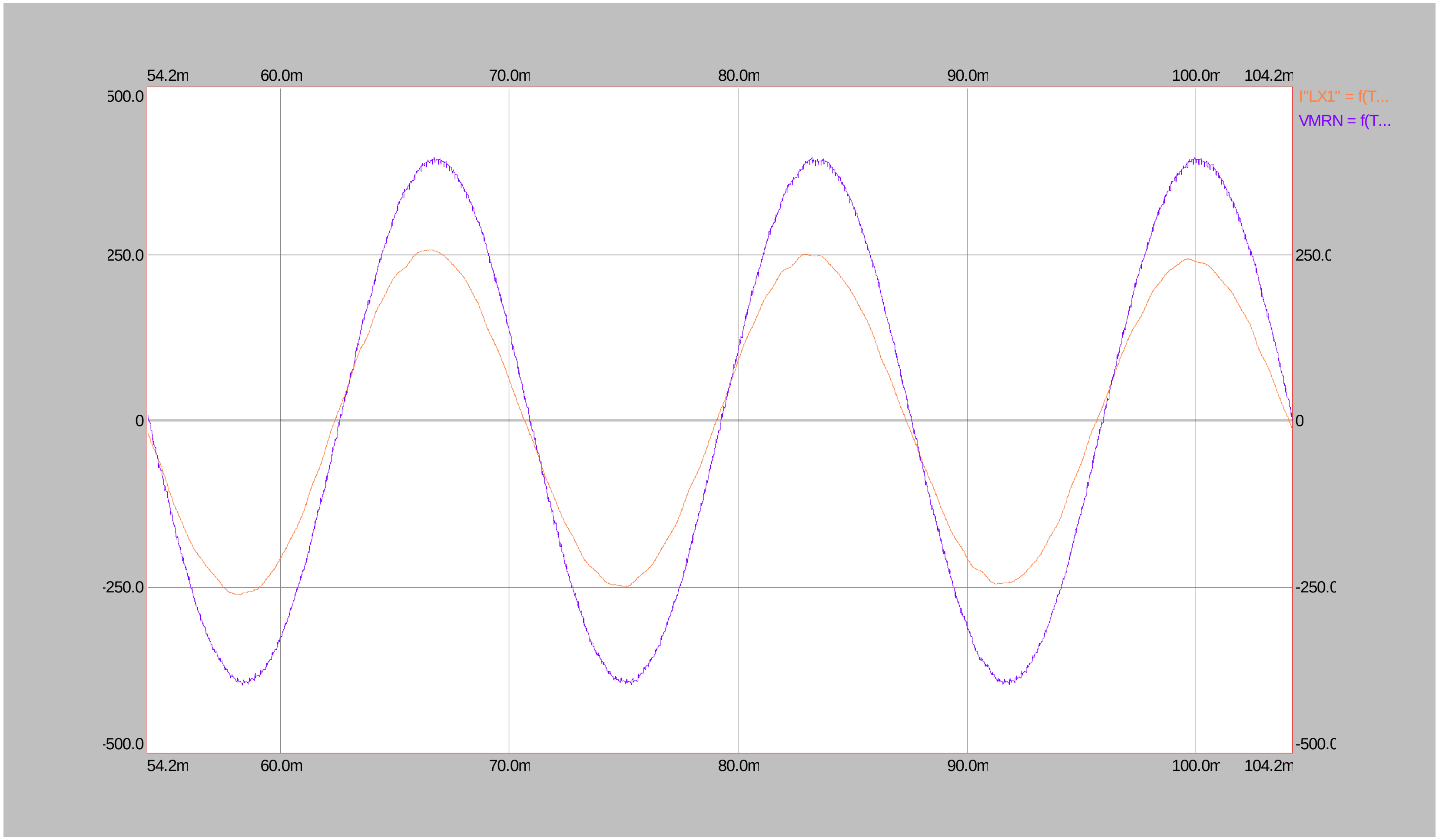
This is the same for Phase B and Phase C except with phase shift



Note: the positive half cycle for B starts 120 degrees after the positive half cycle for A phase, C starts 240 degrees after A.

VFD BASIC

Power Factor



A voltage and Current Sine Wave that are in unity

VFD BASIC

VFD Line and Load Power Measurements at 100% load

Turn to the Experts.

Line KW= 706.7amps X 480vac X 1.73 X 0.95 (PF)

-- = 557KW

1000

Load KW= 823.2amps X 447vac X 1.73 X 0.843

-- = 536KW

1000

Load KW (536KW)

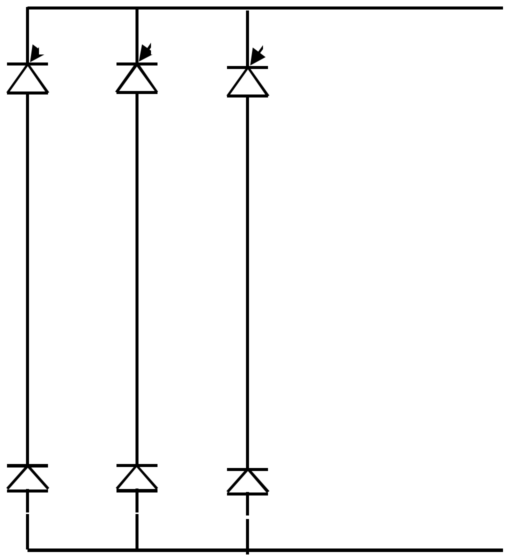
-------------------------- = 0.962

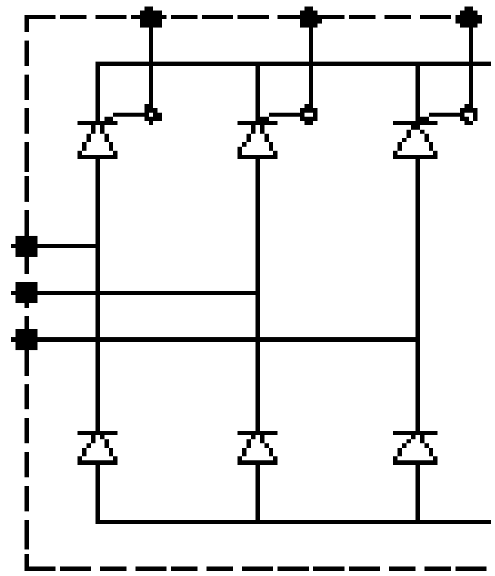
Line KW (557KW)

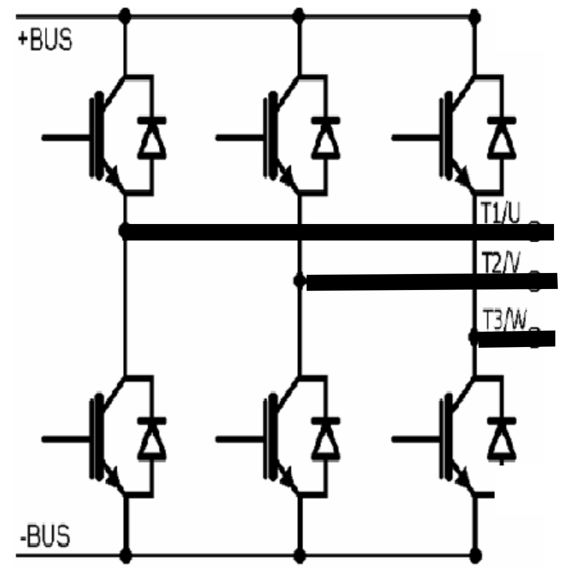
This identifies a drive loss of approximately 3.5% that occurs in a VFD operating at 100% load

VFD BASIC

Drive Design -- Rectifier







Combination of Diodes

Combination of SCR's and Diodes

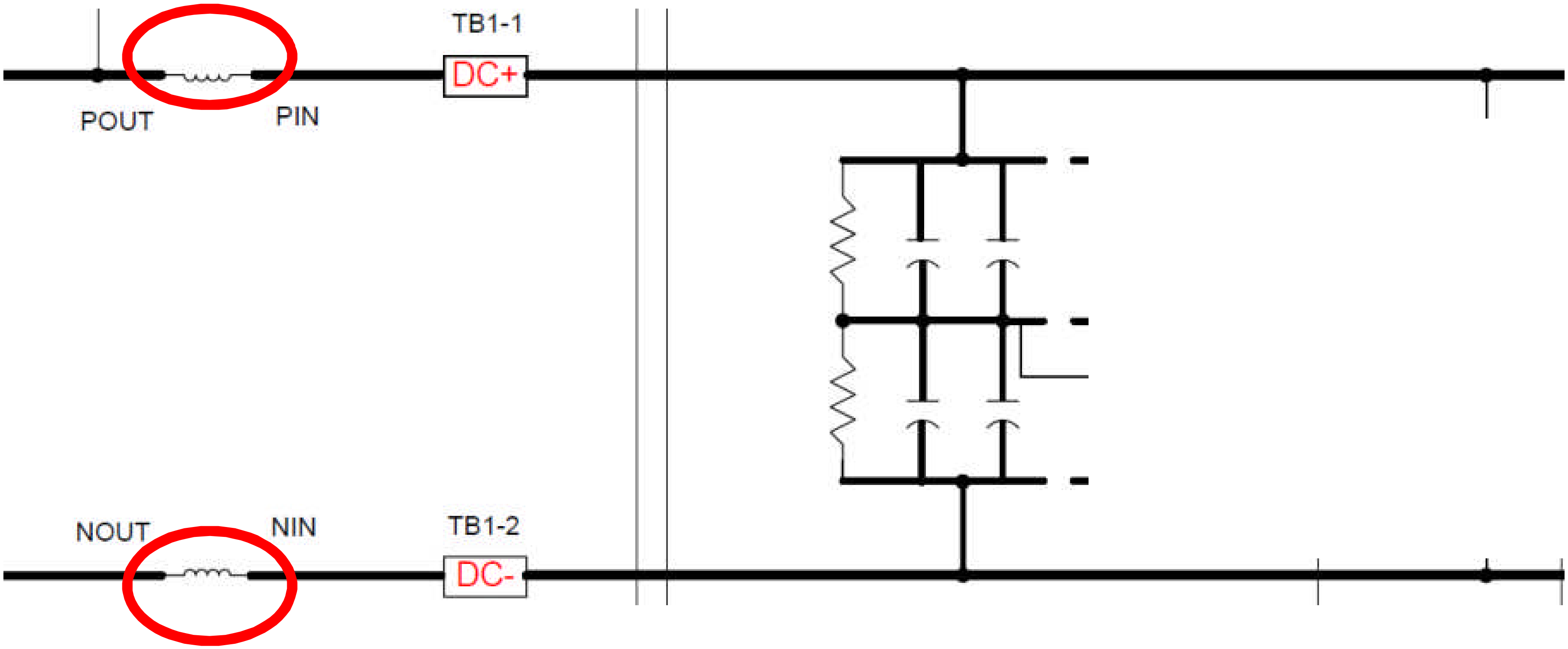
IGBT's which is referred to as an active front end or controlled

<u>Passive Design</u>

<u>Active Design</u>

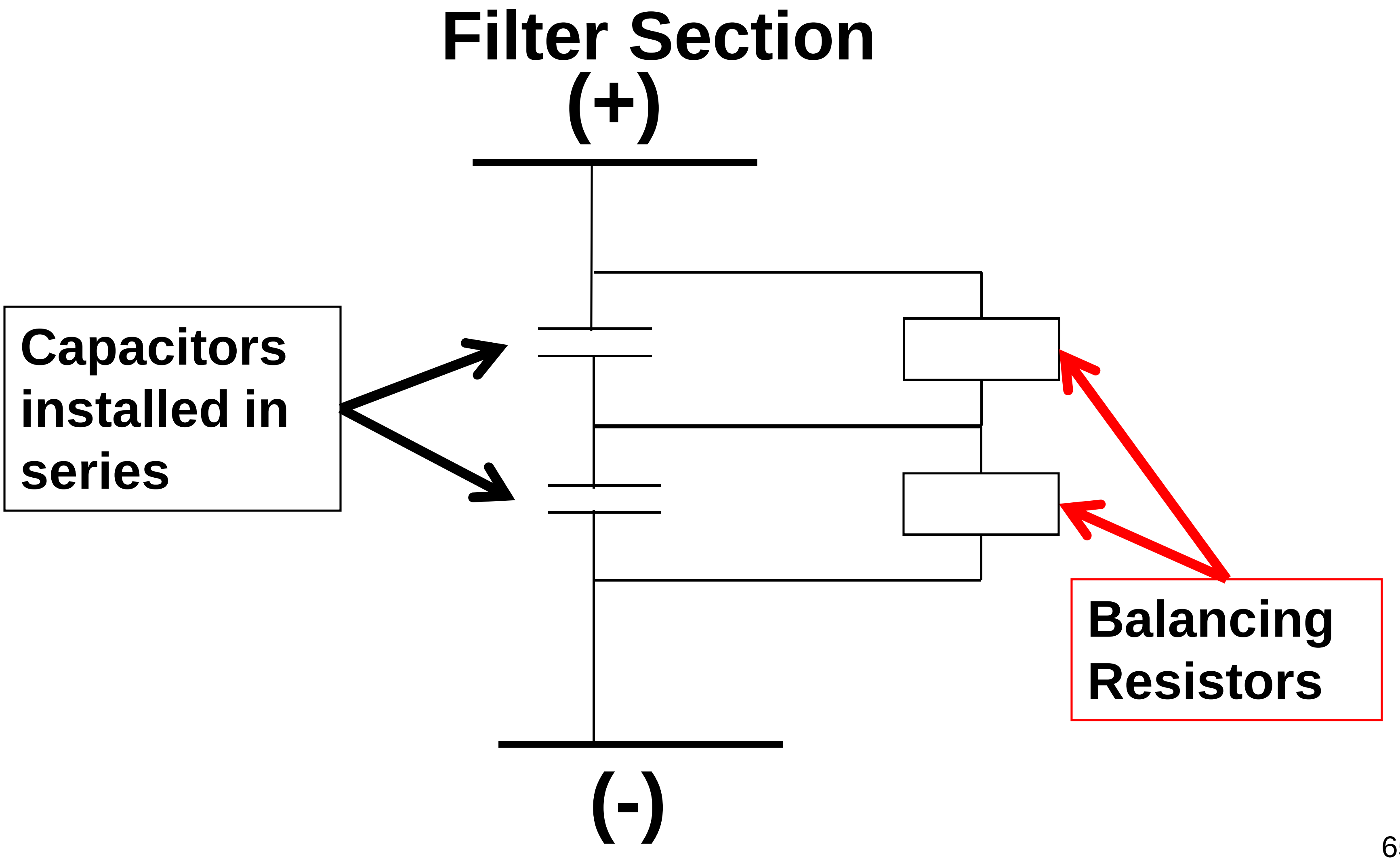
VFD BASIC

Drive Design – DC Chokes & Reactor



Smooth incoming power to DC bus

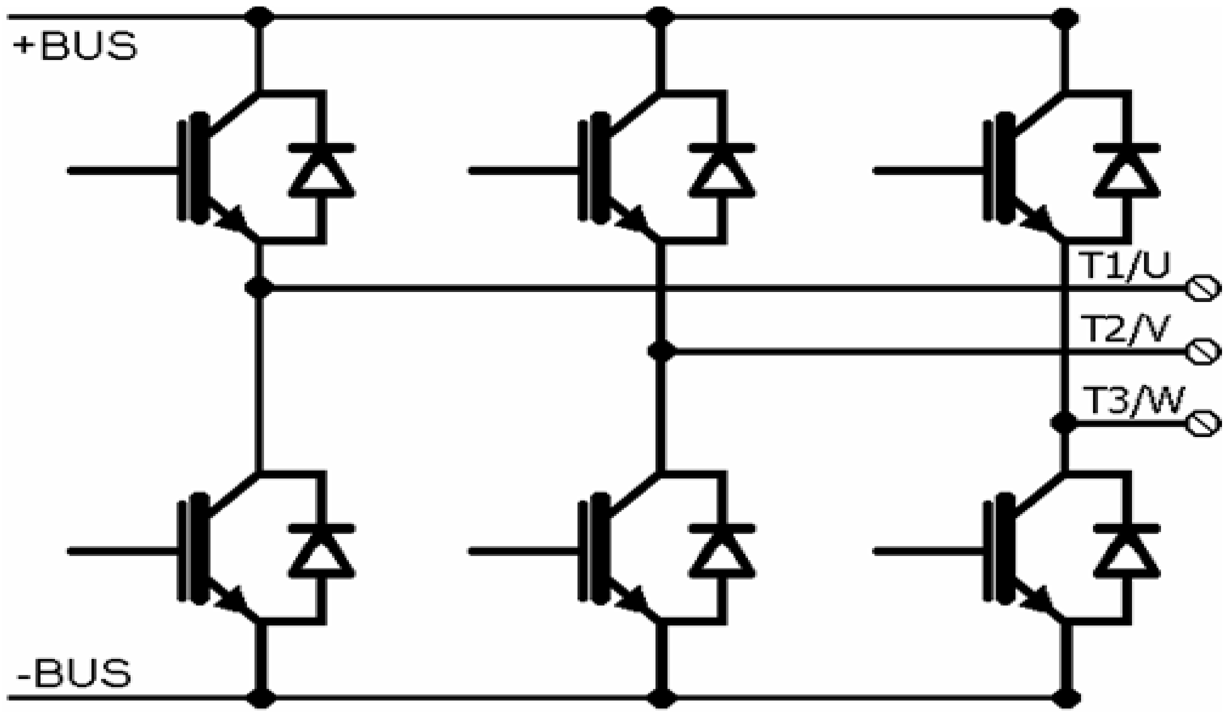
Drive Design – Filter Section



VFD BASIC

Drive Design -- Inverter

Turn to the Experts.

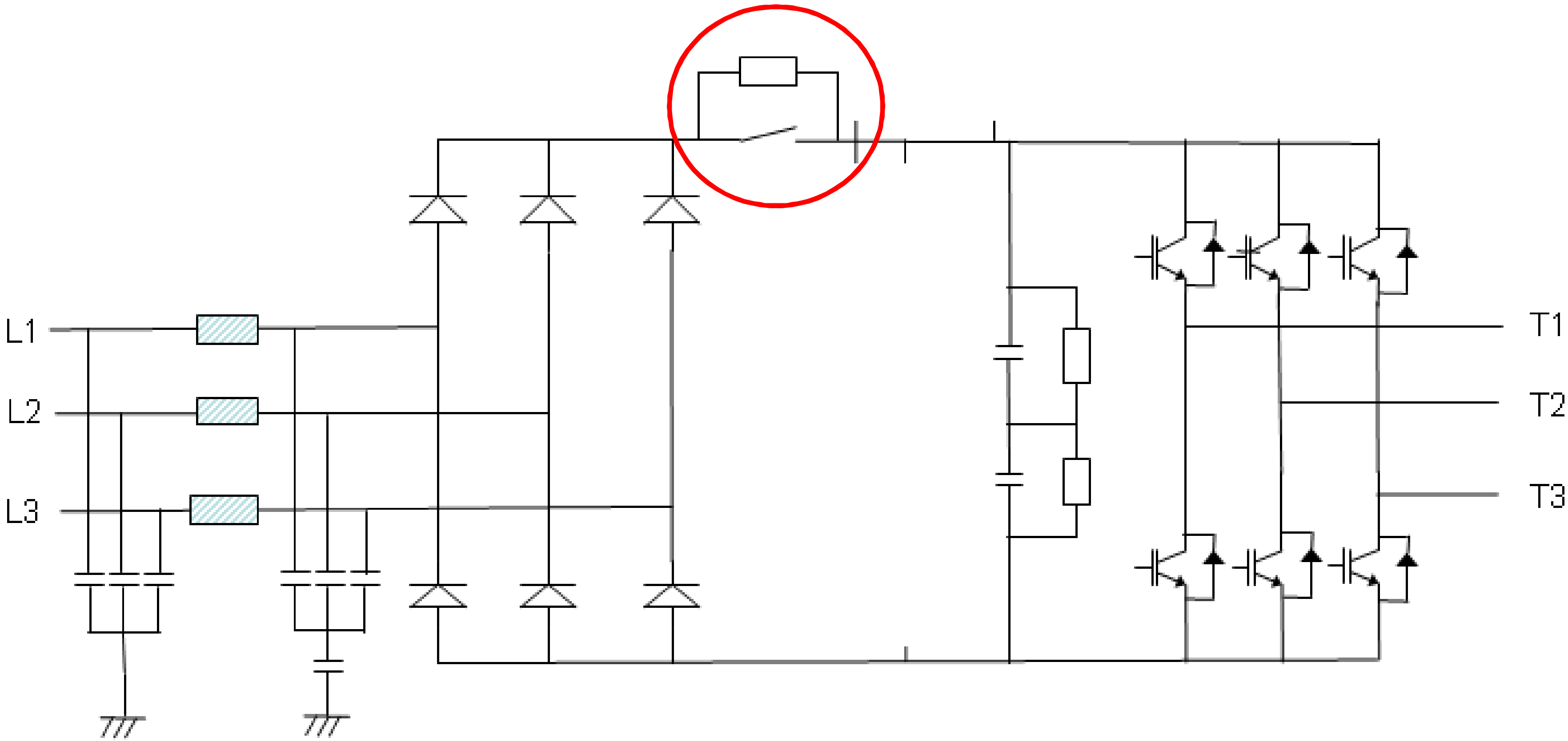


Motor

The PWM or pulse width modulated signal is set for 2Khz on the standard tier drives and either 2 or 4Khz on the Rockwell LF2 drive

VFD BASIC

Drive Design – Overload Control

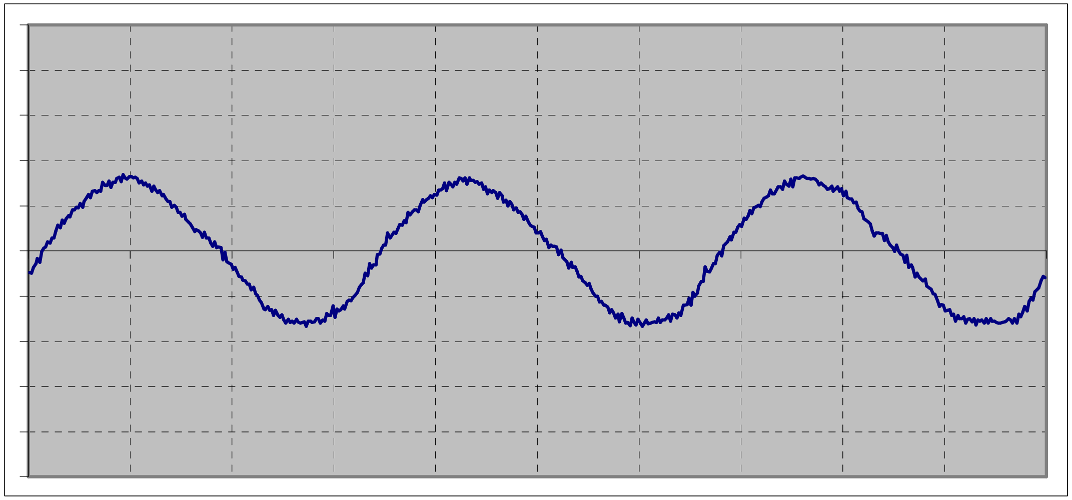


A design using a diode rectifier typically uses a resistor for the initial charging of the filter section with a bypass contactor that is engaged to bypass the resistor when the D/C bus reaches a specific voltage level

VFD BASIC

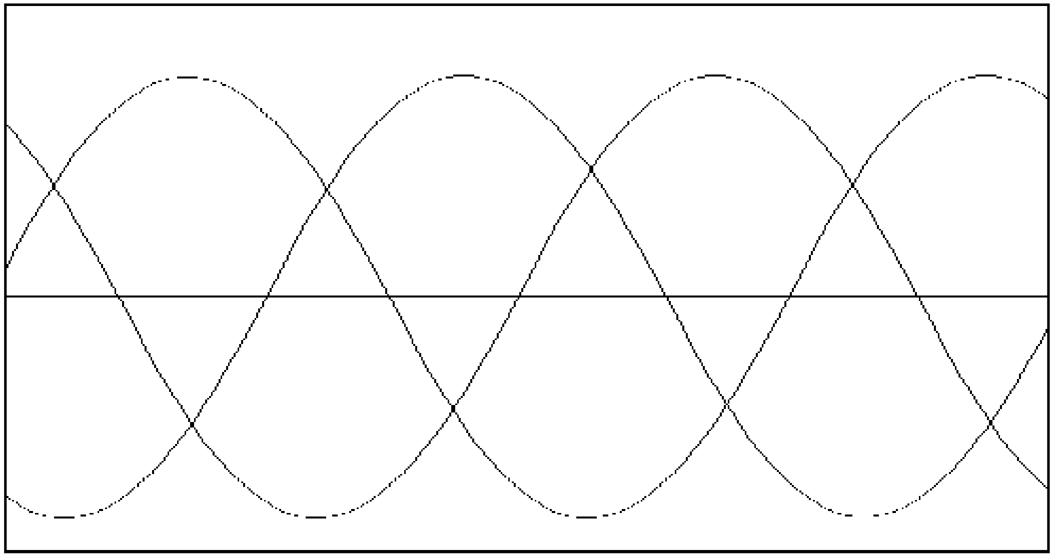
What do VFDs control ?

Frequency



and

Voltage



VFD BASIC

VFD Control Method

Sensorless Vector

VFD output control based on characteristics of motor

Necessary to have correct motor design data (voltage, current, RPM)

Better speed regulation by looking at both voltage and current

Better torque control at low speed

LF2, PF755, Eaton LCX9000 drives

Volts per Hertz

460V/60Hz = 7.67V/hz

Voltage changed proportionately with frequency

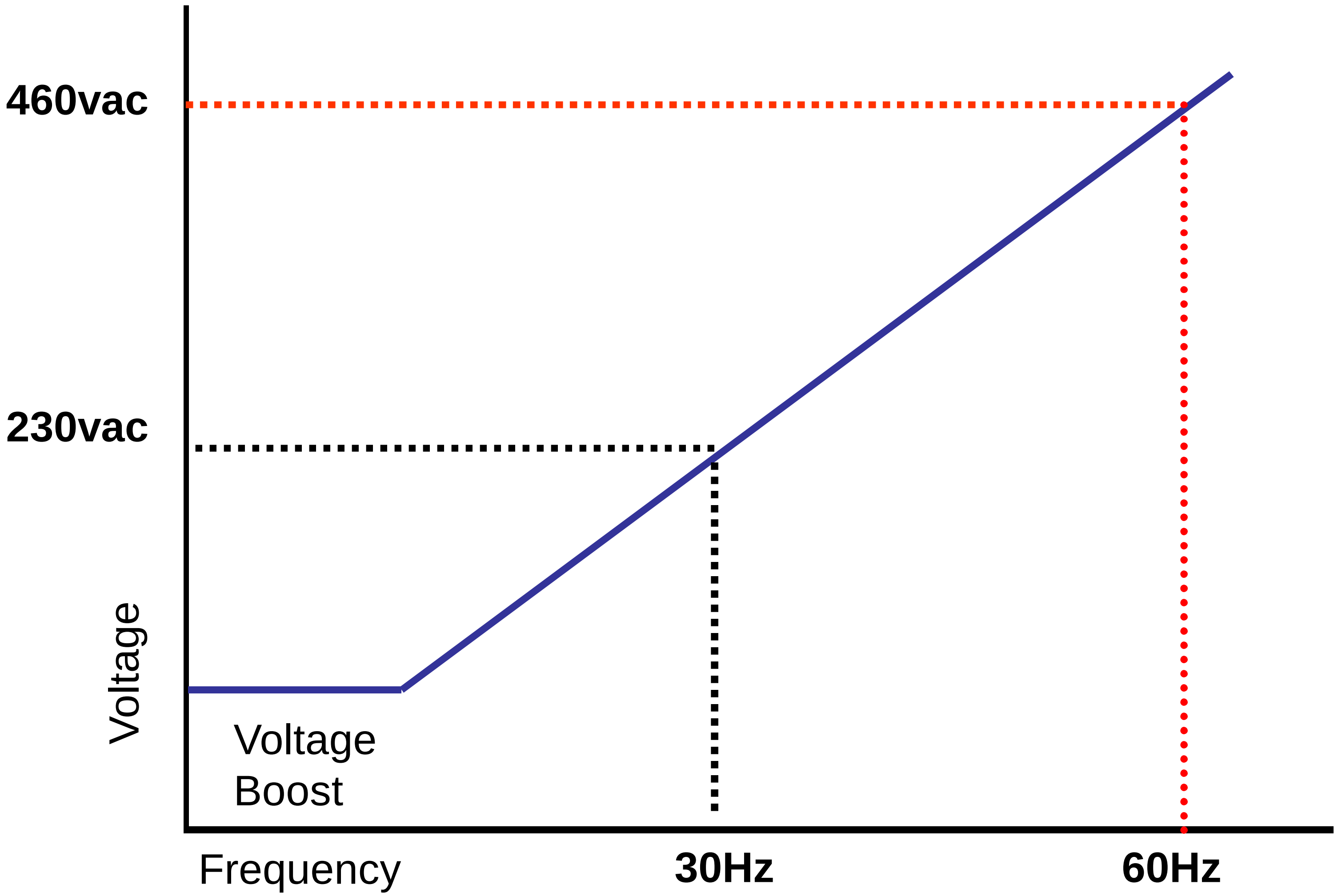
Drive maintain constant v/hz ratio

Unable to maintain torque at low speed

LF1 Drive

VFD BASIC

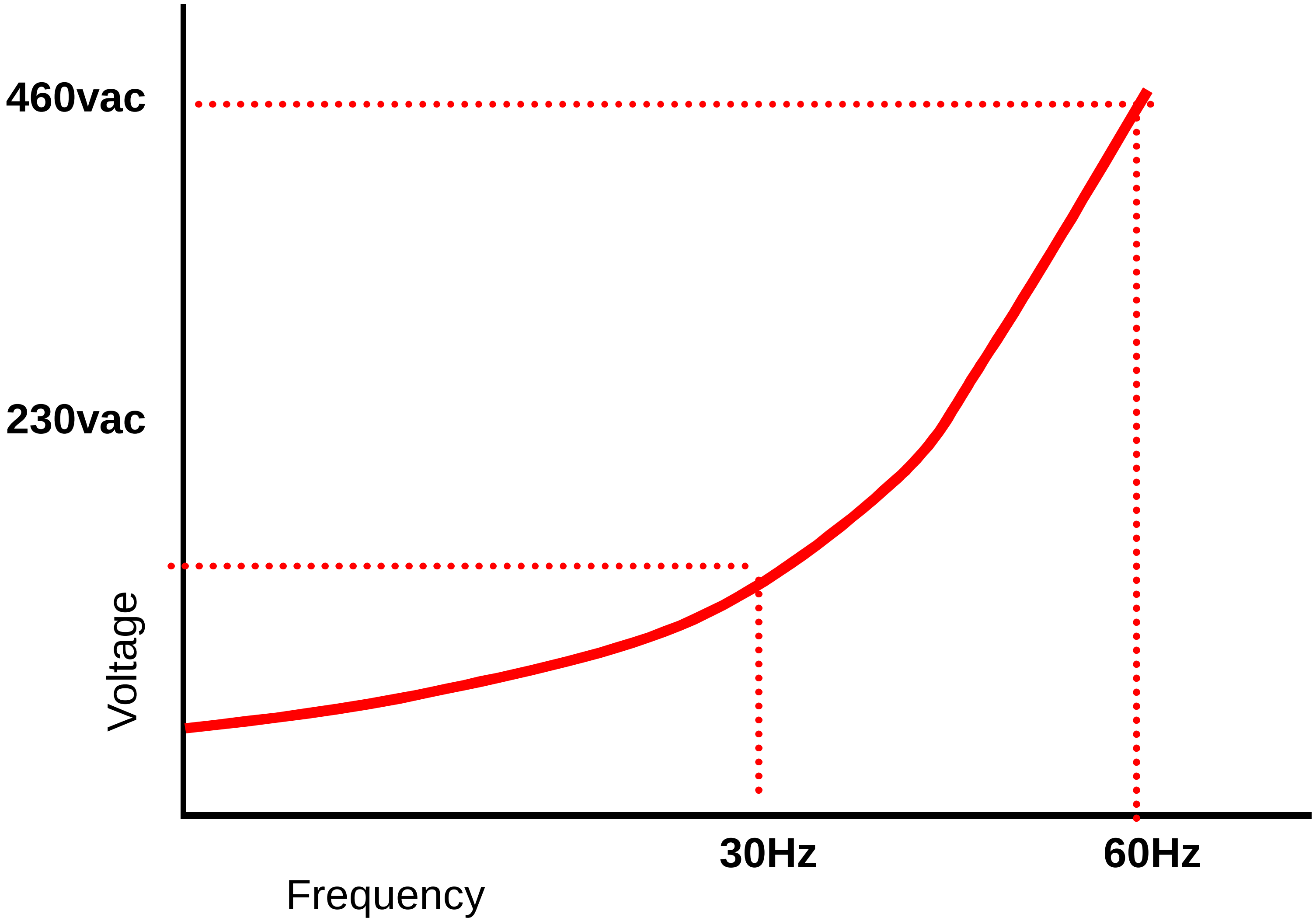
Volts per hertz Control Method



Constant volts per hertz control of the IGBTs

VFD BASIC

Drive Design



Sensorless Vector Control of the IGBTs

VFD BASIC

Harmonic Distortion

VFD design will affect harmonics produced

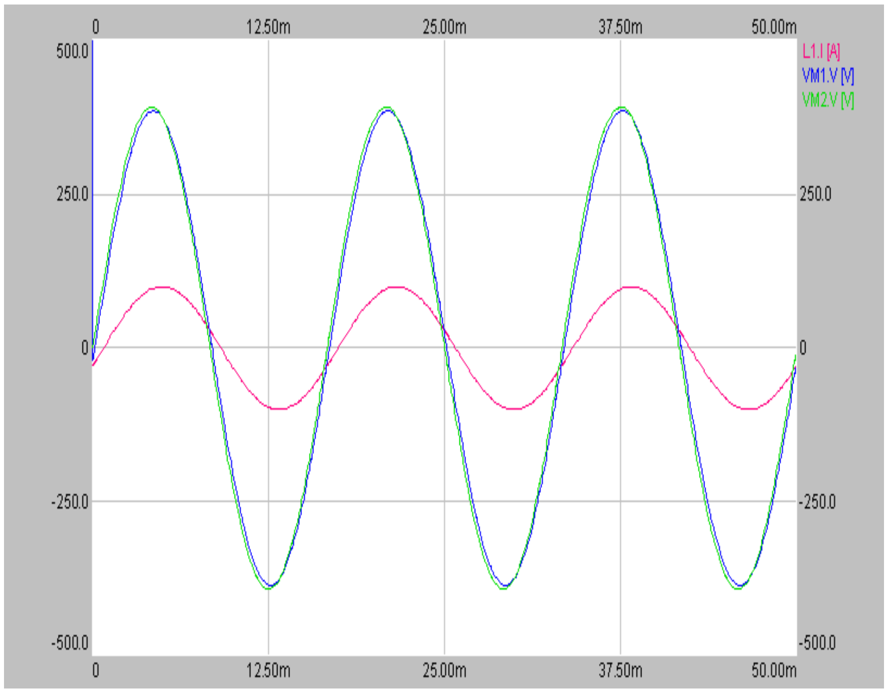
DC link inductors, drive with active front end (transistors in rectifier) have lower harmonic levels

Devices to reduce harmonics –

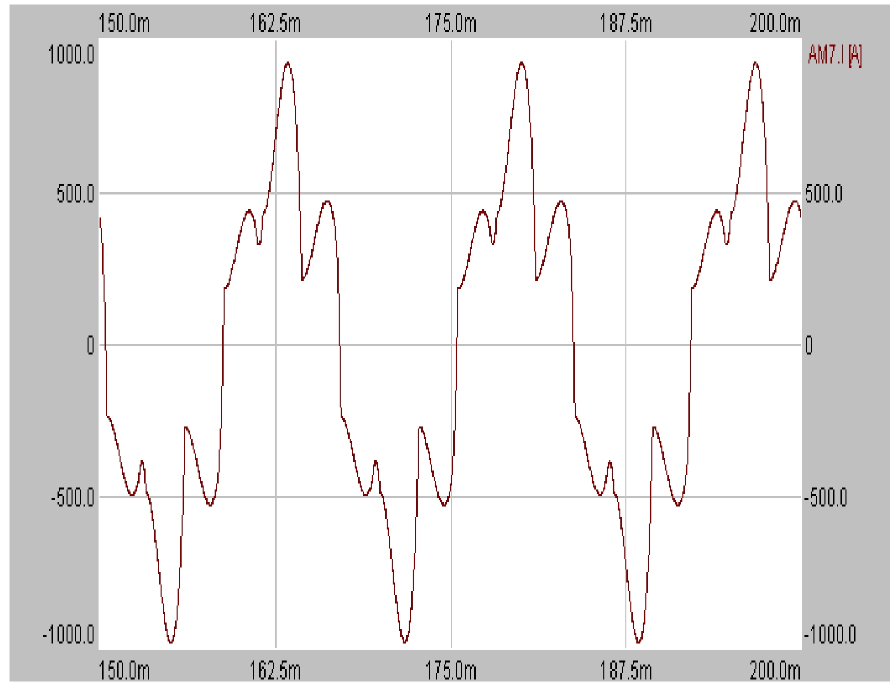
- Line reactors
- Passive filters (inductors, reactors and capacitors)
- Active filters
- Active front end (IGBT rectifiers)
- Higher pulse rectifier (12, 18, 24, 30 pulses)

VFD BASIC

Harmonic Distortion



Normal Sine Wave with no distortion

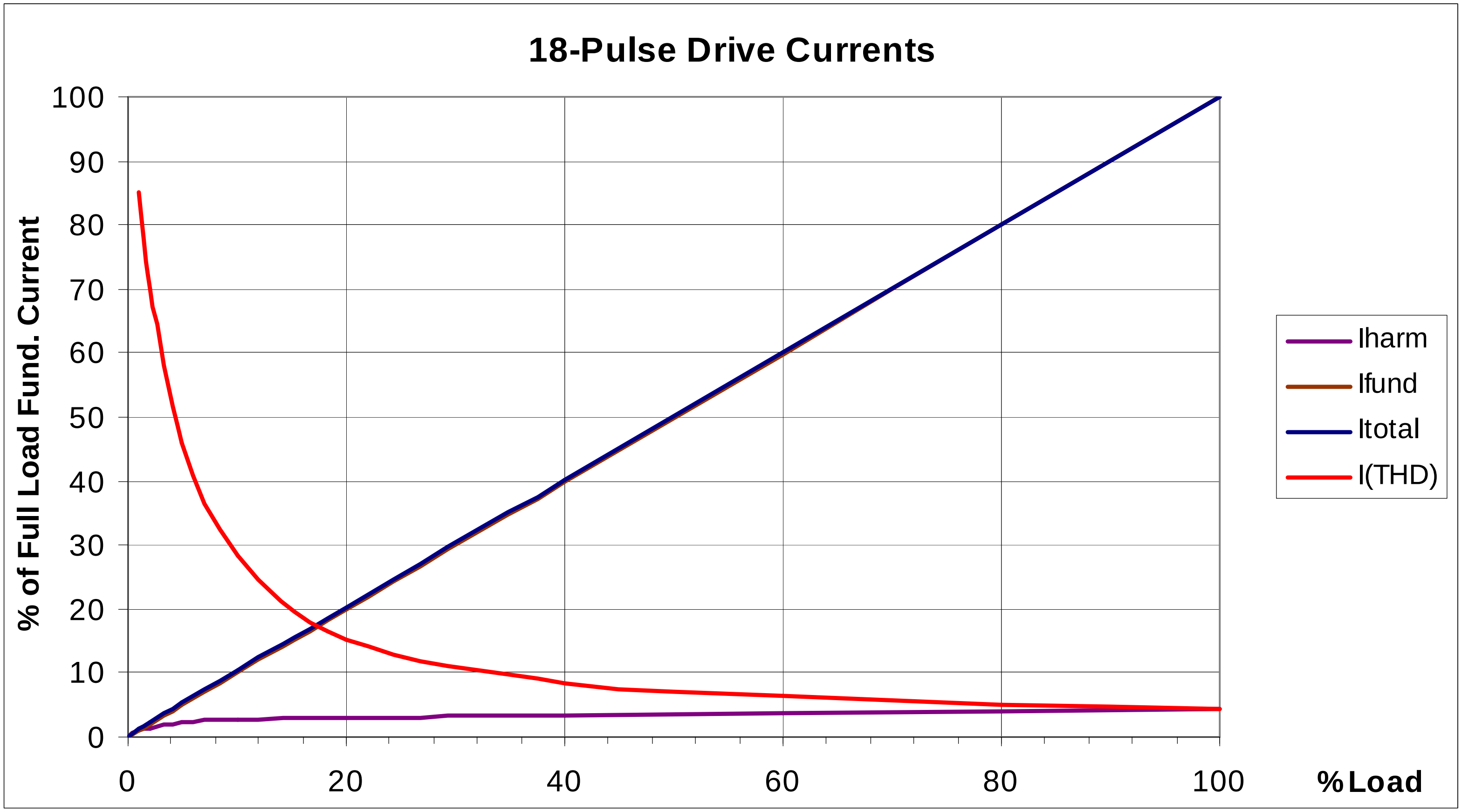


A Sine Wave with significant distortion

VFD BASIC

Harmonic Distortion

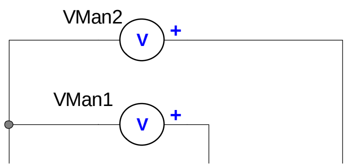
Turn to the Experts.



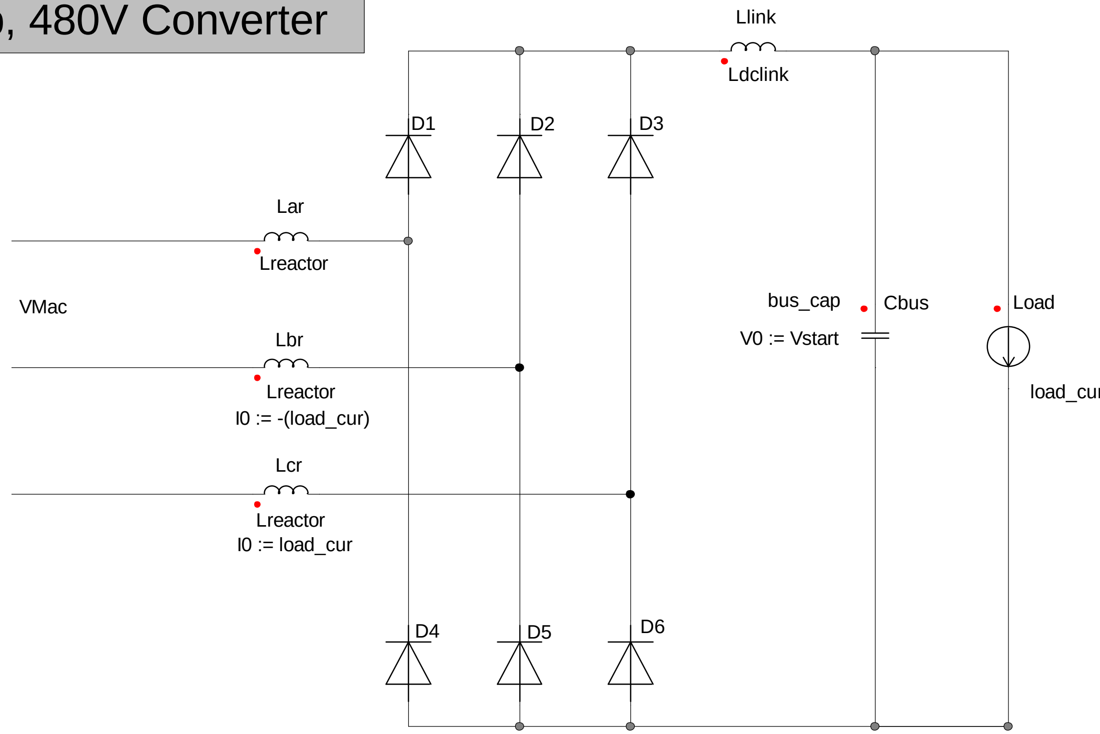
VFD BASIC

Harmonic and Line Reactors

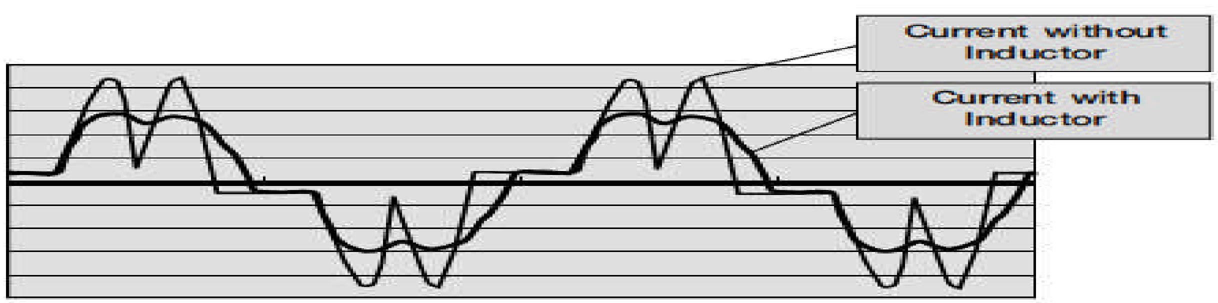
Turn to the Experts.



75hp, 480V Converter



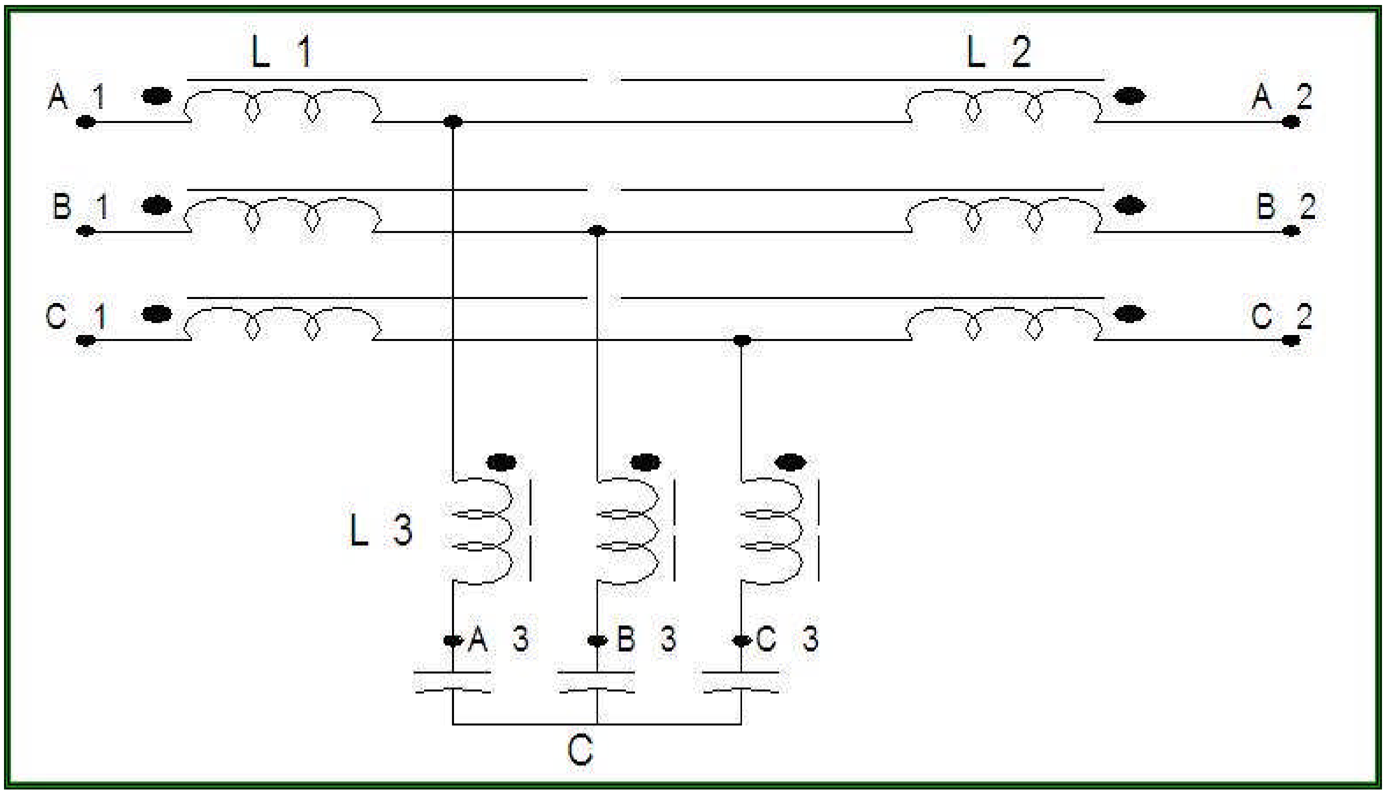
Line reactors are typically offered in 3% or 5% impedance values

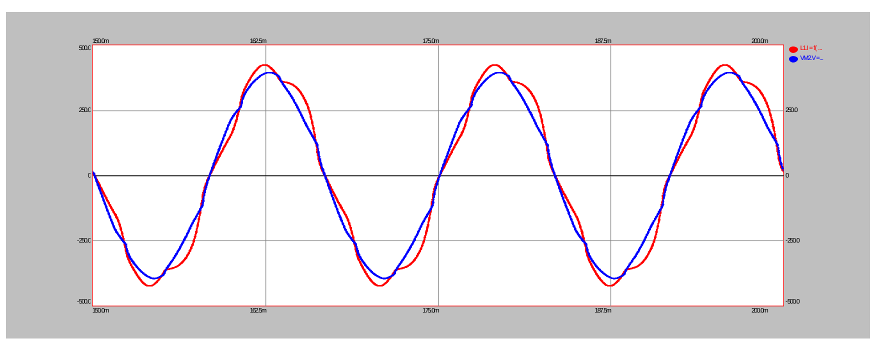


VFD BASIC

Carrier
Turn to the Experts.

Passive harmonic Filters

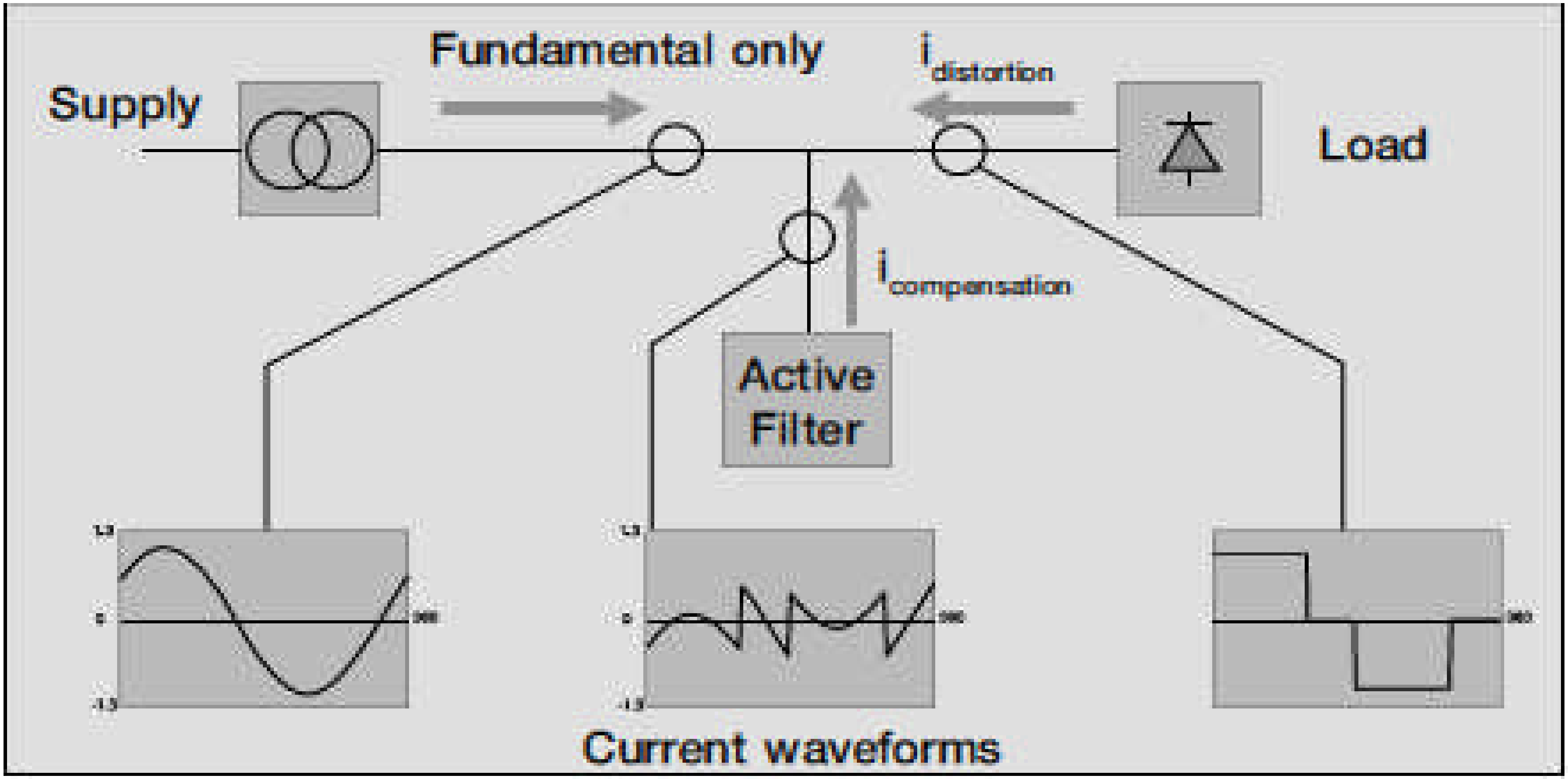


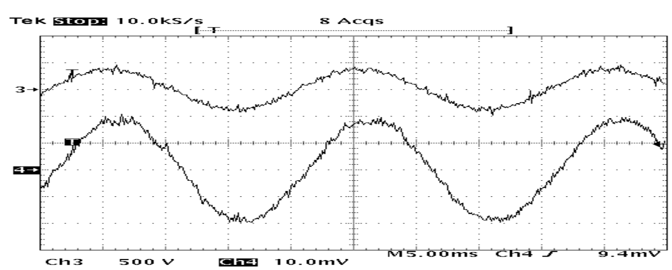


VFD BASIC

Carrier
Turn to the Experts.

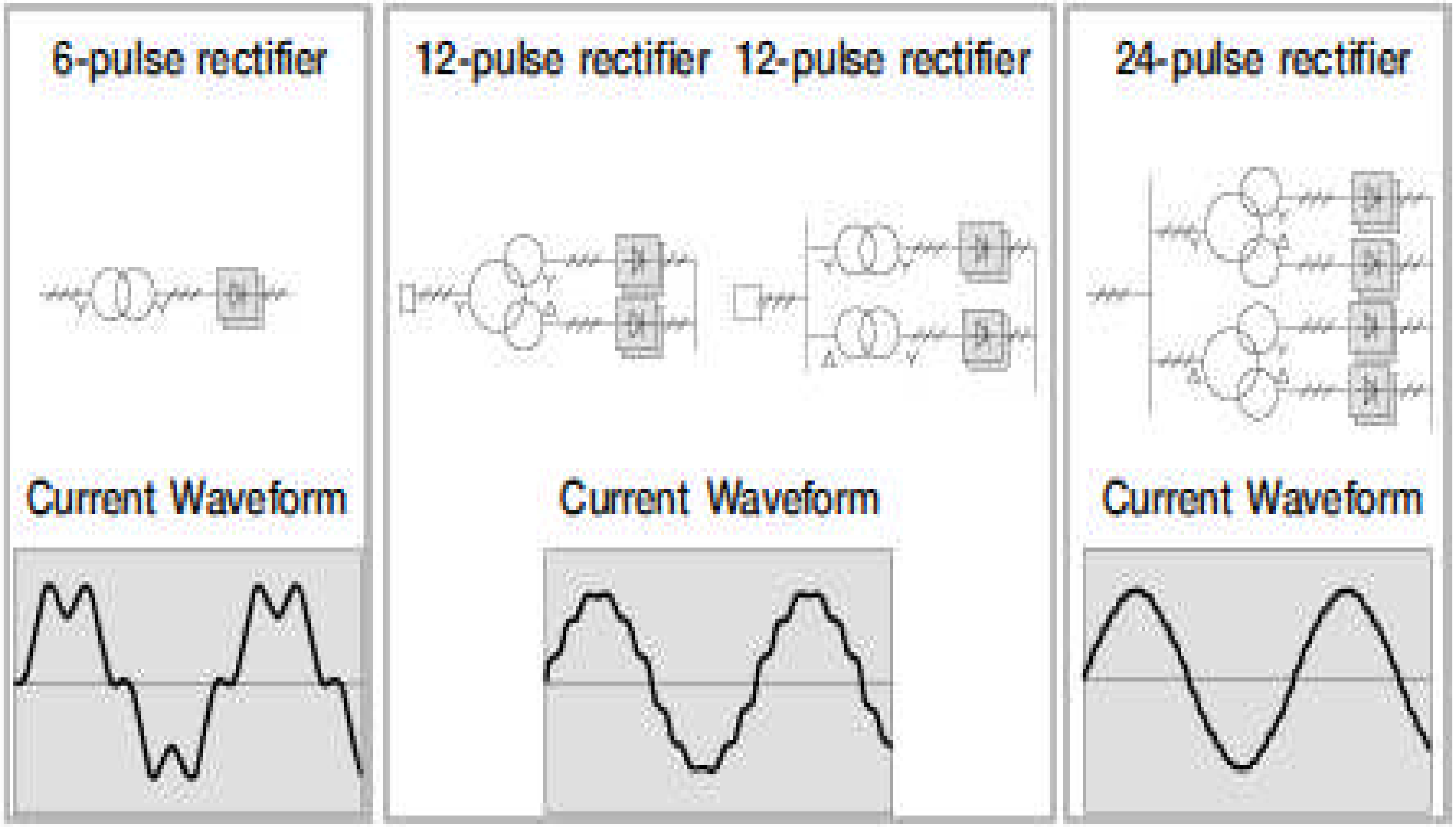
Active harmonic Filters



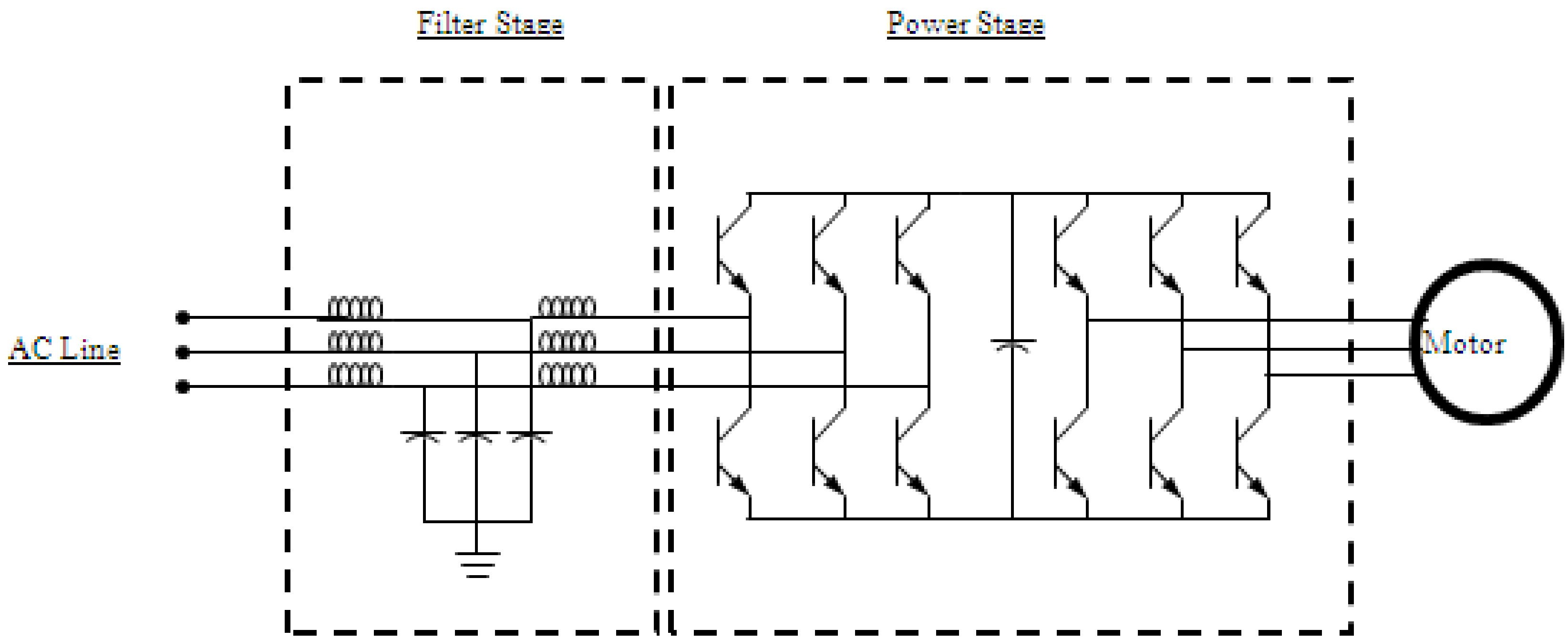


VFD BASIC

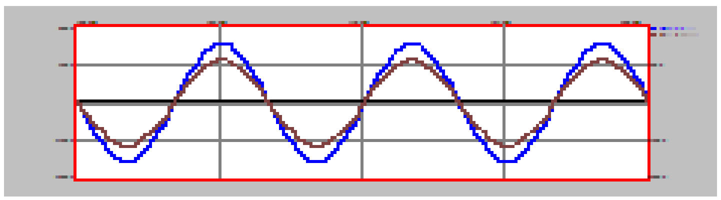
Rectifiers design



Integrated Active Filter



Active Rectifier



VFD BASIC

Electrical Formulas

Peak Voltage of DC Bus (Non-running) = RMS Voltage X 1.414

Peak Voltage of DC Bus (Running) = RMS Voltage X 1.35

RMS Voltage= Peak Voltage X 0.707

KW (three phase) =
(1.732 X RMS Volt X Amp X Power Factor)/ 1000

HP=1.341 x KW

Ohms Law:

I (current)= E (Voltage)/ R (Resistance) or

R = E / I or

E = R X I

VFD BASIC

Installing VFD with a Generator

Turn to the Experts.

What to avoid

- Sizing Generator to load kilowatt rating.
- Flying starts.
- Don’t operate the chiller during a transfer of power from the generator power supply to the primary power supply without a closed transition transfer with phase alignment capability

What to do

- Ramp from 0 Hz.
- Keep same Phase Rotation for various power sources
- The calculated load for a VFD starter should be estimated at 2+ times the actual input KW when sizing the generator
- Transfer load in stages