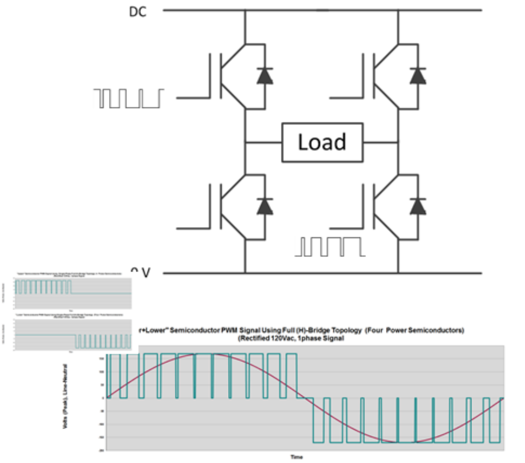
WEBINAR:

Essential Principles of Power Part 2:
Power Conversion – from Semiconductor Devices to Complex Drives

Thank you for joining us. We will begin at 3:00pm CET.

NOTE: This presentation includes Q&A. We will be taking questions during the presentation with answers at the end using the questions section of your control panel.



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Teledyne LeCroy Overview

- LeCroy founded in 1964 by Walter LeCroy
- Origins are high speed digitizers for particle physics research
- Teledyne LeCroy corporate headquarters is located in Chestnut Ridge, NY
- Teledyne LeCroy has the most advanced technology and widest line of Real-Time digital oscilloscopes (from 40 MHz to 100 GHz)
- Long History of Innovation in Digital Oscilloscopes
- Teledyne LeCroy became the world leader in protocol analysis with the purchase of CATC and Catalyst, and creating a protocol analyzer division based in Santa Clara, CA.
- In August 2012, LeCroy was acquired by Teledyne Technologies and was renamed Teledyne LeCroy

About the Presenter

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1. Product Manager with Teledyne LeCroy for over 15 years
2. B.S., Electrical Engineering from Rensselaer Polytechnic Institute
3. Awarded three U.S. patents for in the field of simultaneous physical layer and protocol analysis

Essential Principles of Power
Part 2

Power Conversion -
from Semiconductor Devices to Complex Drives

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Agenda

- Defining “Power”
- “Power” Overview
- The Basics – Power Conversion
- The Basics – Drives
- Distorted Waveform (e.g. PWM drive output) Power Calculations
- Questions & Answers

Defining “Power”

See the elephant

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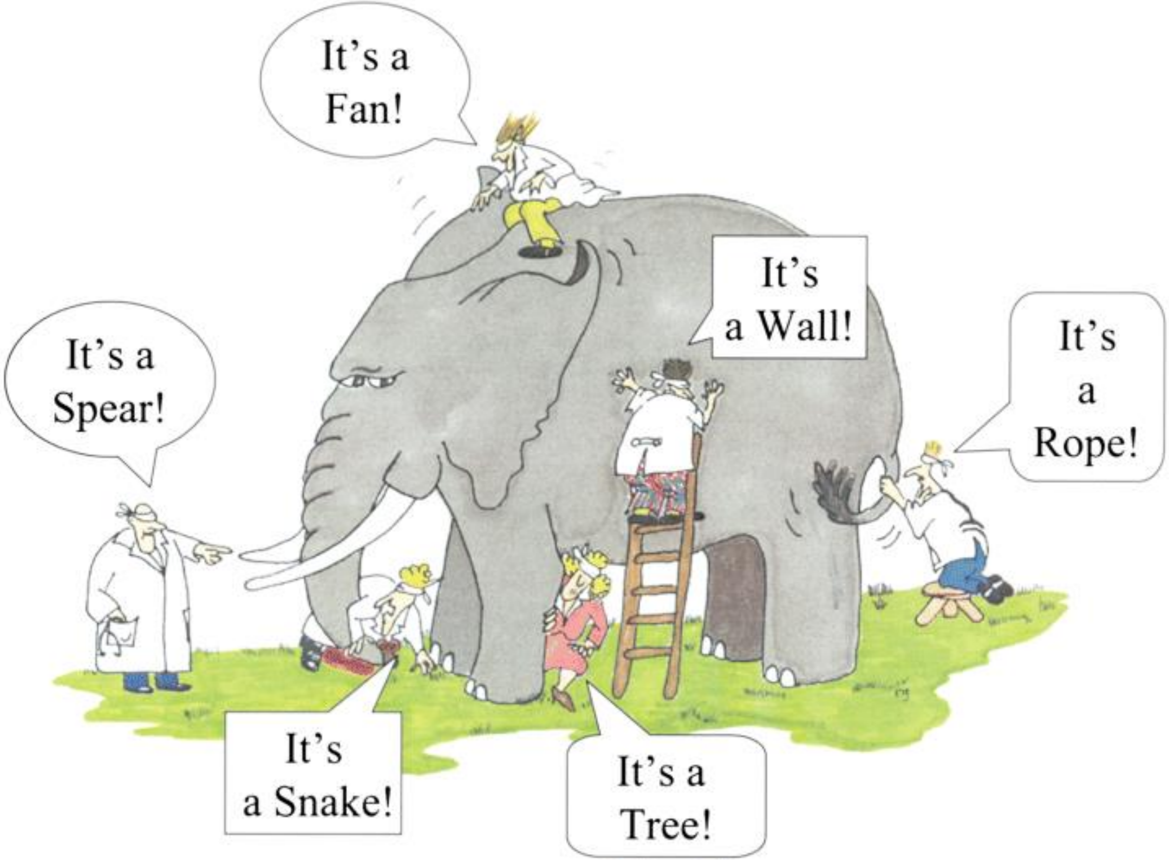
Defining "Power" Can Be Like Blind Men Describing an Elephant…



- Engineers can mean many different things when they say "power"
- In the next three slides, we'll define our "power" focus for this presentation…

“Power” Definitions

These are just a few of them…

- **Utility, Grid, Household, Line, Power Line, Mains “Power”**
  - This is the 50/60 Hz sinusoidal voltage/current power flowing to your home or business, measured by a kWh meter
- **Power Semiconductor Device “Power”**
  - This is the power consumed by the power semiconductor MOSFET or IGBT device during switching, conduction, or OFF states
- **Digital Power Management “Power”**
  - This is the ON/OFF voltage management of the DC power supply rails on a motherboard or embedded computing system
- **Power Supply Startup Sequencing “Power”**
  - This is the management of the ramp times and sequences of different DC power supply rails on a motherboard or embedded computing system
- **Power Electronics Inverter/Converter “Power” Testing**
  - This is the measurement of a complex mix of line (50/60 Hz) frequency input, variable frequency output, DC and control/sensor signals for debug, troubleshooting and validation purposes
- **Power Analyzer “Power Analysis”**
  - This is the measurement of the Watts or Volt-Amperes that a product (“system”) consumes and/or the efficiency of power consumption for the product

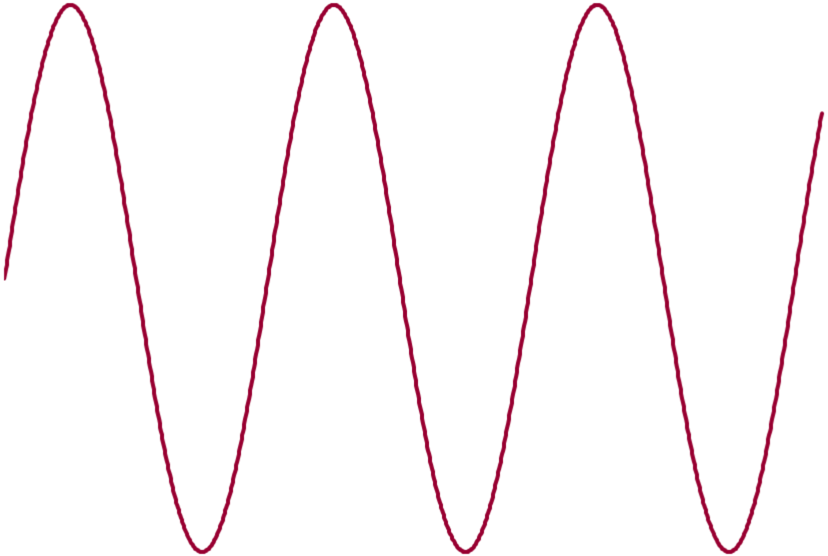
“Line” V, I, and Power Measurements

These are 50/60 Hz signals that are input to power conversion systems

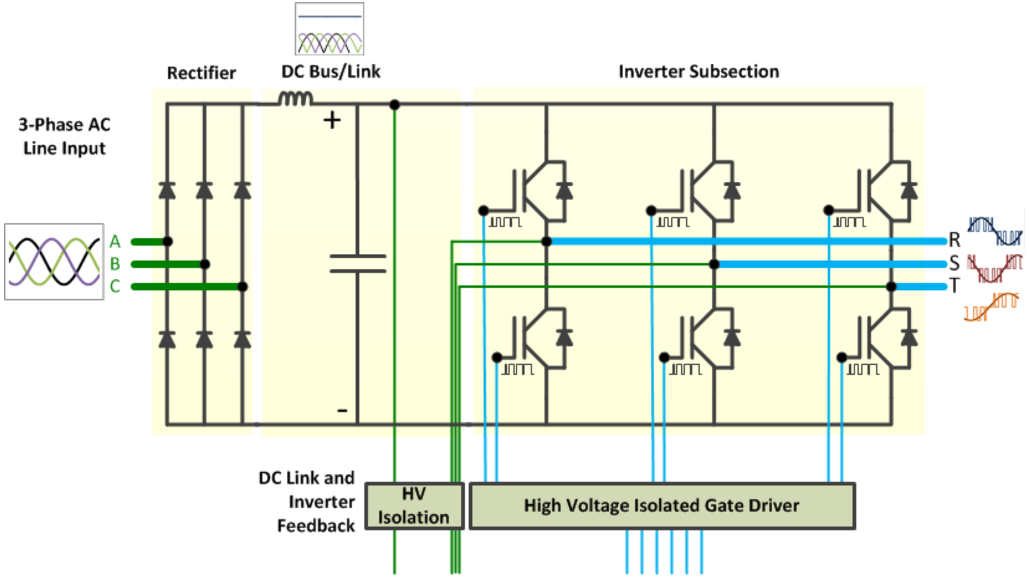
- **Utility, Grid, Household, Line, Power Line, Mains “Power”**
  - This is the 50/60 Hz sinusoidal voltage/current power flowing to your home or business, measured by a kWh meter

The “Line” input of a power conversion (AC-AC or AC-DC) system is typically 50/60 Hz signals.

PWM voltage signals at the output of a power conversion system have a sinusoid fundamental



Power Conversion Systems Measurements



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“Power” Overview:

100 years in 7 slides

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Generation, Transmission & Distribution (GT&D) and Consumption of Power

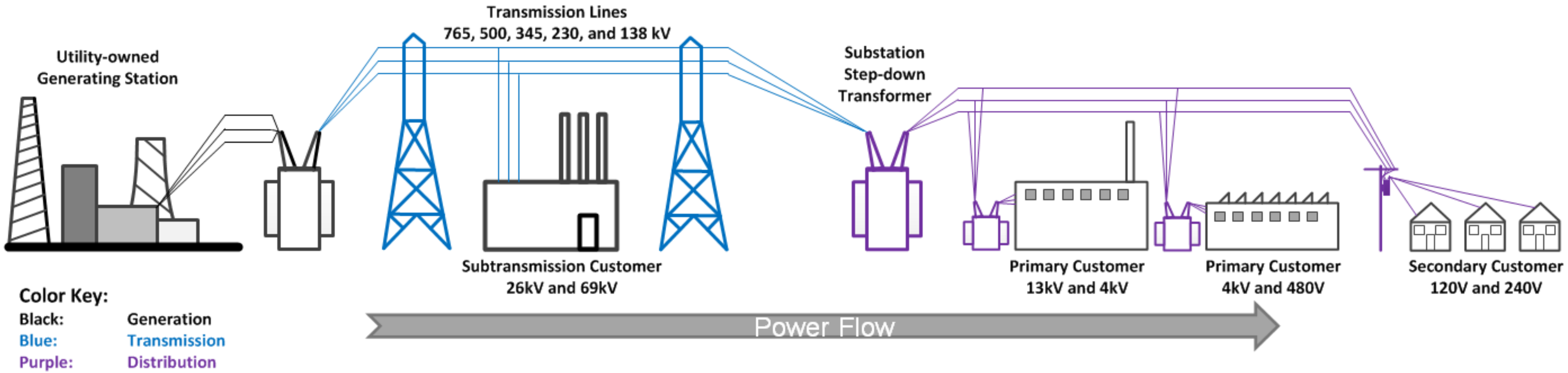
- First - Electricity is ***Generated***
  - Stationary Generators
    - Utility centralized “generating plants”
    - Distributed Generation (DG) (DC inverted to AC)

- Then – Electricity is ***Transmitted and Distributed*** to
  - Homes
  - Commercial Locations
  - Industrial Users

- Finally – Power is ***Consumed***
  - Directly from the utility AC (50/60 Hz) line (no power conversion)
  - Via AC-AC conversion (variable frequency drives)
  - Via AC-DC conversion (“switch-mode” power supplies)
  - Via DC-AC conversion (inverters)
  - Via DC-DC conversion (converters)

Historical Generation, Transmission & Distribution System (GT&D)

Large generation inefficiencies, high T&D losses



- Centralized power generation, utility delivery to customer
- Overall power delivery efficiency = 32%
  - Generation input/output efficiency = 35% (1 BTU in = 0.35 BTU out)
  - T&D efficiency = 93% (0.35 BTU in = 0.32 BTU out)
    - 7% losses in T&D system components, e.g.
      - Step-up, Power, Substation, and Distribution transformers
      - Power Cables

Transmission & Distribution System Loss Measurements

T&D equipment suppliers would validate equipment losses prior to shipment to utility

- Transformer power frequency loss measurements
  - 50 or 60 Hz
  - Load (Copper, or I^2R) Losses
  - Excitation (Core) Losses
  - Efficiencies

- Validation Test
  - Loss validation
  - Efficiency measurements

- Report provided to end utility customer as part of sale

Power Consumption – Motors

Motors have represented the largest single opportunity to reduce energy consumption

- 45% of worldwide delivered electricity is consumed by electric motors
  - 9% of this by small motors
    - Up to 750W (**90% of motors**)
    - AC Induction, BLDC, PMSM
  - 68% of this by medium motors
    - Up to 375 kW (**9.9% of motors**)
    - Mostly AC Induction
  - 23% of this by large motors
    - Up to 1000 kW (**0.03% of motors**)
    - AC Induction
- Motors were essentially only line-powered prior to the 1990s
  - Power semiconductor-based “drives” revolutionized motor speed and torque control
  - Various government mandates were enacted to increase motor efficiency

AC induction motor

Permanent Magnet Synchronous Motor

Brushless DC Motor

ENERGY STAR

EPCAct92

CEMEP
European Committee of Manufacturers of Electrical Machines and Power Electronics

NEMA Premium

IEC
60034-30

Power Analysis of Electric Motors (1990s and earlier)

Focus was on the larger motors (10% of unit volume) that consumed 91% of the electricity

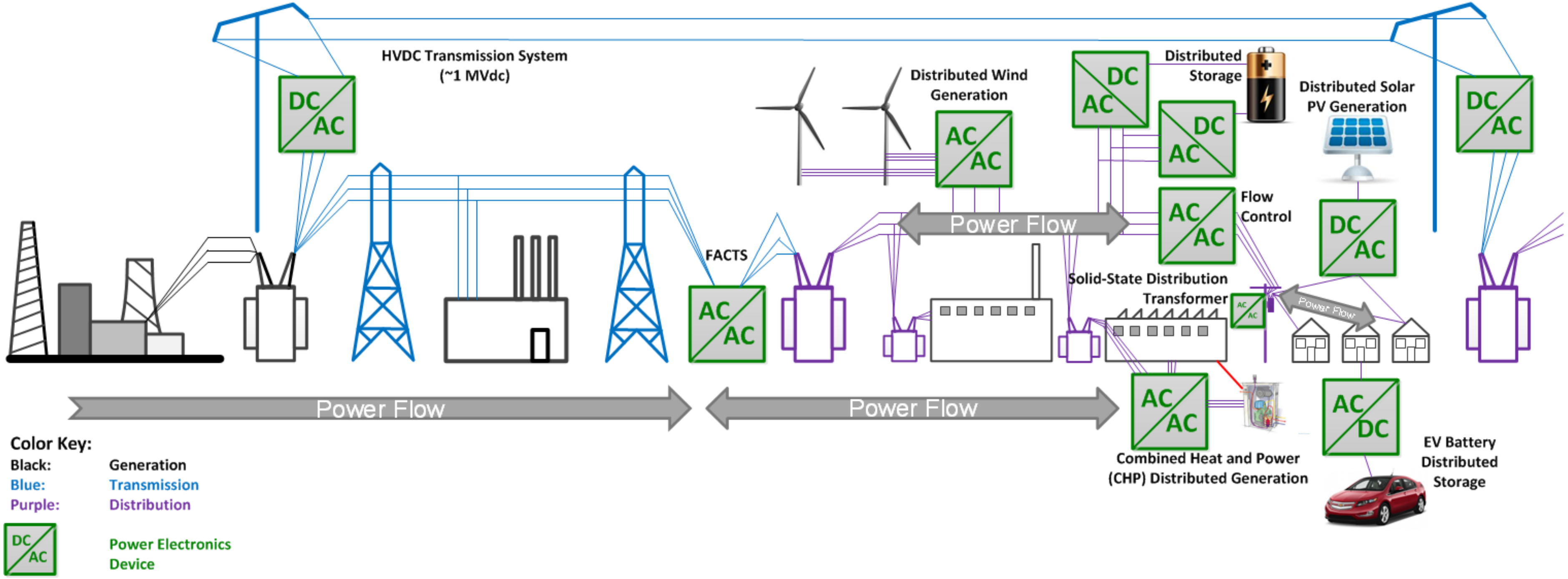
- Dynamometer Test Stand
  - **“Static”** load testing
  - Analog or digital (pulse) tachometer
  - Analog torque transducer

- Rudimentary Test Validation and Reporting
  - **Efficiency** measurements – one speed/load
  - **“Numbers only”**

- Not an Integrated Design Tool
  - No (or very limited) waveform capture
  - No “Dynamic” load measurement
  - No “Complete System” test with controls debug
  - Not well-suited for small motor test and debug

Now: Today's Evolving Power Grid

Power conversion is playing an essential role in the evolving power grid



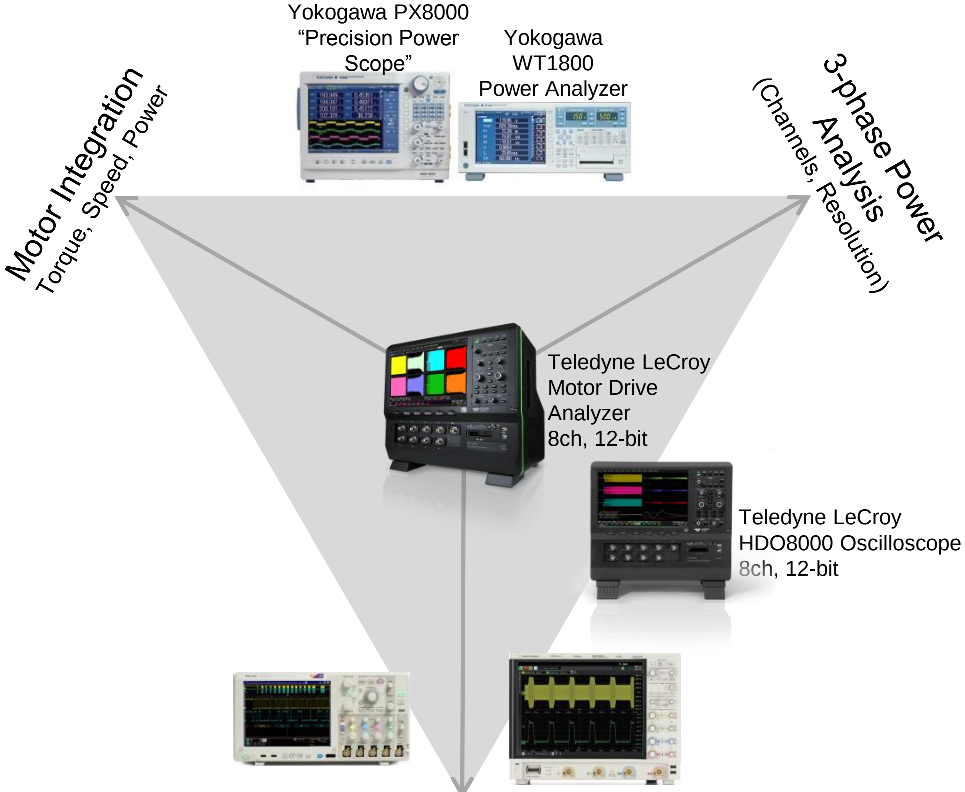
Generation is becoming "distributed". Power conversion systems play a key role in providing generation to the grid, and in maintaining grid stability.

The Power Electronics / Power Conversion Revolution

As costs reduced and reliability increased, power conversion and drives became pervasive

Teledyne LeCroy Motor Drive Analyzers

It’s an 8ch/12-bit Oscilloscope, and it’s also a Power Analyzer with Motor Integration



Yokogawa PX8000 “Precision Power Scope”

Yokogawa WT1800 Power Analyzer

Motor Integration
Torque, Speed, Power

3-phase Power Analysis
(Channels, Resolution)

Teledyne LeCroy Motor Drive Analyzer
8ch, 12-bit

Teledyne LeCroy HDO8000 Oscilloscope
8ch, 12-bit

Oscilloscope Capabilities
(BW, SR, Memory, MSO, Serial Trigger/Decode, IGBT/MOSFET Device Test)

- **Traditional “AC Power Analyzers”**
  - Only calculate **“static”** (steady-state) “mean” power values
  - Some don’t integrate motor torque and speed data (mechanical power)
- **General-purpose 4ch, 8-bit scopes** don’t have enough channels or resolution for three-phase systems
- **Motor Drive Analyzers perform every function**
  - **Static** (steady-state) “mean value” power tables, like a power analyzer
  - **Dynamic** (transient) power analysis
  - **Complete** embedded control debug (i.e. it is a fully-functional oscilloscope)
    - Viewing 3-phase waveform systems
    - High SR, BW, Memory
    - MSO
    - Serial Trigger & Decode

The Basics – Power Conversion

Power electronics circuits are used to “convert” line power to different voltages and frequencies, depending on user and application requirements.

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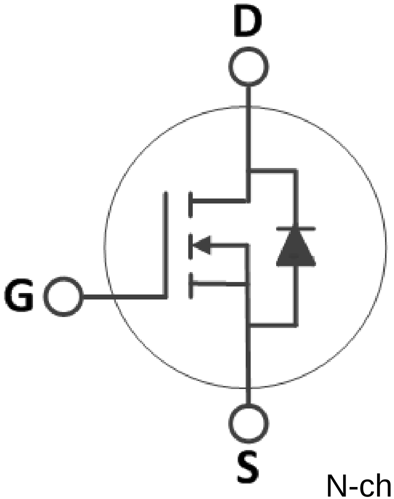
Power Conversion – Definition

- “Power Conversion” is the conversion of electric power from one form to another, from one voltage to another, or one frequency to another, or some combination of these
  - AC-AC
    - AC line voltage conversion to a different voltage and/or frequency
  - AC-DC or DC-AC
    - AC line voltage conversion to a specified DC voltage, or vice-a-versa
  - DC-DC
    - DC voltage conversion to a different specified DC voltage
- “Power Conversion” involves use of fast power semiconductor “switching” devices to enable the conversion in the most efficient manner
  - 1 to 100 kHz (typical) power semiconductor switching frequencies
  - 50/60 Hz core/coil device would not be considered “power conversion” devices

Power Semiconductor Device “Building Blocks”

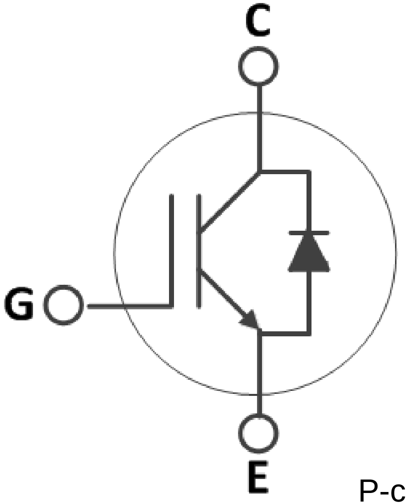
Different nomenclature, but same functions

- Power MOSFET
  - Gate (G)
  - Drain (D)
  - Source (S)



N-channel Enhancement Mode
MOSFET shown

- IGBT
  - Gate (G)
  - Collector (C)
  - Emitter (E)

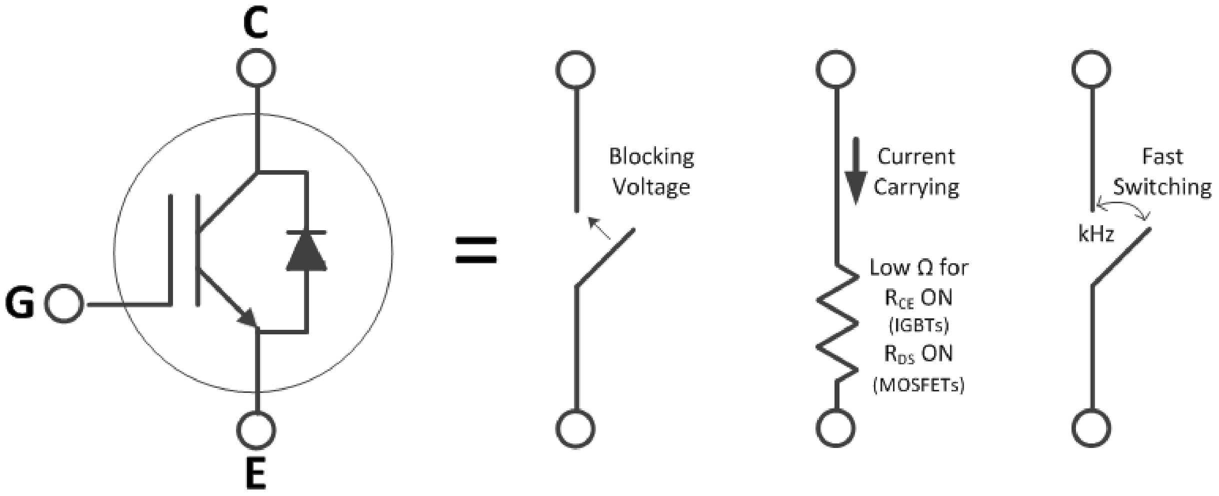


P-channel (minority-carrier)
IGBT shown

Power Semiconductor Device Operation

Think of a Power MOSFET or an IGBT as a fast switch

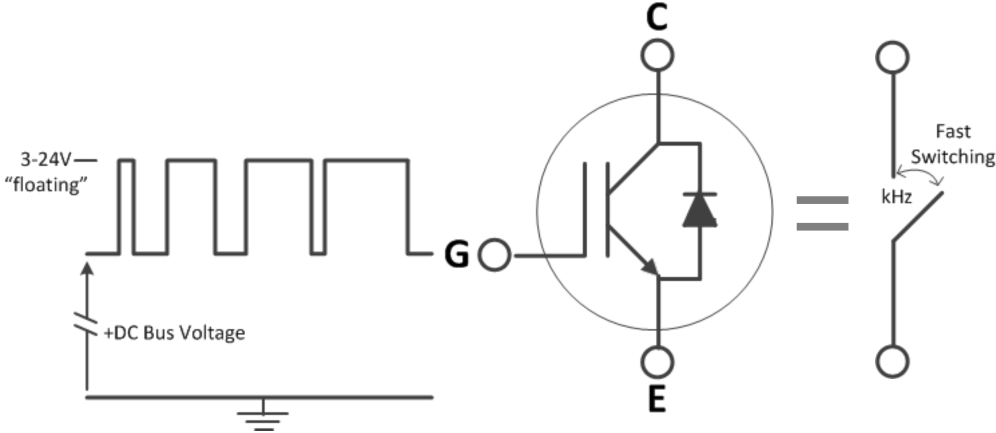
- The power semiconductor can be simply thought of as a very fast switch
  - With a rated “withstand” (blocking) voltage
  - That can conduct a lot of current
  - With low losses (low forward voltage drop)
  - That can switch at very fast frequencies (kHz)



Power Semiconductor Device Operation

The switching is easily controllable with a varying pulse width signal

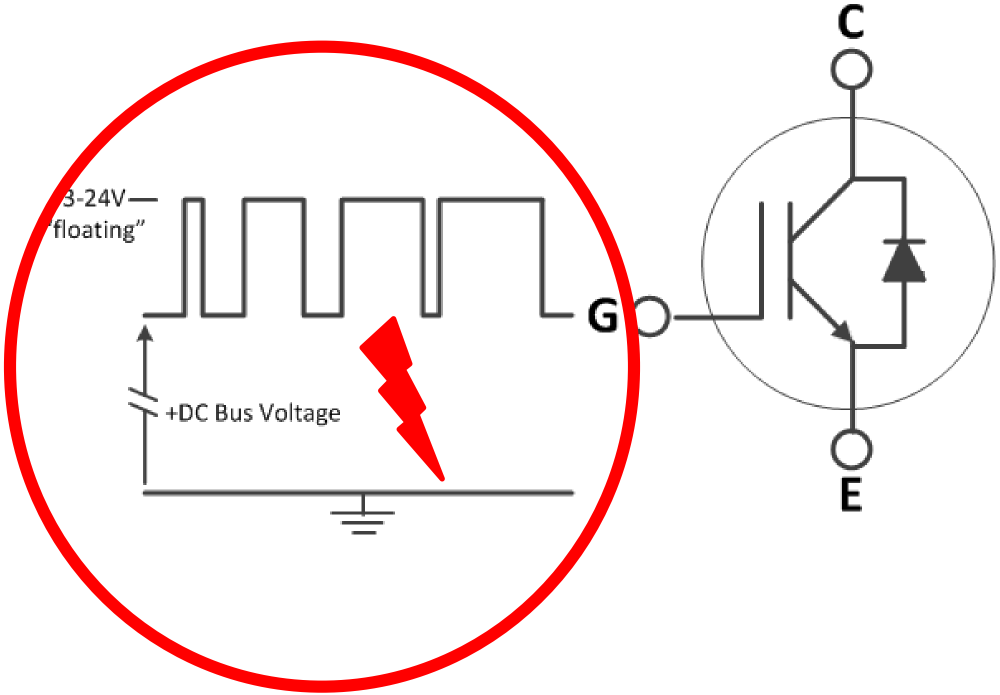
- The Gate (G) controls the switching activity
- A pulse-width modulated (PWM) signal is applied at the gate to control the switching
  - This signal is usually from 3-24V in amplitude, depending on the power semiconductor
  - This signal is usually called the “Gate Drive Signal” or “Gate Driver”
- The power semiconductor then performs the same switching at a higher voltage/current level



Power Semiconductor Device Operation

The gate drive signal is "floating" and requires HV isolation to measure

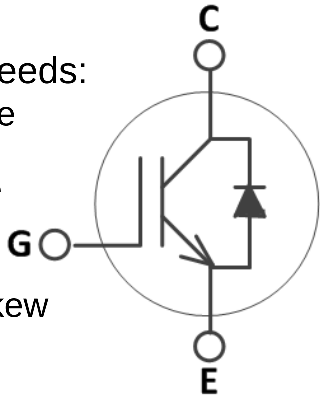
- This gate drive signal is floating at full or half of DC bus voltage, depending on inverter topology
  - This usually requires an isolated input channel on the oscilloscope
    - e.g., 1000Vrms Ch-Ch and Ch-Gnd
  - Or a high voltage differential probe (e.g., Teledyne LeCroy's HVD3000 series) with an appropriate rating
  - For ≤50V drive designs (MOSFETS), a passive probe is often used

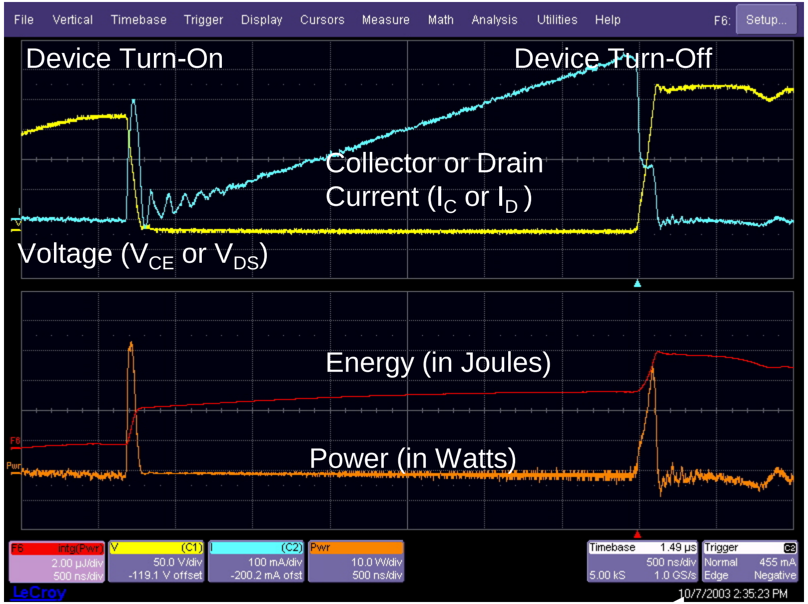


Power Semiconductor Device Operation

Engineers perform “device characterization” on a single power semiconductor

- The “Device Engineer” will characterize how efficient the device is operating at, and will measure:
    - Switching/Conduction Loss
    - R_{DS} ON (MOSFET), dV/dt, dI/dt
    - Safe Operating Area
- Device Engineers have specialized needs:
    - High bandwidth (fast switching time measurement)
    - Excellent overdrive recovery in the measurement system
    - High resolution (accuracy)
    - Precision voltage and current deskew
- Equipment used often includes
    - Specialized differential amplifier
    - Precision deskew calibration device
    - High bandwidth current probes
    - Power Measurement Software
    - High voltage differential probes





DA1855A Differential Amplifier with DXC100A voltage probe lead set

CP031A Current Probe

DCS015 Deskew Calibration Source

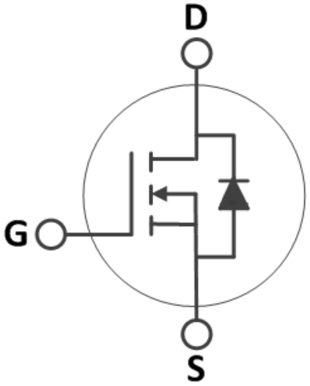
HVD3000 Series 1, 2, and 6 kV HV Differential Probes

Silicon (Si) Power Semiconductor Device Types

These two devices are dominant in most applications for switching at high frequencies

Silicon Power MOSFET

Metal Oxide Semiconductor
Field- Effect Transistor

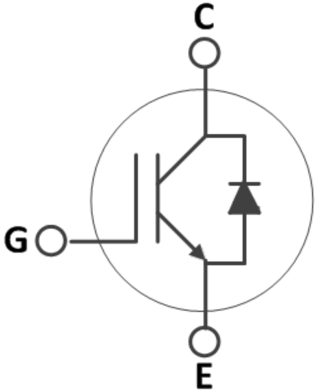


Characteristics

200V blocking voltage (typical) – up to 500V
10s of amperes current handling capability
Higher forward voltage drop at higher voltages
Higher switching frequencies – 20 to 100 kHz typical
Widely deployed in 50V/120/240V applications

Silicon IGBT

Insulated Gate
Bipolar Transistor



Characteristics

1200V blocking voltage (typical) – up to 6000V
100s of amperes current handling capability
Lower forward voltage drop – 2 volt typical
Lower switching frequencies – 1.5 to 10 kHz typical
Widely deployed in 600V class applications

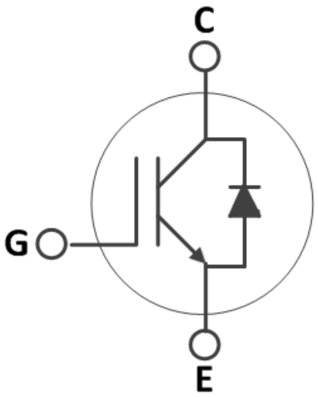
“Wide-bandgap” (SiC and GaN) Power Semiconductor Devices

These will become more widely used in the future

- Silicon Carbide (SiC) and Gallium Nitride (GaN)
  - Higher breakdown voltages (SiC)
  - Faster switching frequencies
  - Lower leakage currents
  - Lower thermal resistance
- System Advantages
  - Reduced heat-sink sizes
  - Reduced size filter components (capacitors, inductors)
  - Lower weight
  - Higher power density
  - Higher efficiencies
- Disadvantages
  - Reliability (design experience)

Silicon Carbide (SiC) IGBT

Insulated Gate Bipolar Transistor



Characteristics

12 kV blocking voltage
100s of amperes current handling capability
Lower forward voltage drop – <1 volt typical
Faster switching speeds – 20 kHz to 100 kHz
Will be increasingly adopted in ≥600V class designs

Power Semiconductor Device Types

Other devices you may have heard about…but these are declining in usage

- Thyristors (various)
  - Applications
    - Very high power levels
    - Very high voltages
    - Low switching frequencies (as low as once per 50/60 Hz half period)
  - Switching
    - Switchable “ON” but not “OFF” (OFF = zero crossing)
      - Silicon-controlled rectifier (SCR)
    - Switchable “ON” and “OFF”
      - Gate turn-off thyristor (GTO)
      - Gate-commutated thyristor (GCT)
      - Insulated gate-commutated thyristor (IGCT)
      - MOS-controlled thyristor (MCT)
  - Wide-bandgap material power semiconductors are likely to replace most or all of these devices in their current applications

Power Semiconductor Types – Historical Market Segmentation

By blocking voltage, current delivery, and switching frequency

- Power MOSFET
  - 120/240V Switch-mode power supplies
  - 120/240V Lighting ballasts
  - Low voltage (<50V) or low power 120V/240V motor drives
  - Low power, lower voltage
- IGBT
  - 600V class motor drives
  - Propulsion (“traction”) motor drives
  - Uninterruptible power supply (UPS)
  - Welding, robotics
  - Higher power, high voltage
- SCR/GTO
  - Utility T&D equipment
  - Very high voltage, very high power
  - Likely superseded by wide-bandgap (SiC) IGBTs

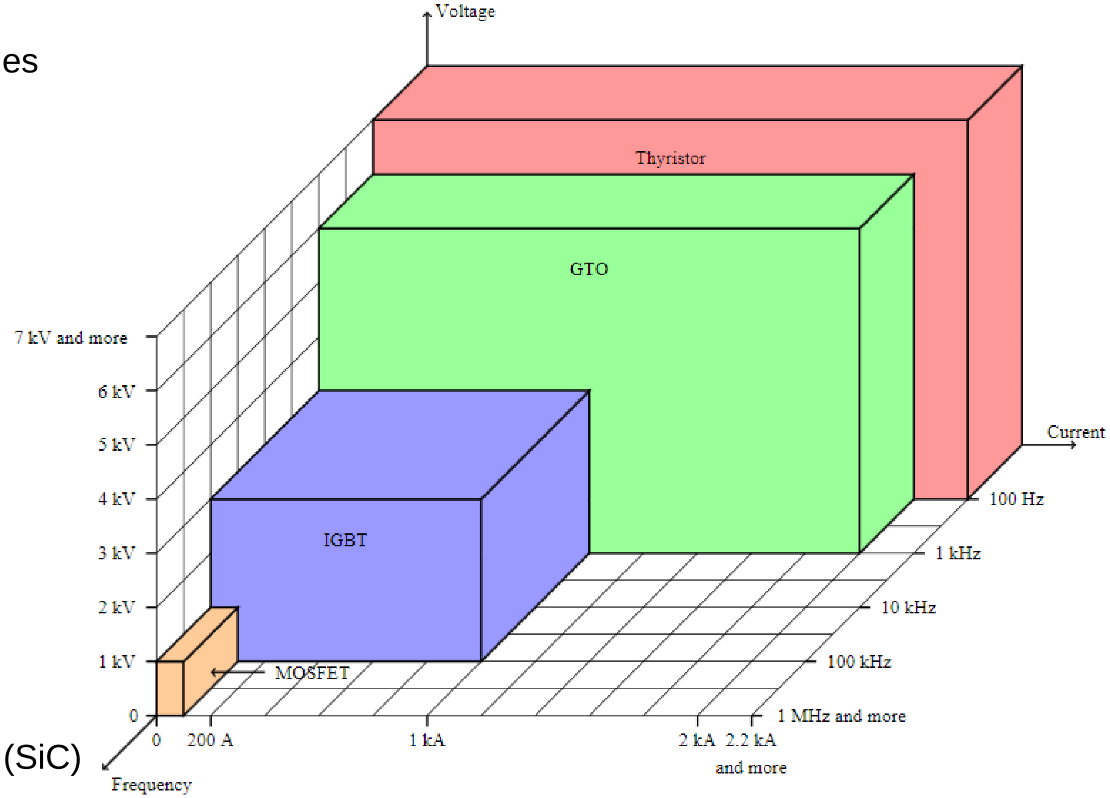
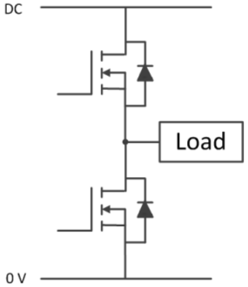


Image from https://en.wikipedia.org/wiki/Power_semiconductor_device

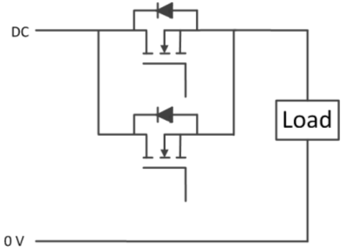
Power Semiconductor Implementation

Series/parallel combinations provide higher voltage/current

- Power Semiconductors can be connected in
  - Series (half-bridge shown)
    - To provide higher voltage



  - Or parallel
    - To provide higher current



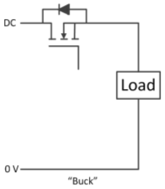
- The can also be connected in various “full-bridge” or “cascaded” topologies to achieve
  - Multi-phase operation
  - Multi-(output) level operation
    - Lower harmonics
  - Bi-directional control/power flow
- The only practical limitation to infinite series/parallel combinations are:
  - Increasing costs
  - Increasing control complexity

Typical Power Conversion Topologies

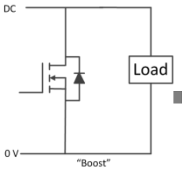
These are the typical "building blocks" for power conversion circuits

Low Power
Low Voltage
Few Semiconductors

- Single-stage (Boost)
  - MOSFET-based
- Applications
  - DC-DC Converter
  - LED driver

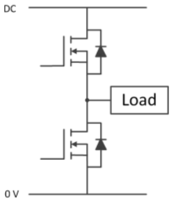


"Buck"



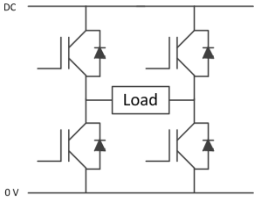
"Boost"

- Half-Bridge
  - Usually MOSFET-based
- Applications
  - CFL lighting ballast
  - Switch-mode power supply (SMPS)

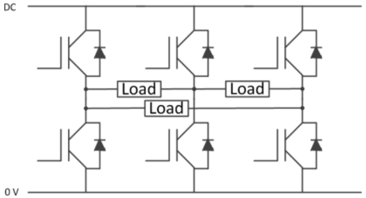


Higher Power
Higher Voltage
More Semiconductors

- Full-Bridge (H-Bridge)
  - MOSFET or IGBT-based
- Applications
  - 1-phase grid-tied inverter
  - 1-phase motor drive
  - UPS
  - Higher Power DC-DC converter



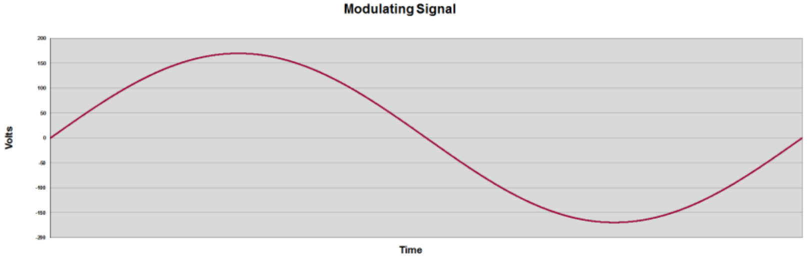
- (Three-Phase) Cascaded H-Bridge
  - MOSFET or IGBT-based
- Applications
  - Motor Drive
  - Grid-tied inverter

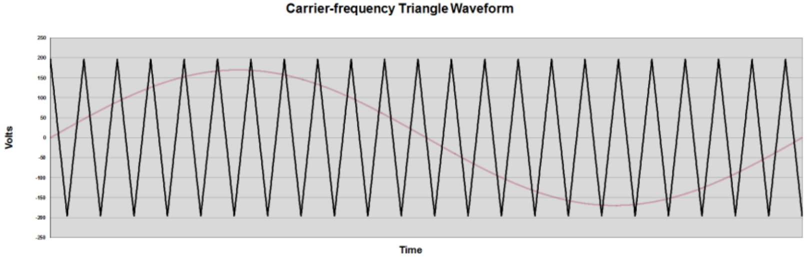


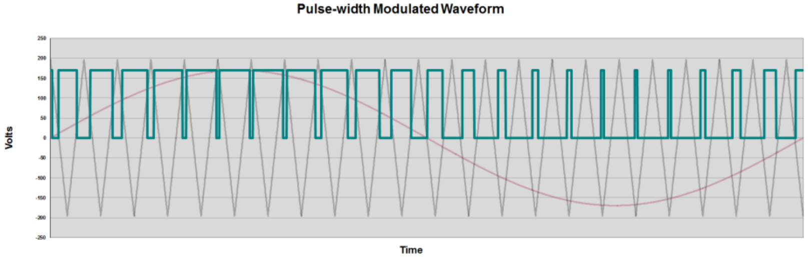
Pulse-width Modulation (PWM) Basics

This example is for a carrier-based PWM technique - there are other methods

- A modulating waveform defines the desired output voltage and frequency
- A high-frequency (1 to 100 kHz) carrier waveform is generated
  - The carrier waveform is often a triangle waveform
  - It is shown here as <<1 kHz to make it easy to see in relation to the lower frequency modulating waveform
- The intersection of the carrier waveform and modulating waveform defines the pulse width creation
  - This is a simple example for a single-device circuit
  - This is simply meant to be illustrative


Modulating Signal

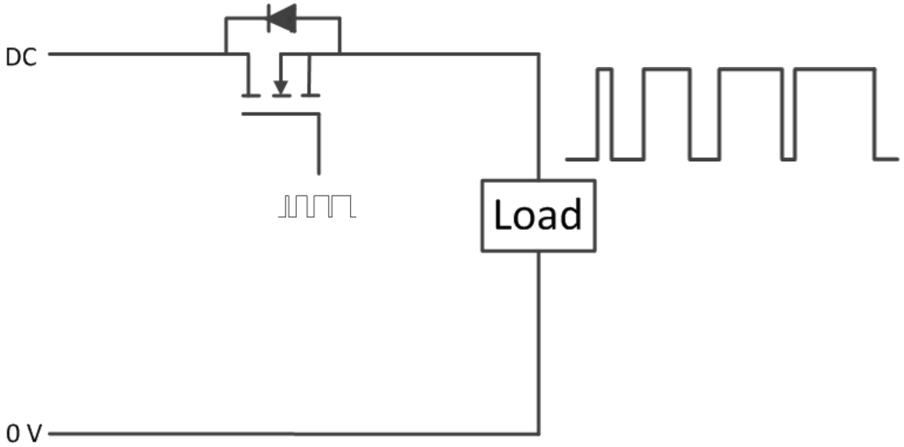

Carrier-frequency Triangle Waveform

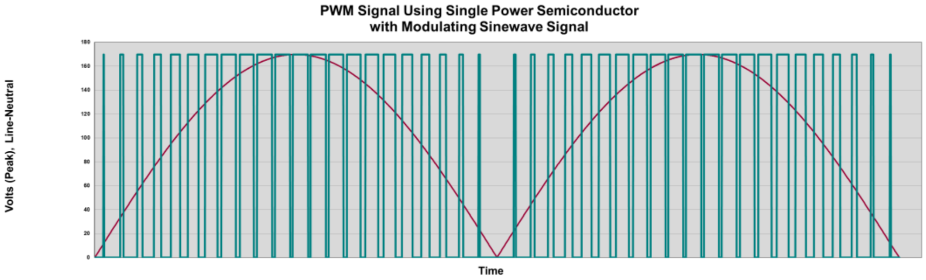

Pulse-width Modulated Waveform

Single-stage (Boost) Implementation

Let's understand this operation as a foundation for more complicated topologies

- Power semiconductor "opens" and "closes" based on gate-drive signal to supply DC voltage and current at load
  - Assume DC voltage = 170Vdc
- PWM signal at Gate creates "digital" PWM signal at load
  - "1" level = 170Vdc
  - "0" level = 0 Vdc
- If PWM signal is modulated with AC sinusoid, then fundamental frequency of PWM signal on load is a rectified AC sinusoid
  - Note: the rectified modulating sinusoid is shown to the right overlaid on the PWM signal

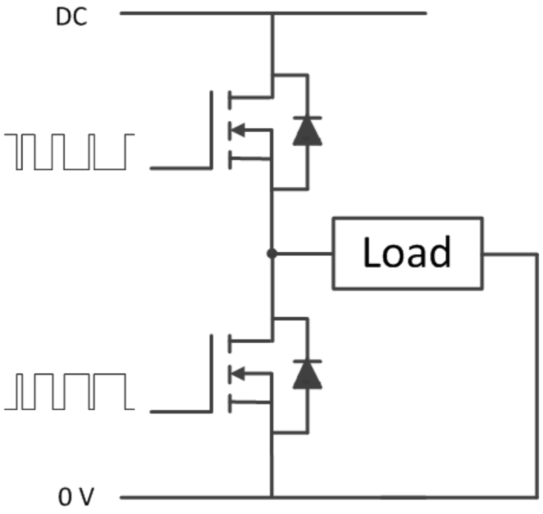


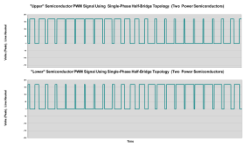


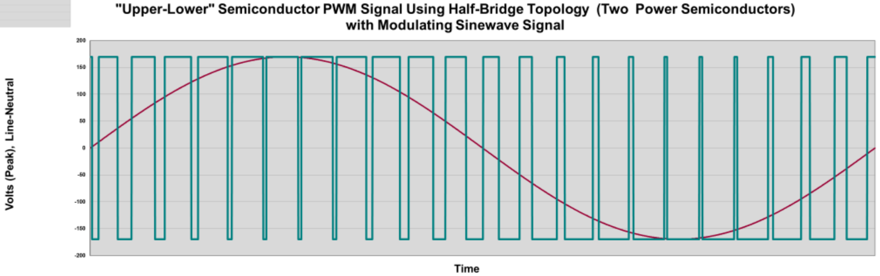
Half-Bridge (Series Connection) Implementation

Higher voltage AC sinusoidal output, single-direction power flow via load termination

- Load is connected at midpoint of circuit and could be terminated at either
  - The upper rail (DC)
  - The lower rail (0V) (as shown)
- Complementary PWM signals are applied at the Upper Device and Lower Device gate
  - Both devices can not be “on” (conducting) at the same time or there will be a short circuit
- Upper and Lower Devices Both
  - “1” level = 170Vdc
  - “0” level = 0 Vdc
- Upper-Lower Device = Load
  - +170Vpk to -170Vpk
  - 50% PWM duty cycle = 0V



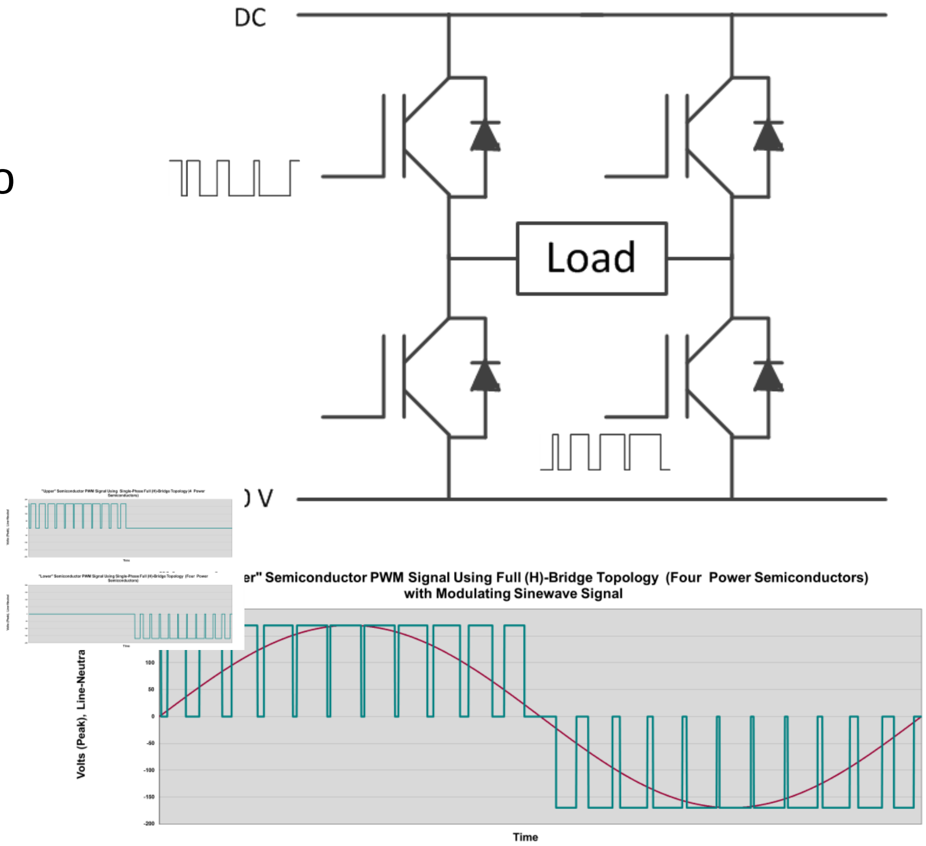




Full-Bridge (H-Bridge) Implementation

Higher voltage AC sinusoidal output, bi-directional power flow and braking

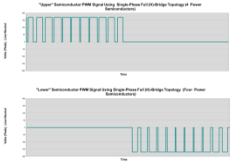
- A Full-Bridge is essentially two Half-Bridges in Parallel with the load connected at the midpoint of each
- Device switching can be programmed to provide
  - “Forward” current flow through load
  - “Reverse” current flow through load
  - “Braking” from forward direction
  - “Braking” from reverse direction
  - “Stop” (no current flow)
- Gate drive signals are complementary, but…
  - Upper device is modulated for positive half of sinewave and lower device is modulated for negative half of sinewave
  - Load sees +170Vpk to -170Vpk



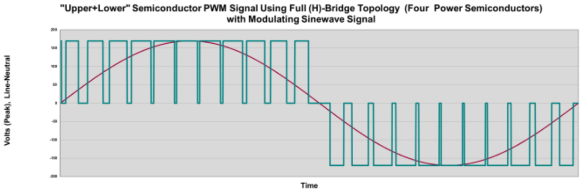
Full-Bridge (H-Bridge) Implementation

Positive Direction Current Flow

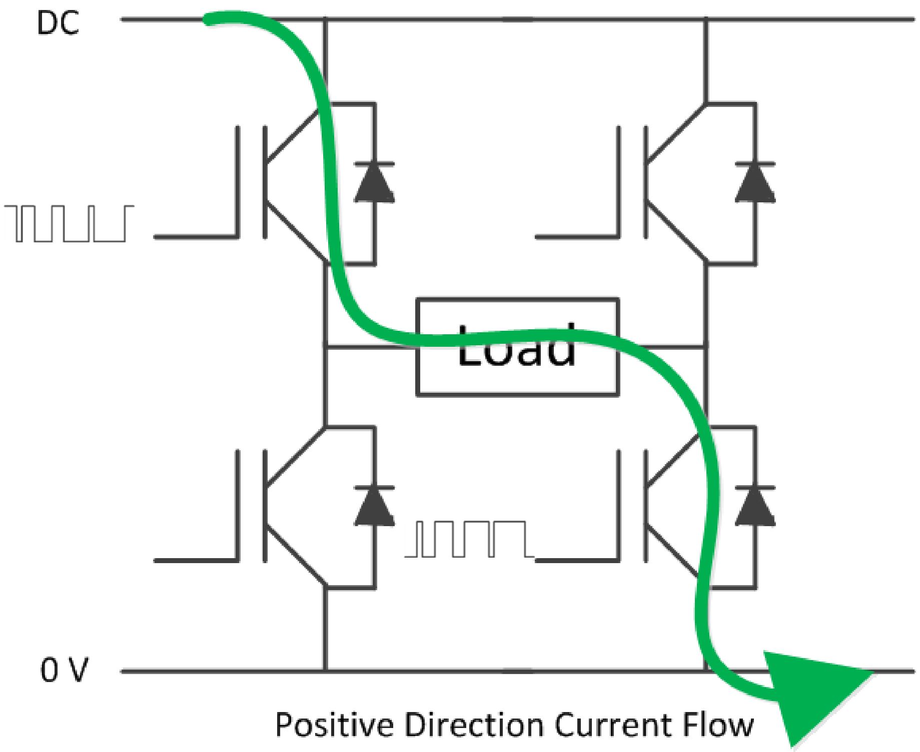
- Upper left and lower right devices are switched ON with PWM gate drives
    - As with the Half-bridge, gate drives are complementary



    - Output across load is Upper-Lower = +170Vpk to -170Vpk PWM signals



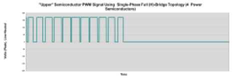
- Lower left and upper right devices are OFF (open)

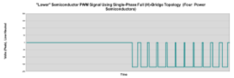


Full-Bridge (H-Bridge) Implementation

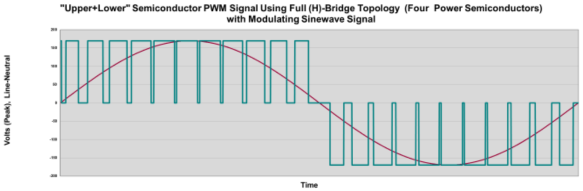
Negative Direction Current Flow

- Upper right and lower left devices are switched ON with PWM gate drives
  - As with the Half-bridge, gate drives are complementary

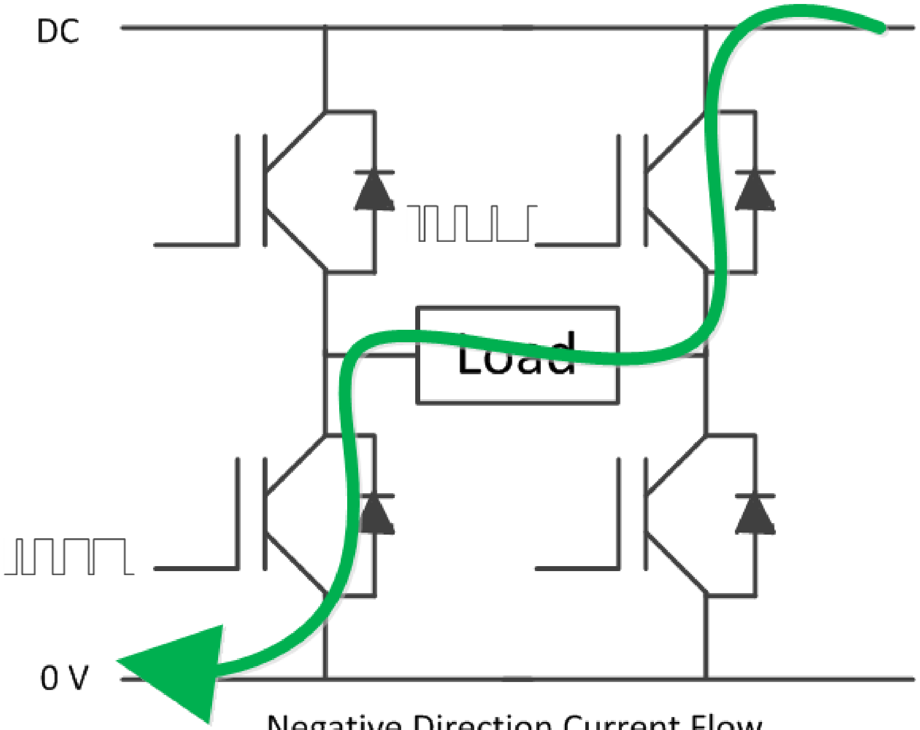




  - Output across load is Upper-Lower = +170Vpk to -170Vpk PWM signals



- Lower left and upper right devices are OFF (open)

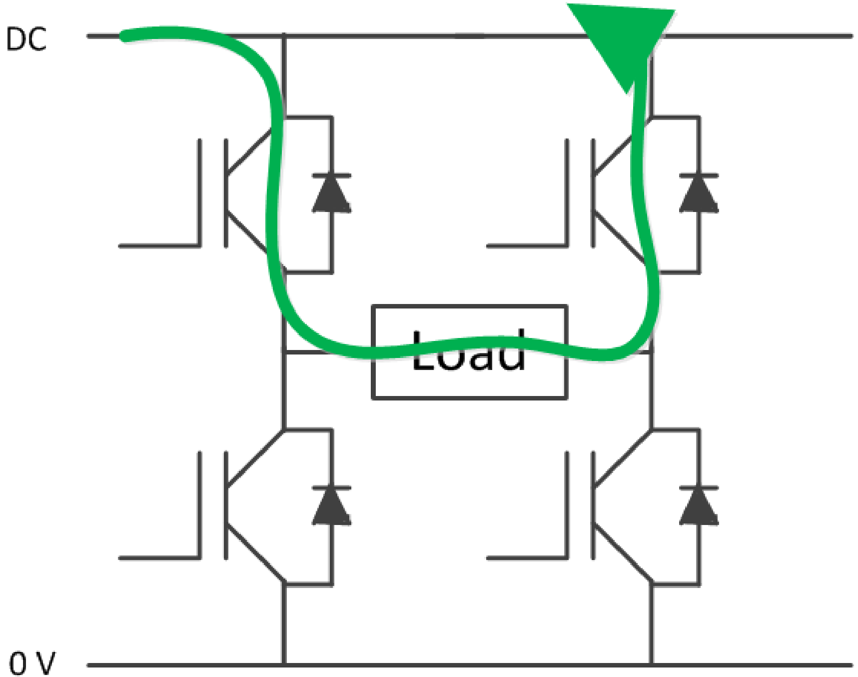


Negative Direction Current Flow

Full-Bridge (H-Bridge) Implementation

Braking a motor from a positive current flow direction

- Upper left and upper right devices are switched ON (conducting) creating a path for current to flow from the motor terminals back to the DC supply
    - "Static" braking – motor simply spins down delivering energy to DC supply
    - "Dynamic" braking – PWM signals are applied to brake the motor faster or in a controlled fashion
- Lower left and lower right devices are switched OFF (open)



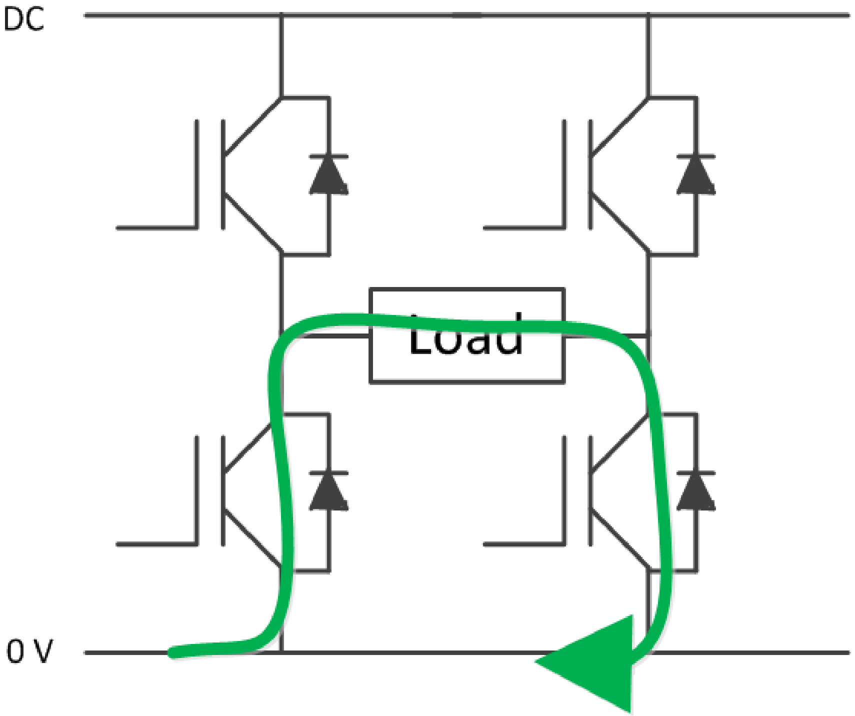
Braking Enabled When Motor is Running in Positive Direction

Full-Bridge (H-Bridge) Implementation

Braking a motor from a negative current flow direction

- Low left and lower right devices are switched ON (conducting) shorting the motor terminals to ground
  - “Static” braking – motor simply spins down delivering energy to DC supply
  - “Dynamic” braking – PWM signals are applied to brake the motor faster or in a controlled fashion

- Upper left and upper right devices are switched OFF (open)

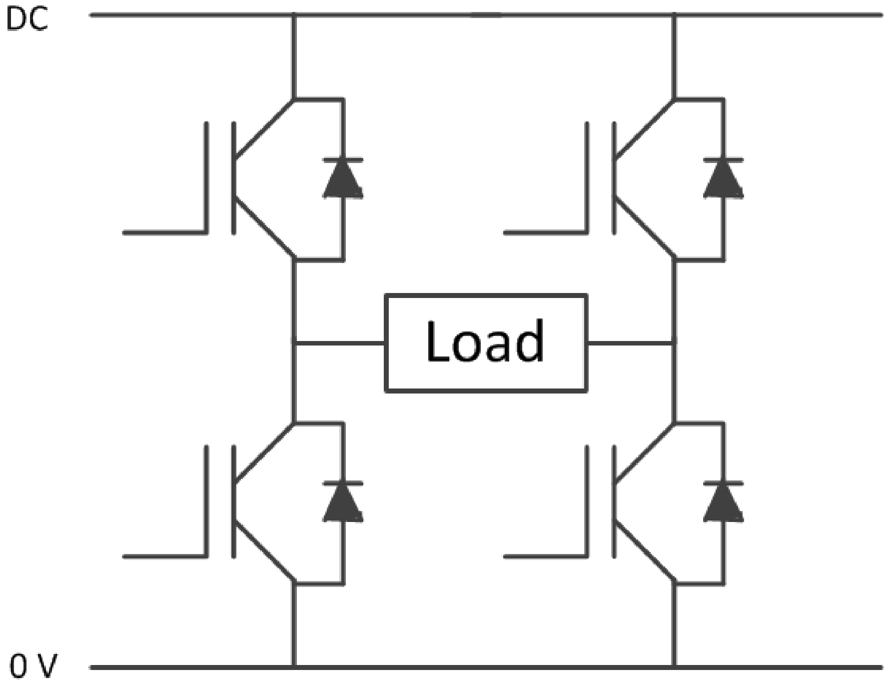


Braking Enabled When Motor is Running in Negative Direction

Full-Bridge (H-Bridge) Implementation

Holding a motor in a "stopped" position

- All devices are switched OFF (open)
    - No current flows in the circuit

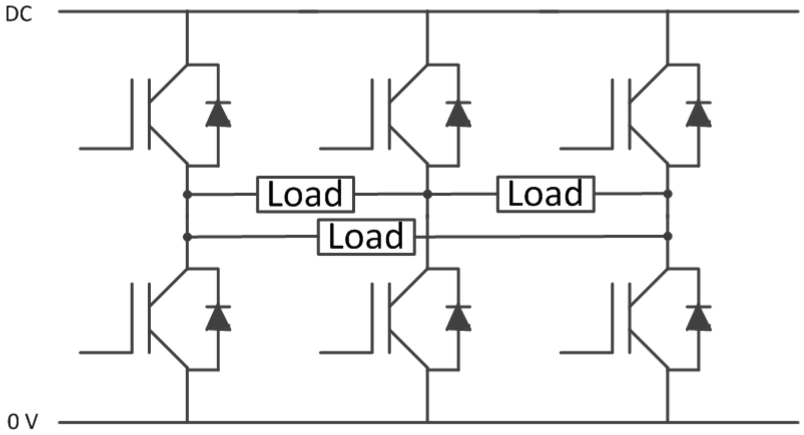


Cascaded H-Bridge Implementation

Three-phase AC sinusoidal output, bi-directional power flow and braking

- A Cascaded H-Bridge is essentially three H-Bridges with three loads (phases) connected across each series pair
  - These loads are the three “phases”
  - The loads are connected “line-line”
    - e.g. U-V, V-W, W-U; or R-S, S-T, T-R depending on the nomenclature used

- There are two basic methods to create the three-phase output waveforms
  - “Sine” modulated
    - Carrier-based PWM
    - Space Vector Modulation (SVM)
  - Six-step commutated



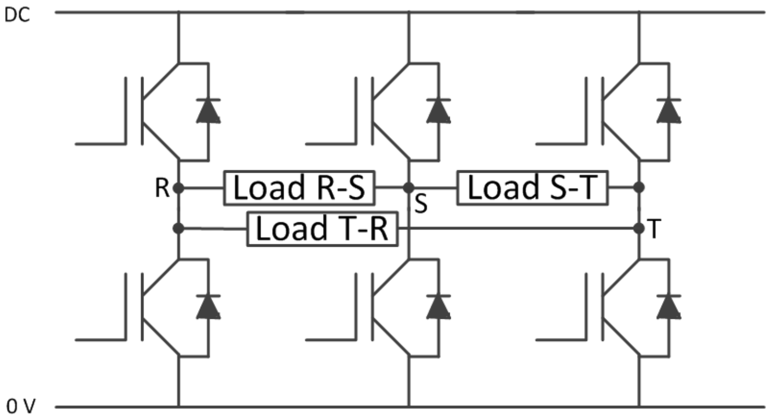
Polling Question #1

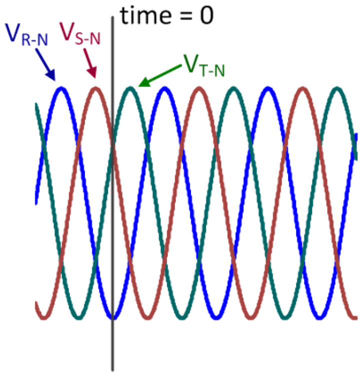
- What power conversion topology do you generally utilize in your designs? (Choose one answer)
  - Single-stage (buck or boost)
  - Half-bridge
  - Full-bridge (H-bridge)
  - Cascaded H-bridge
  - Other

Cascaded H-Bridge Implementation

"Sine" modulated control principles

- Voltage is generated across all three loads (phases) at all times using three carrier-frequency (sinewave) modulating signals 120° apart
- Example: at time=0, output voltages are desired to be
  - V_R = -170V
  - V_S = +85V
  - V_T = +85V
- Gate drive PWM signals can be calculated to create current flow consistent with these voltages



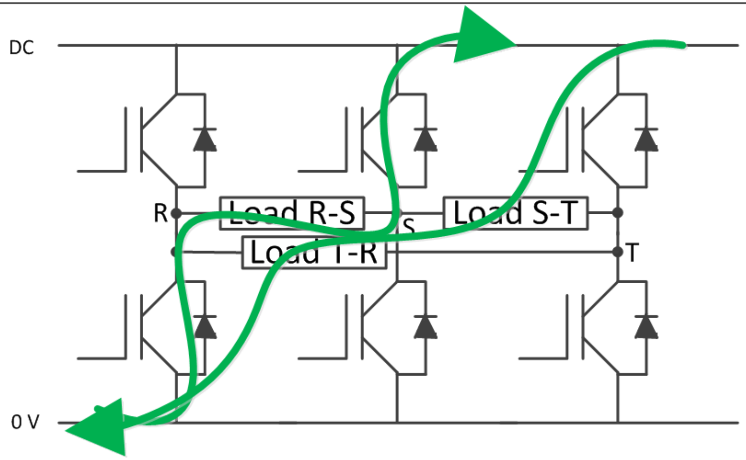


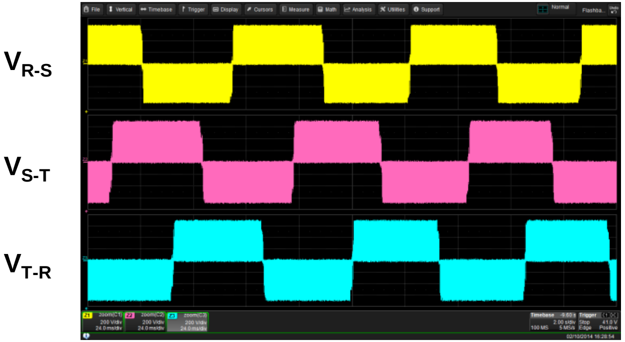
Modulating sinewave signals

Cascaded H-Bridge Implementation

“Sine” modulated control example

- At time=0, devices switch “on” (PWM) or “off” (open)
  - Upper R device is “off”
  - Lower R device is “on” – PWM negative
  - Upper S device is “on” – PWM positive
  - Lower S device is “off”
  - Upper T device is “on” – PWM positive
  - Lower T device is “off”
- PWM during “on” interval defines motor voltage and frequency applied
  - Duty cycle of pulse width defines voltage level
  - Carrier frequency determines frequency
- PWM outputs appear as in an H-Bridge, but for three-phases
  - At right are three-phase *line-line* output PWM waveforms for a sine-modulated Cascaded H-Bridge

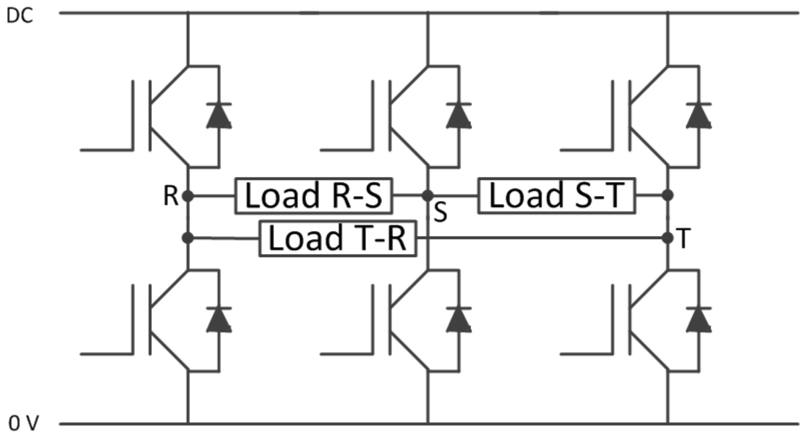


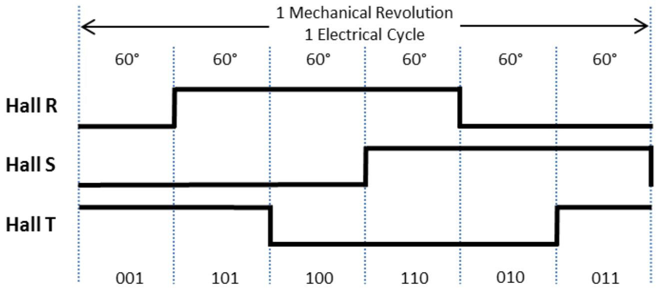


Cascaded H-Bridge Implementation

Six-step commutation (modulated) control principles

- Voltage is generated across only two loads (phases) at any given time
- There are six “steps” per commutation period
  - These steps are often determined by Hall sensors embedded in the rotor
  - The Hall sensors generate a 3-bit pattern that defines gate drive operation at any given moment in time
- Voltage “commutation” (application) is defined by each “step” interval
  - PWM within the “step” interval defines the amount of voltage applied



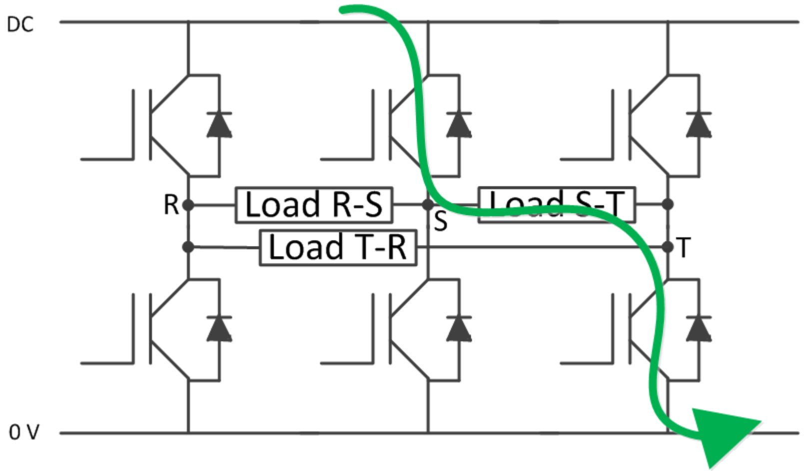


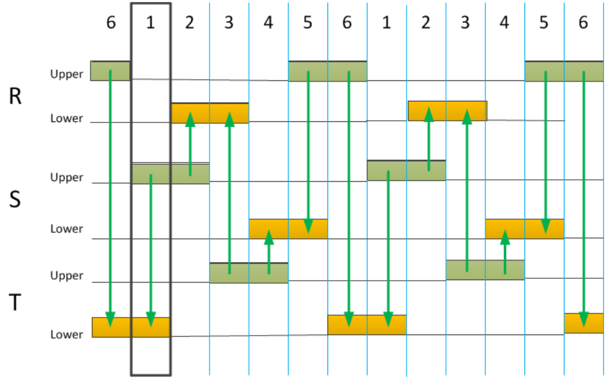
Three Hall effect sensors, 120° degrees apart, 1 rotor pole-pair

Cascaded H-Bridge Implementation

Six-step commutation (modulated) control principles, continued

- e.g. at Step 1 (in image at below right)
  - R = not energized (open)
  - S = positive PWM
  - T = negative PWM
- Devices switch “on” (conducting) or “off” (open)
  - Upper R device is “off”
  - Lower R device is “off”
  - Upper S device is “on” – PWM positive
  - Lower S device is “off”
  - Upper T device is “off”
  - Lower T device is “on” – PWM negative
- PWM during “on” interval defines motor voltage and frequency applied
  - Duty cycle of pulse width defines voltage level
  - Carrier frequency determines frequency



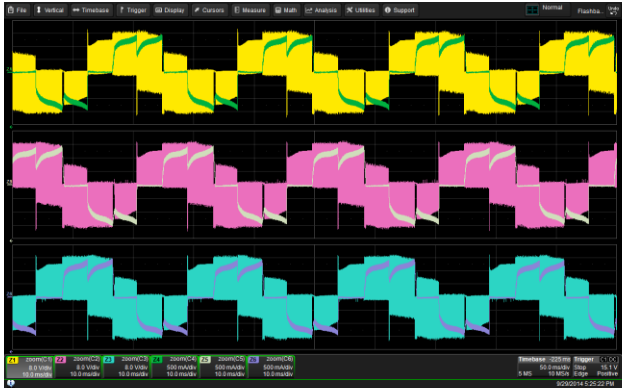


Cascaded H-Bridge Implementation

Six-step commutation (modulated) control example

- Six-step commutation is a common control/modulation methodology for Brushless DC motors
  - Low cost
  - Reasonable performance
  - High torque ripple (sometimes undesirable)
  - High audible noise (sometimes undesirable)

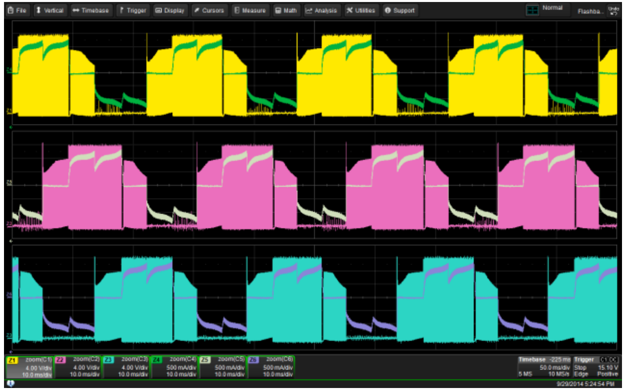
- Waveforms look very different from sine-modulated waveforms
  - Line-Line voltage waveforms at top right
  - Line-Reference voltage waveforms at bottom right



V_{R-S}

V_{S-T}

V_{T-R}



V_{R-ref}

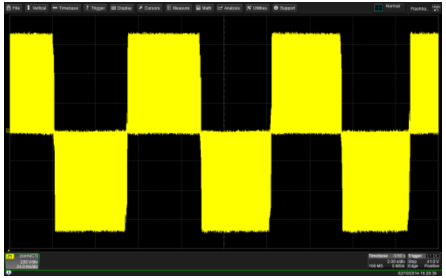
V_{S-ref}

V_{T-ref}

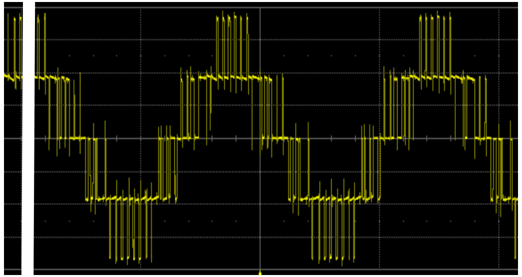
A Three-Phase Multi-level (3) Neutral-Point Clamped (NPC) Inverter

Is essentially just two Cascaded H-Bridge topologies

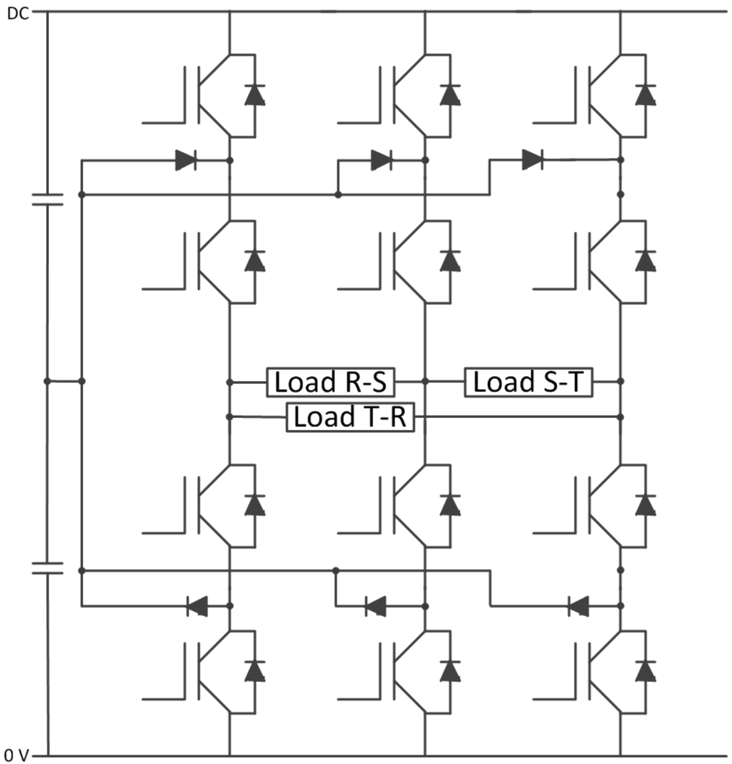
- More power transistors provides more output voltage resolution
  - Lower harmonics
  - More easily scalable to >600V class outputs
  - But more complex and costly



Two Level
Cascaded H-Bridge Inverter
(Line-Line Voltage)

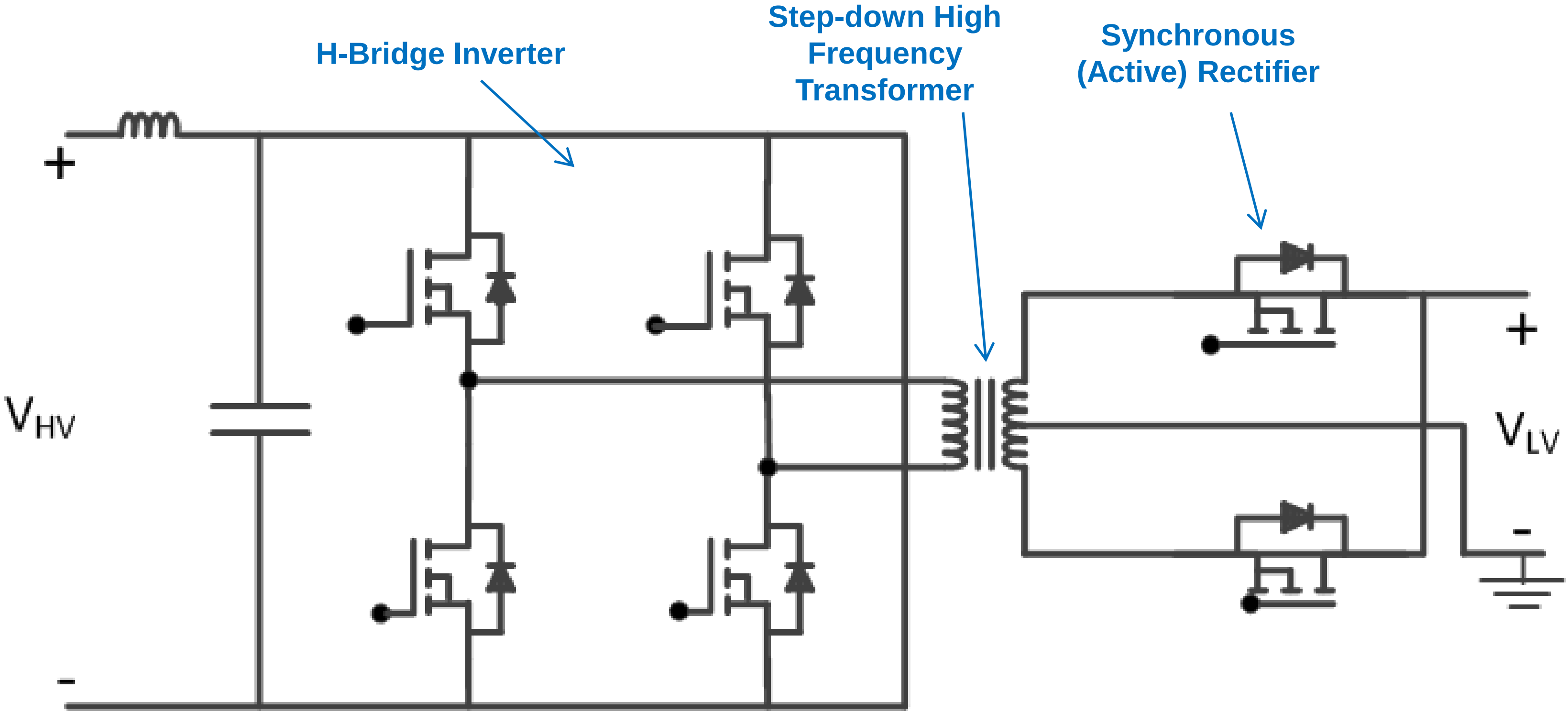


Three Level
NPC Inverter
(Line-Line Voltage)



DC-DC Converter for High-Power Applications

This is a “generic” full-bridge (H-bridge) electric/hybrid vehicle ~400V_{DC} to 12V_{DC} converter



H-Bridge Inverter

Step-down High Frequency Transformer

Synchronous (Active) Rectifier

Summary – Power Conversion Topologies

- The power conversion topology is chosen based on application
  - "Single-stage" – low voltage, simple
  - Half-Bridge – single-phase, uni-directional power flow
  - Full-Bridge (H-Bridge) – single-phase, high power, bi-directional power flow
  - Cascaded H-Bridge – three-phase, high power, bi-directional power flow

- There are several methods used to modulate the output
  - Sine modulation
    - Carrier-frequency
    - Space Vector (Vector controls)
  - Six-step commutation

- The power conversion output waveforms differ in appearance based on the modulation method

The Basics – “Drives”

AC-AC Power Conversion systems are often referred to as “drives”, with Motor Drives the most common. Variable Frequency Drives (VFDs), Variable Speed Drives (VSDs) and Inverter Drives are other names for Drives.

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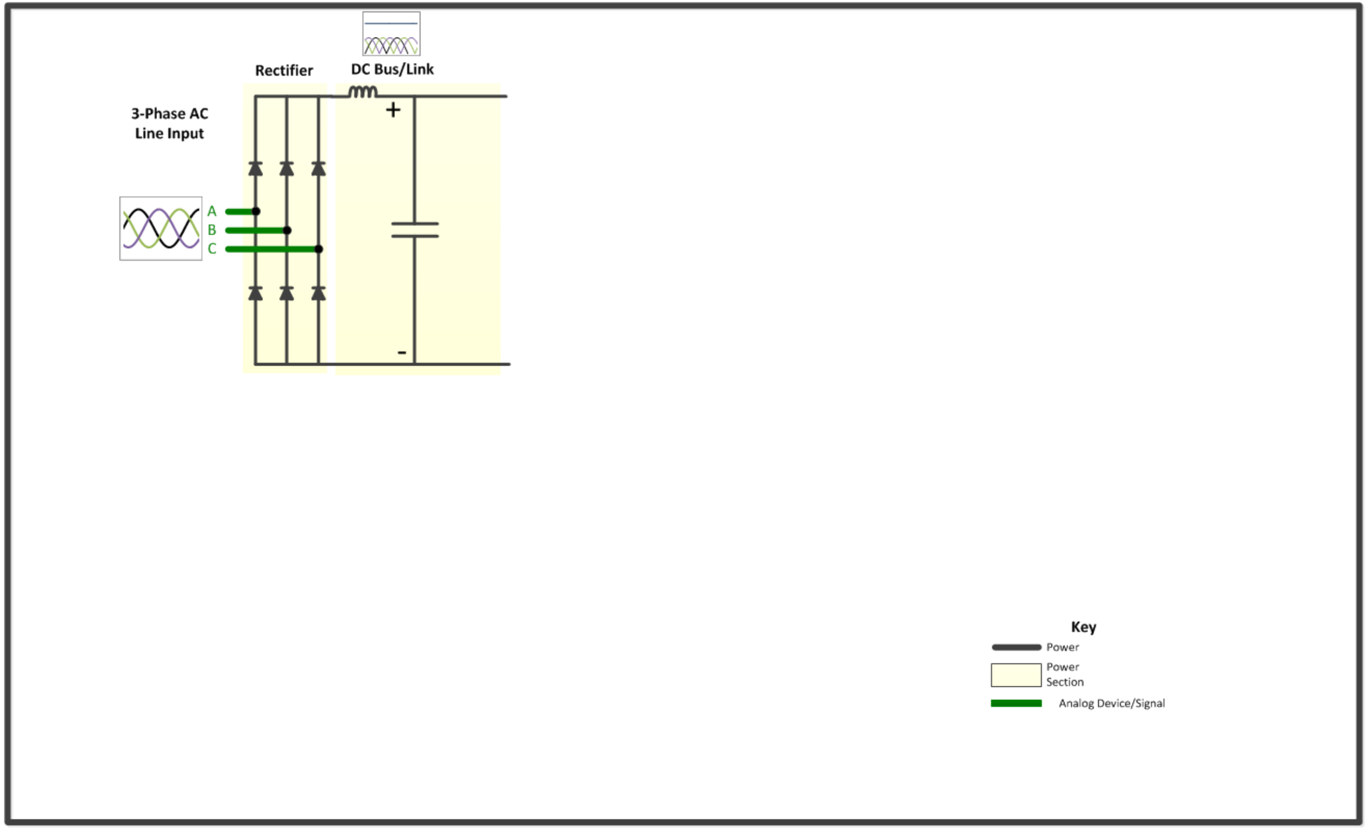
What is a “Drive”?

- A “Drive” converts line AC (typically 50/60 Hz) to variable frequency AC
- A “Drive” contains the following:
  - AC line input
  - AC-DC rectifier, filter, and energy storage
  - Inverter subsection
    - Single-Phase = Full-Bridge (H-Bridge) topology
    - Three-Phase = Cascaded H-Bridge topology
  - (Power semiconductor) gate drivers
  - Embedded control system
  - User and system control inputs
  - Drive Feedback sensing
- A “Motor Drive” is a drive that powers a motor in a controlled manner to achieve higher efficiencies and/or better operating characteristics than would be possible with line AC.
  - Torque and speed feedback signals

AC Line Input, AC-DC Rectifier, and Filter/Energy Storage

This section would be omitted if the drive is powered directly from a battery

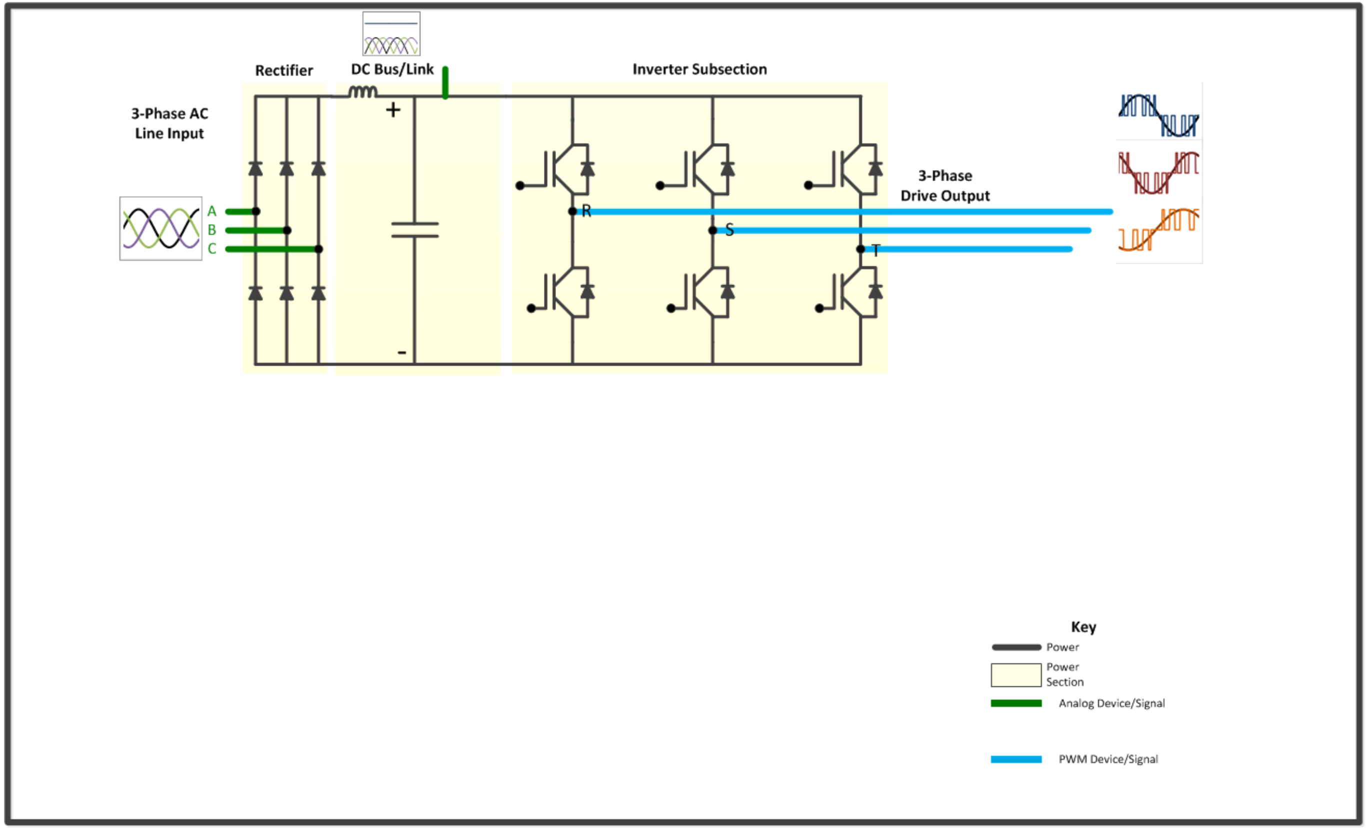
- Rectified AC with filtering and energy storage creates "stiff" DC to supply Inverter Subsection



Plus the Inverter Subsection

This is the Cascaded H-Bridge power conversion topology discussed in the previous section

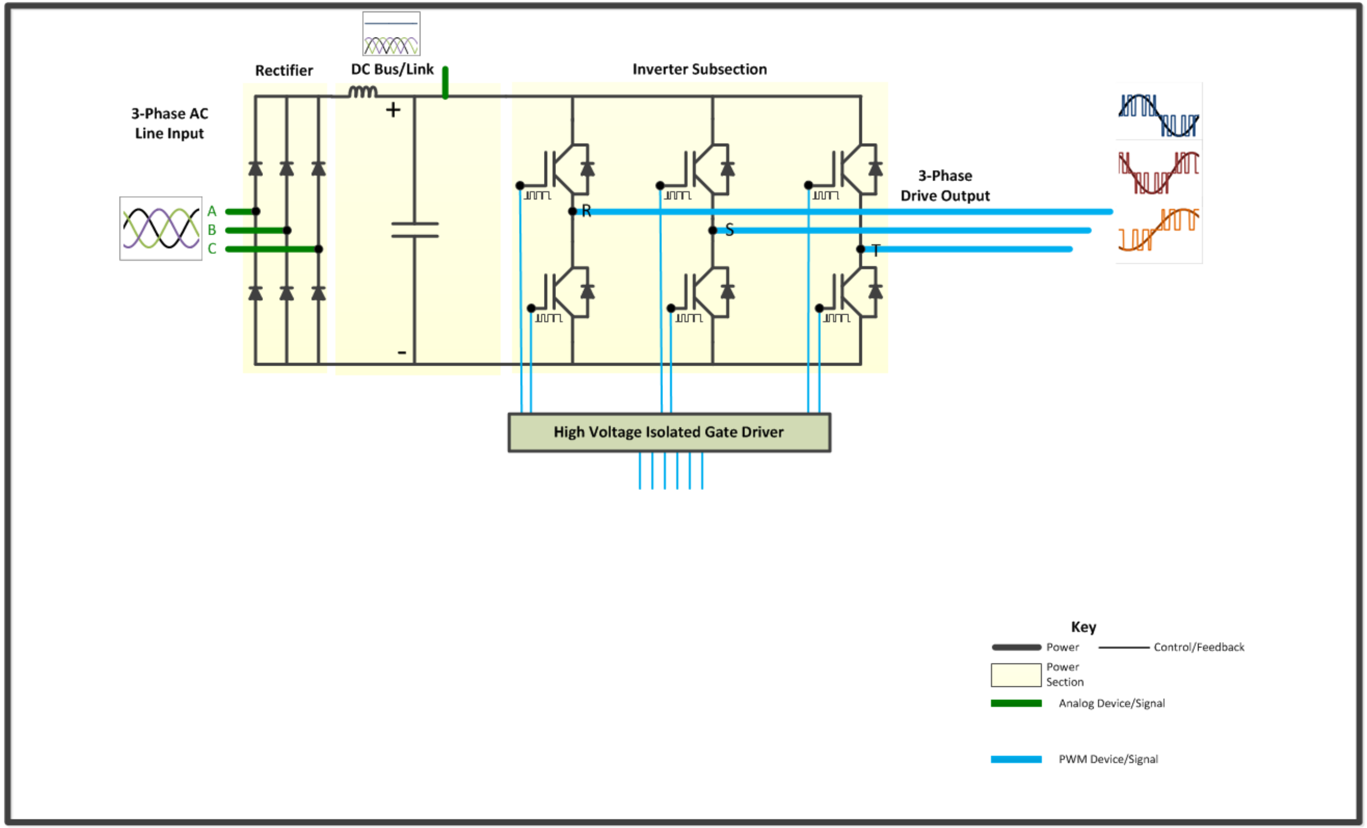
- Inverter Subsection creates PWM output waveforms
  - PWM duty cycle = voltage magnitude
  - Positive / Negative period = frequency



Power Semiconductor Gate Drive Signals

May be optically isolated from the controls, or simply floated with the control system

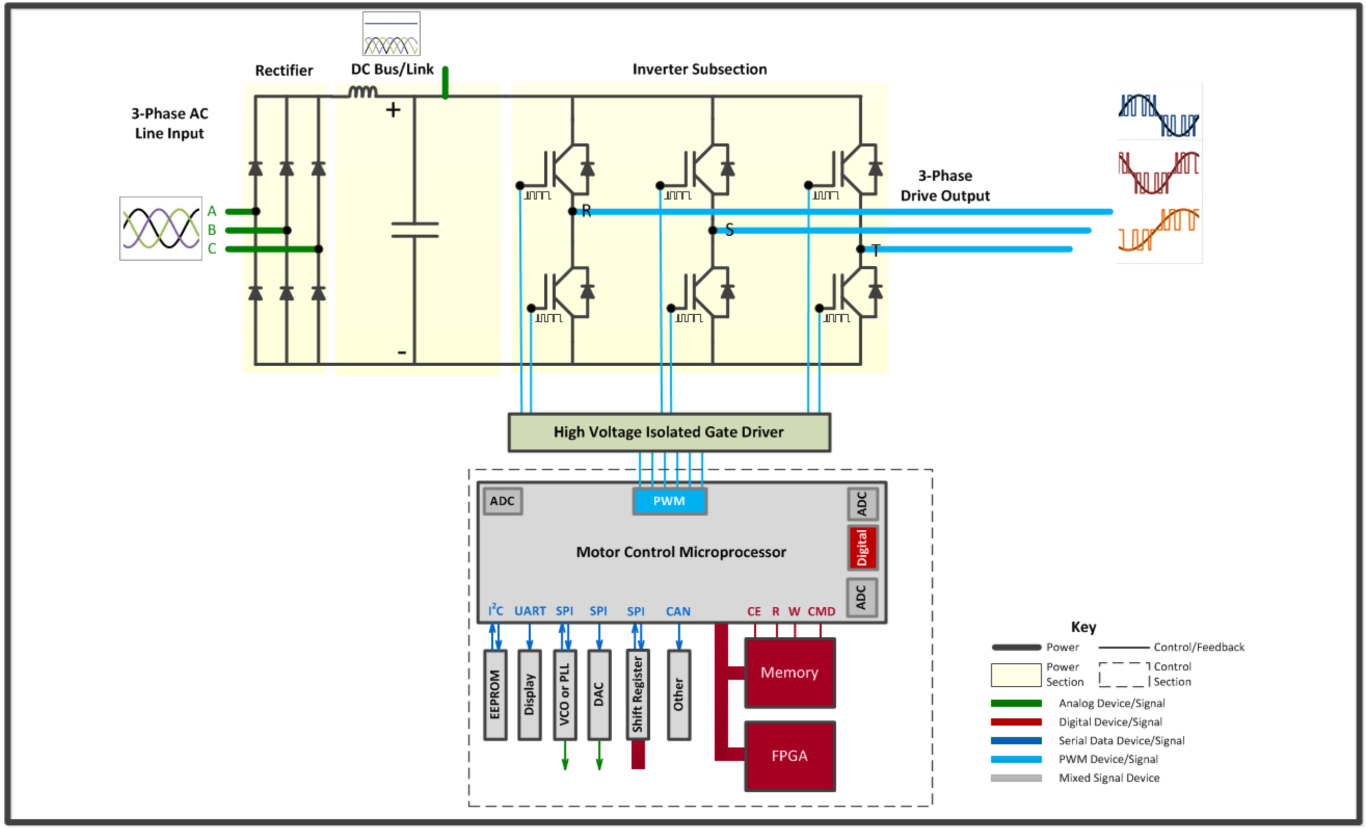
- Gate drive signals provide on/off switching instructions to the device
- HV Isolation necessary as inverter subsection “floats” at DC Bus/Link potential



Embedded Control System

Could require a very high speed microprocessor, depending on the control algorithm used

- Control system primary purpose is to integrate user commands and feedback signals and generate gate drive signals
- “Classic” mixed-signal debug needs



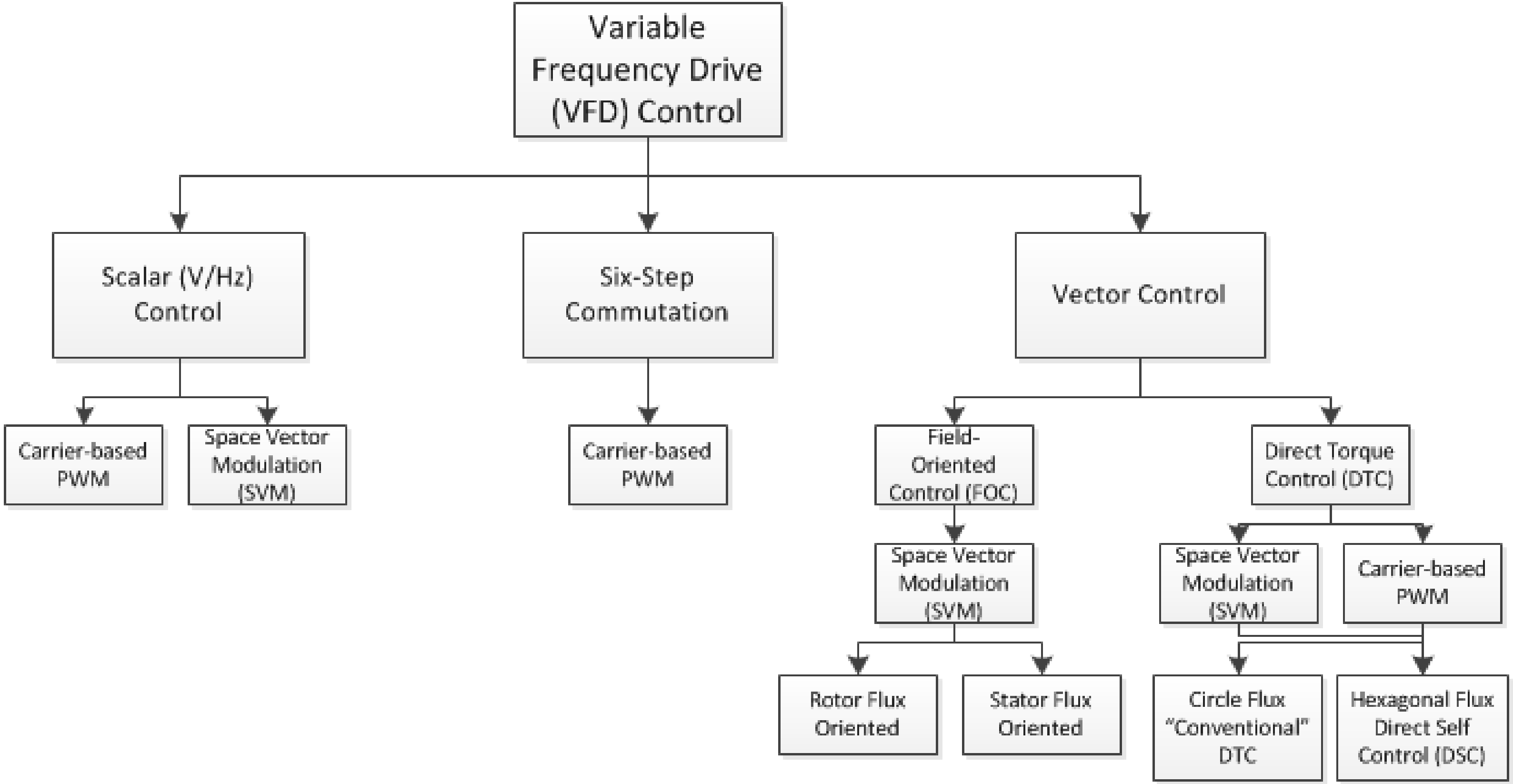
Types of Motor Drive Control Algorithms

Control algorithm is chosen based on application need and cost target

- Scalar (Volts/Hz, or V/Hz)
  - Simplest, lowest cost “sine-modulated”
  - Least control capability, but good for simple applications
    - Blower
    - Ceiling Fan
- Six-Step Commutated
  - BLDC specific
  - Medium complexity, cost
  - Good control capability if only speed or torque need control
    - Power tools
    - Small pumps
- Vector Field-Oriented Control (FOC)
  - High complexity, cost, “sine-modulated”
  - Simultaneous torque and speed control
    - Appliances and HVAC
    - Electric vehicle propulsion

Types of Motor Drive Control Algorithms

With types of modulation commonly employed



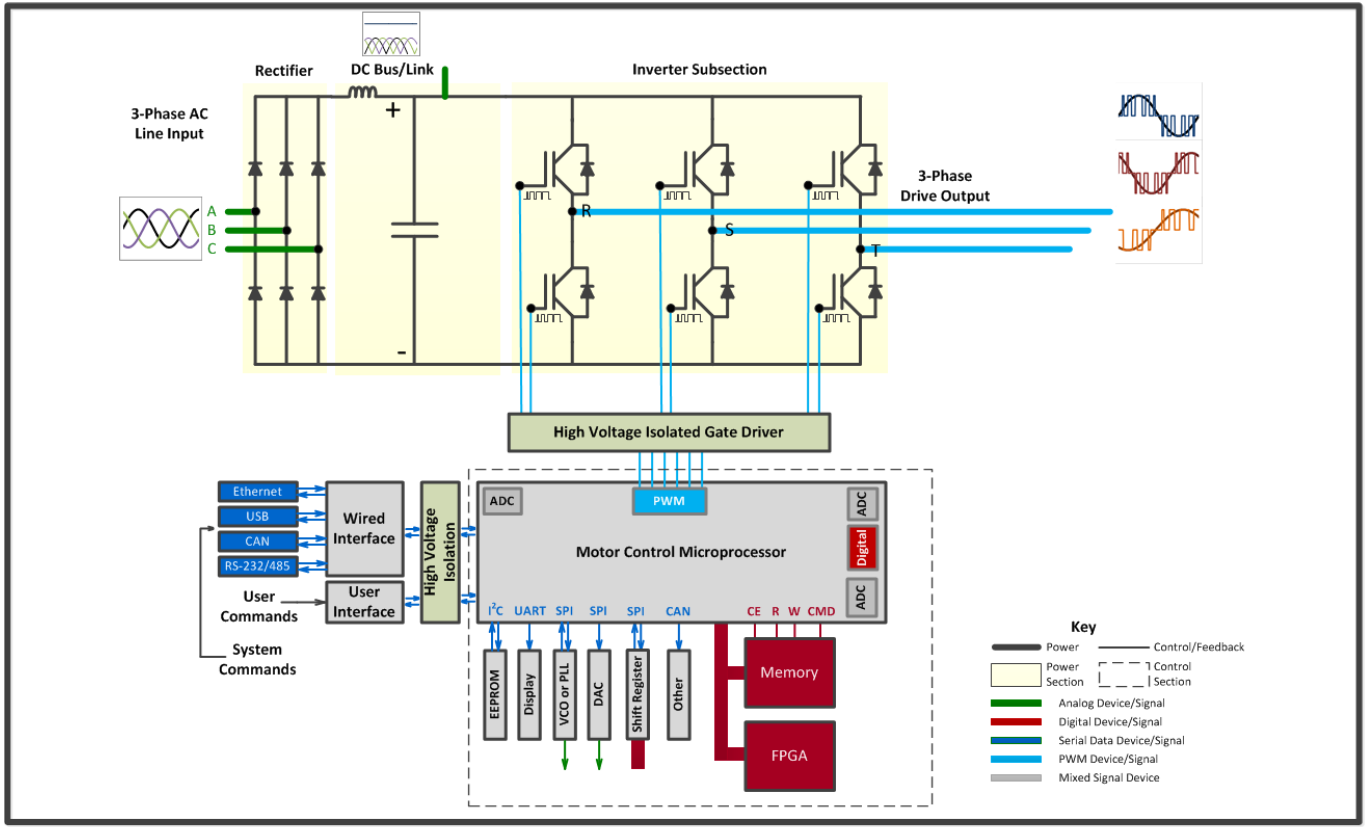
Polling Question #2

- What control methodology do you use in your designs? (Choose all that apply)
    - Scalar V/Hz or similar
    - Six-step commutated
    - Vector (FOC or other)
    - None of the above

User and System Control Inputs

Could be input through a user keypad /interface or an industrial control system

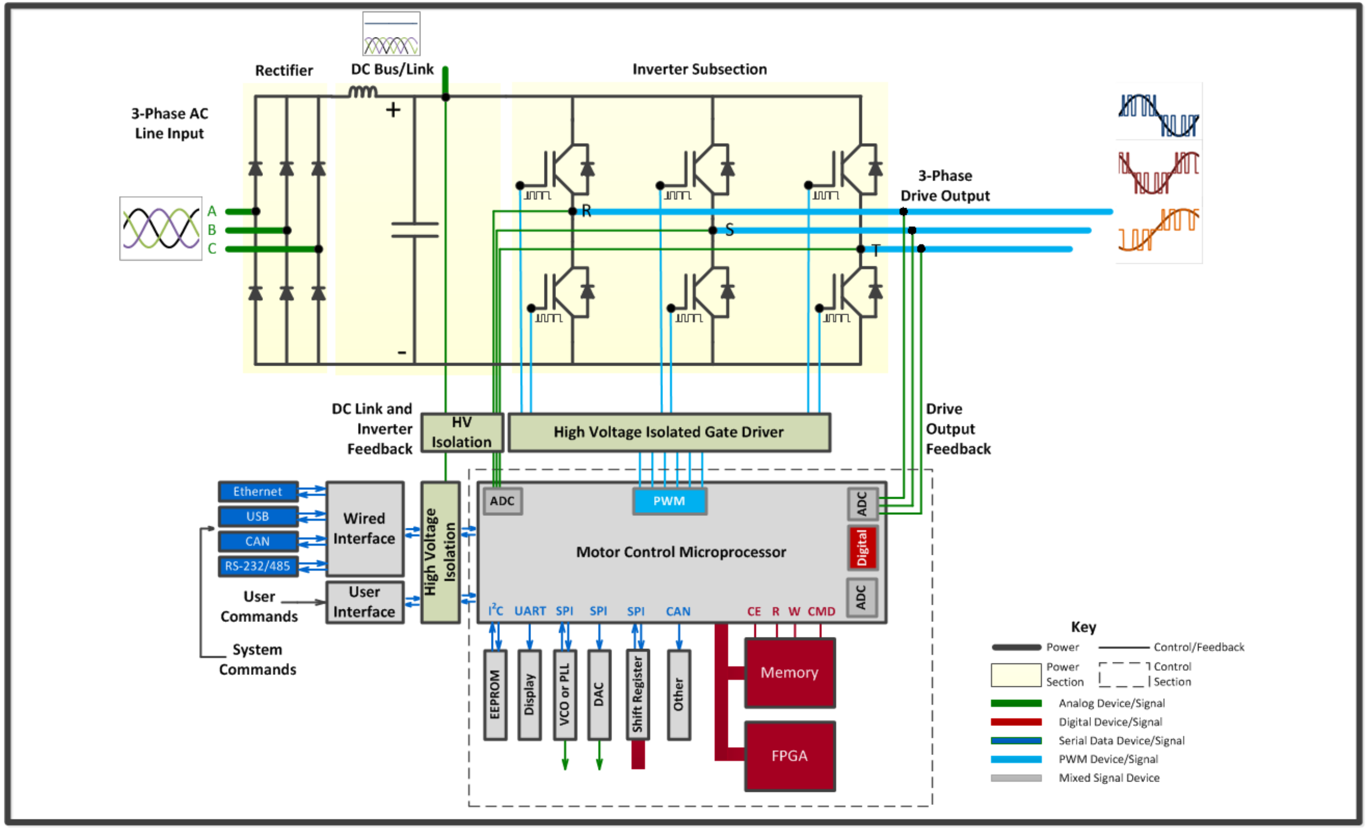
- User and system command inputs
  - Speed
  - Torque
  - On/Off
  - Other



Drive Feedback Sensing

More sophisticated control algorithms require more sophisticated feedback systems

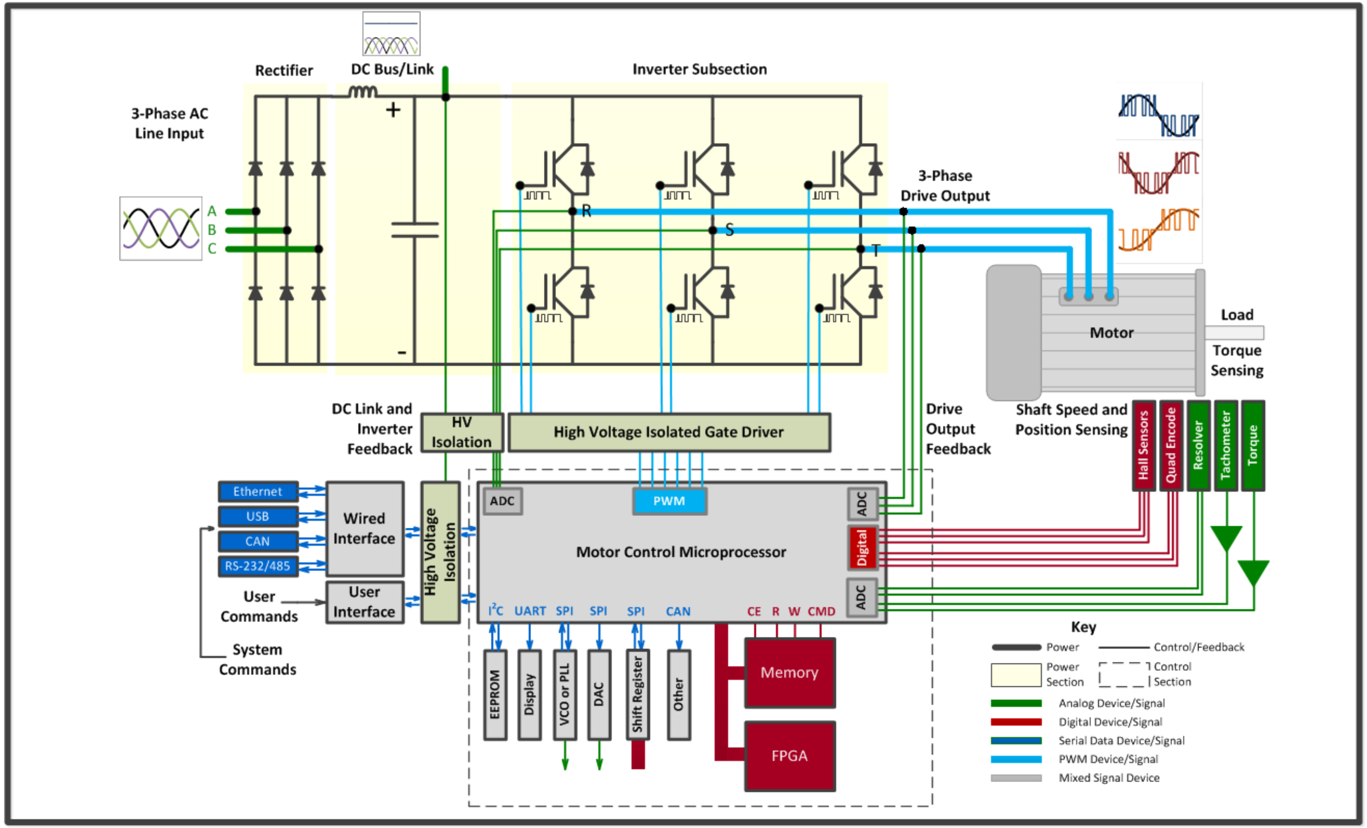
- Drive voltage and current signals are monitored
  - DC Bus
  - Drive Output
- Control system uses these values for gate drive calc's and system monitoring



Motor Drive + Motor System Operation

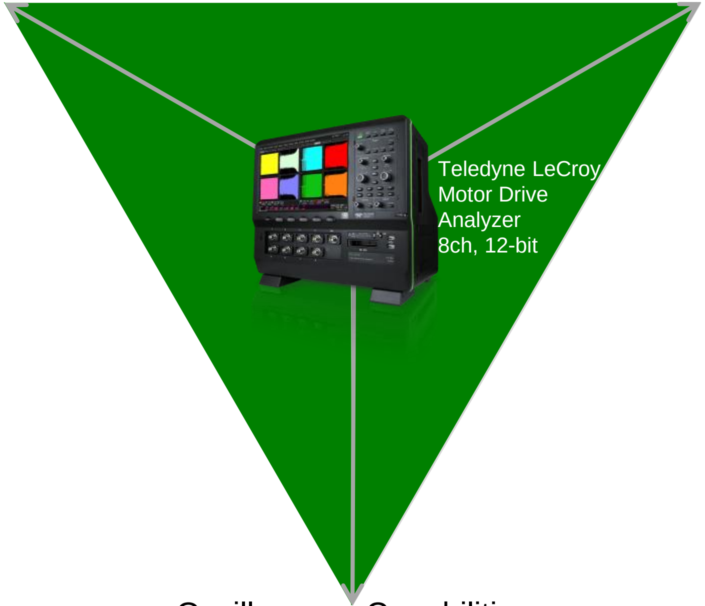
Vector FOC control algorithms require motor shaft speed, direction, and position sensors

- Motor Performance is Monitored
  - Shaft Speed and Position
  - Rotation
  - Torque
- Control System Responds with Commands



Teledyne LeCroy Motor Drive Analyzer

First to provide controls debug, inverter subsection analysis, and complete power analysis

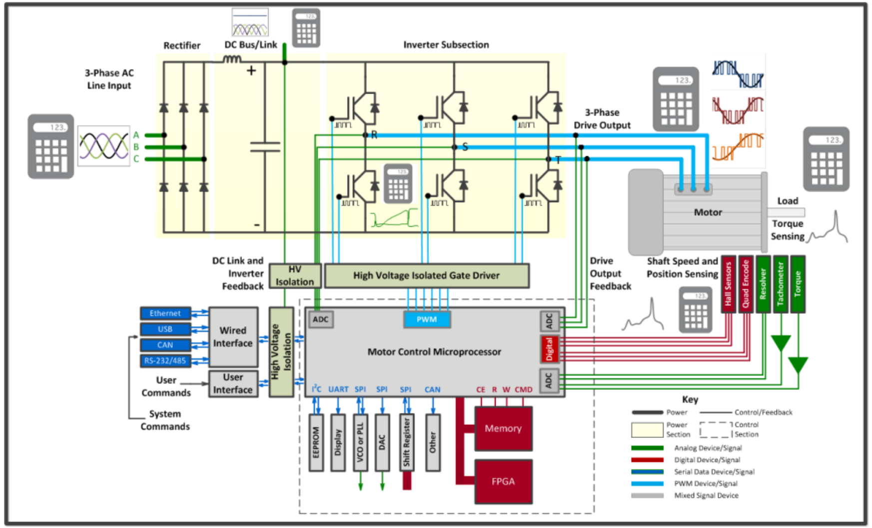


Motor Integration
Torque, Speed, Power

3-phase Power Analysis
(Channels, Resolution)

Teledyne LeCroy
Motor Drive
Analyzer
8ch, 12-bit

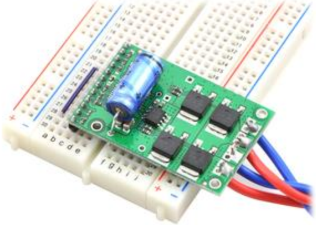
Oscilloscope Capabilities
(BW, SR, Memory, MSO, Serial Trigger/Decode,
IGBT/MOSFET Device Test)



Motor Drive Sizes and Ratings

Range from very small to very large, but share the same basic principles

- Voltage Rating
  - Low Voltage
    - ≤50Vac, MOSFET-based
    - Primarily small Brushless DC (BLDC) motors and Permanent-magnet Synchronous Motors (PMSMs)
  - ~300Vac to ~600Vac
    - IGBT-based
    - AC Induction Motors (ACIMs), PMSMs, and BLDC Motors
  - 5kV class
    - IGBT-based with different architectures
    - ACIMs
- Power Rating
  - Watts to 100s or 1000s of kWs
- Physical Size
  - Large, stand-alone box
  - Small, integrated PCA



Polling Question #3

- What equipment do you use today for measuring power or debugging power conversion circuits (Choose all that apply)
  - 4 channel oscilloscope
  - 8 channel oscilloscope
  - Power Analyzer
  - Motor Drive Analyzer
  - None of the above

Distorted Waveform (e.g. PWM) Power Calculations

Distorted voltage and current waveforms are comprised of multiple frequencies, and the simple techniques that are used to measure power for pure single-frequency sinusoidal signals cannot be used for these waveforms

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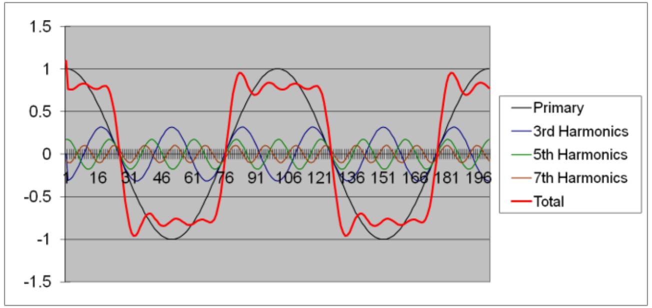
“Distorted” Waveforms are Complex Sums of Sinusoids

- Any “distorted” (e.g. PWM) waveform is composed of different amplitudes of odd integer sinewave harmonics (“orders”)

$$x_{\text{square}}(t) = \frac{4}{\pi}\sum_{k=1}^{\infty}\frac{\sin\left((2k-1)2\pi ft\right)}{(2k-1)}$$
$$= \frac{4}{\pi}\left(\sin(2\pi ft) + \frac{1}{3}\sin(6\pi ft) + \frac{1}{5}\sin(10\pi ft) + \cdots\right).$$

Square Wave Harmonics

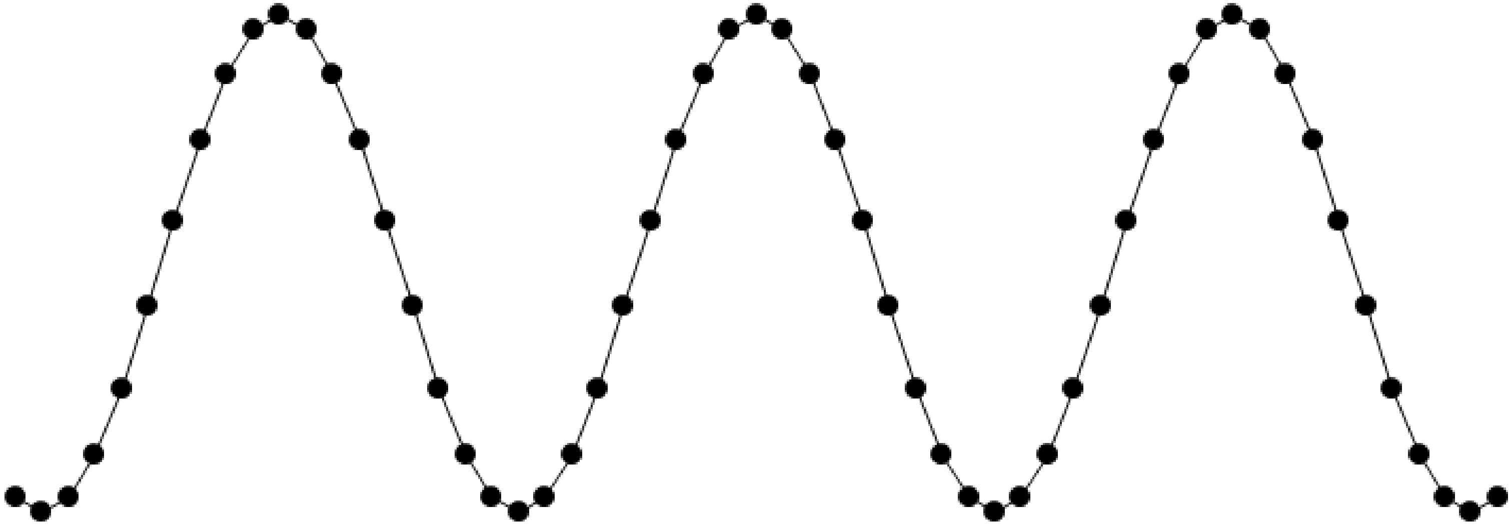


- The voltage and current waveforms will have different magnitude contributions from different harmonic orders
- The phase relationships between voltage and current waveforms for different harmonic orders is not a constant
- Therefore, there is no practical method to measure phase angle between a voltage and current signal to calculate real power from apparent power

Digital Sampling Technique for Power Calculations

Required for distorted waveforms, but also works for sinusoidal waveforms

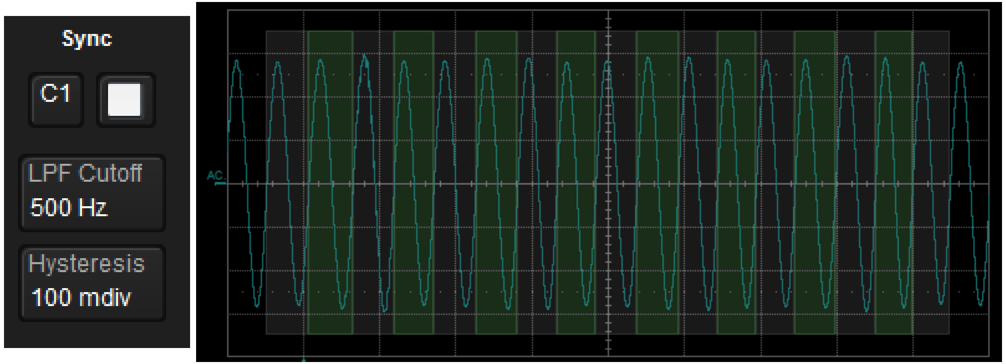
- A “digital” acquisition system samples the analog signal at a given rate (the “sample rate”)



A Calculation Period is Determined for all Digitally Sampled Signals

The selected Sync signal determines the measurement period

- An acquired digitally sampled signal is chosen to be the reference “Sync” signal
- A low pass filter (LPF) is applied to this signal
- A Hysteresis (band) value is set
- A software algorithm determines a zero-crossing point on the LPF signal, ignoring crossings that occur within the Hysteresis band



Sync

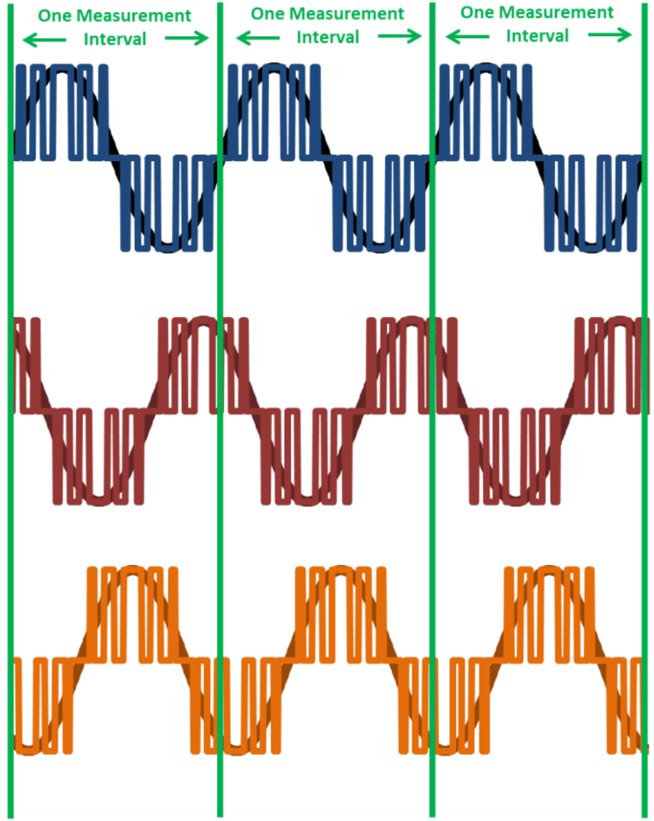
C1

LPF Cutoff

500 Hz

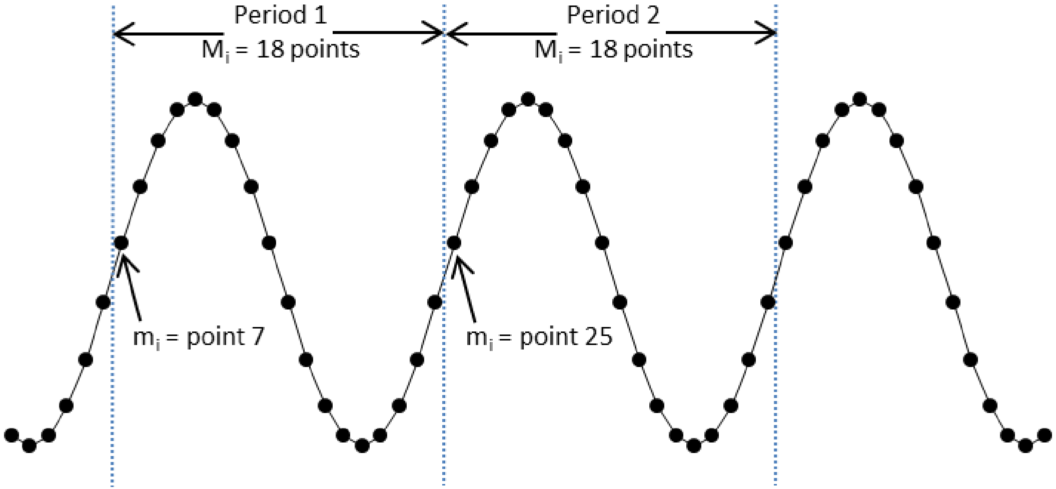
Hysteresis

100 mdiv



Calculated Per-cycle Values from Digitally Sampled Data

- The digitally samples in each signal are now grouped into measurement periods (cycles), as determined by the Sync signal.
- For a given cycle index *i*….
- the digitally sample voltage waveform is represented as having a set of sample points *j* in cycle index *i*…
- For a given cycle index *i*, there are M_i sample points beginning at m_i and continuing through $m_i + M_i - 1$.
- Voltage, current, power, etc. values are calculated on each cycle index *i* from 1 to *N* cycles.



Example

- Period 1 is cycle index i = 1
- There is a set of j sample points in Period 1, beginning with point 7 and ending with point 24
- All Period 1 voltage, current and power calculations are made with this set of points
- Period 2 is cycle index i = 2
- There is a set of j sample points in Period 2, beginning with point 25 and ending with point 42
- All Period 2 voltage, current and power calculations are made with this set of points
- And so on through Period N

Formulas Used for Per-cycle Digitally Sampled Calculations

“Mean” values are calculated from the per-cycle data set

	Per-Cycle Calculated Values	Mean Calculated Values
V_{RMS}	$Vrms_i = \sqrt{\frac{1}{M_i}\sum_{j=m_i}^{m_i+M_i-1} {V_j}^2}$	$Vrms = \frac{1}{N}\sum_{i=1}^{N} Vrms_i$
I_{RMS}	$Irms_i = \sqrt{\frac{1}{M_i}\sum_{j=m_i}^{m_i+M_i-1} {I_j}^2}$	$Irms = \frac{1}{N}\sum_{i=1}^{N} Irms_i$
Real Power (P, in Watts)	$P_i = \frac{1}{M_i}\sum_{j=m_i}^{m_i+M_i-1} V_j * I_j$	$P = \frac{1}{N}\sum_{i=1}^{N} P_i$
Apparent Power (S, in VA)	$S_i = Vrms_i * Irms_i$	$S = \frac{1}{N}\sum_{i=1}^{N} S_i$
Reactive Power (Q, in VAr)	$magnitude\ Q_i = \sqrt{{S_i}^2 - {P_i}^2}$ *sign of Q_i is positive if the fundamental voltage vector leads the fundamental current vector*	$Q = \frac{1}{N}\sum_{i=1}^{N} Q_i$

Formulas Used for Per-cycle Digitally Sampled Calculations

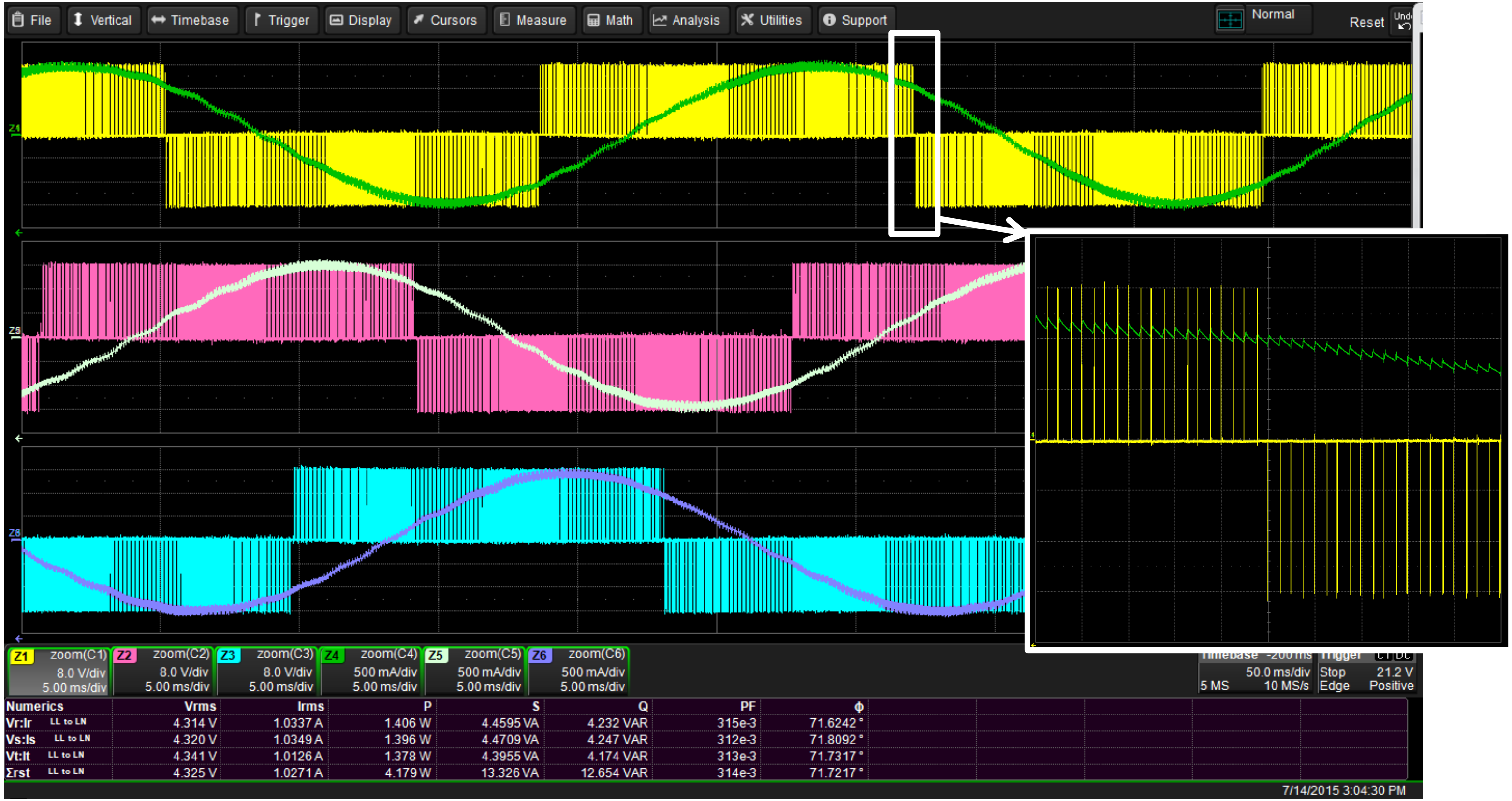
“Mean” values are calculated from the per-cycle data set

	Per-Cycle Calculated Values	Mean Calculated Values
Power Factor (λ)	$\lambda_i = \frac{P_i}{S_i}$	$\lambda = \frac{1}{N}\sum_{i=1}^{N}\lambda_i$
Phase Angle (φ)	$magnitude\ \phi_i = \cos^{-1}\lambda_i$ *sign of ϕi is positive if the fundamental voltage vector leads the fundamental current vector*	$\phi = \frac{1}{N}\sum_{i=1}^{N}\phi_i$

For more details, reference the Teledyne LeCroy
Motor Drive Analyzer Software Instruction Manual at
http://cdn.teledynelecroy.com/files/manuals/motor-drive-analyzer-software-operators-manual.pdf

Example – PMSM Three-Phase Voltage and Current

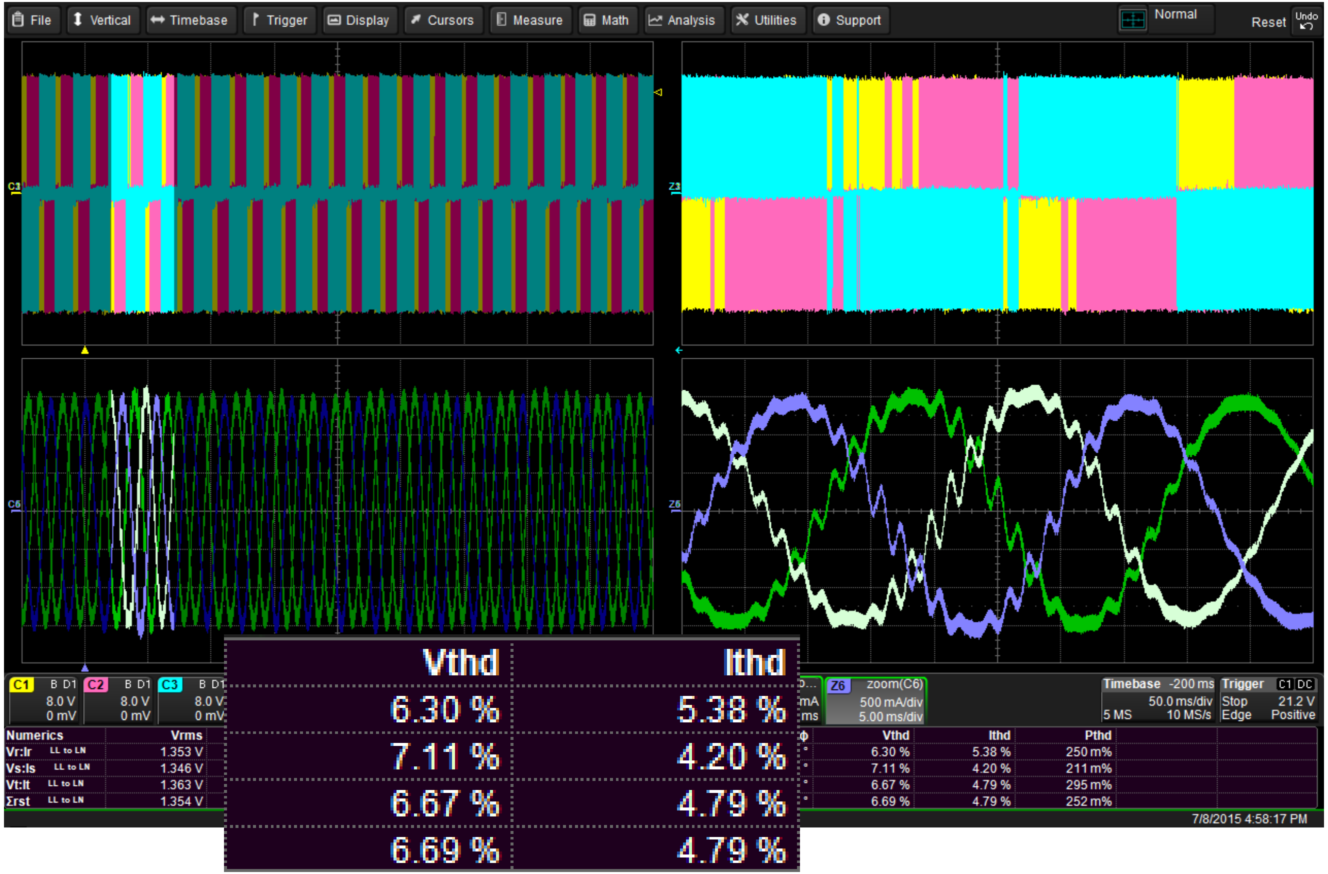
What appears to be a sinusoidal AC current has a “sawtooth” shape…



Numerics	Vrms	Irms	P	S	Q	PF	Φ
Vr:Ir LL to LN	4.314 V	1.0337 A	1.406 W	4.4595 VA	4.232 VAR	315e-3	71.6242 °
Vs:Is LL to LN	4.320 V	1.0349 A	1.396 W	4.4709 VA	4.247 VAR	312e-3	71.8092 °
Vt:It LL to LN	4.341 V	1.0126 A	1.378 W	4.3955 VA	4.174 VAR	313e-3	71.7317 °
Σrst LL to LN	4.325 V	1.0271 A	4.179 W	13.326 VA	12.654 VAR	314e-3	71.7217 °

During Overload Conditions, Distortion Can Increase Greatly

THD dramatically increases during a near-overload event



Vthd	Ithd
6.30 %	5.38 %
7.11 %	4.20 %
6.67 %	4.79 %
6.69 %	4.79 %

Numerics		Vrms
Vr:Ir	LL to LN	1.353 V
Vs:Is	LL to LN	1.346 V
Vt:It	LL to LN	1.363 V
Σrst	LL to LN	1.354 V

φ	Vthd	Ithd	Pthd
°	6.30 %	5.38 %	250 m%
°	7.11 %	4.20 %	211 m%
°	6.67 %	4.79 %	295 m%
°	6.69 %	4.79 %	252 m%

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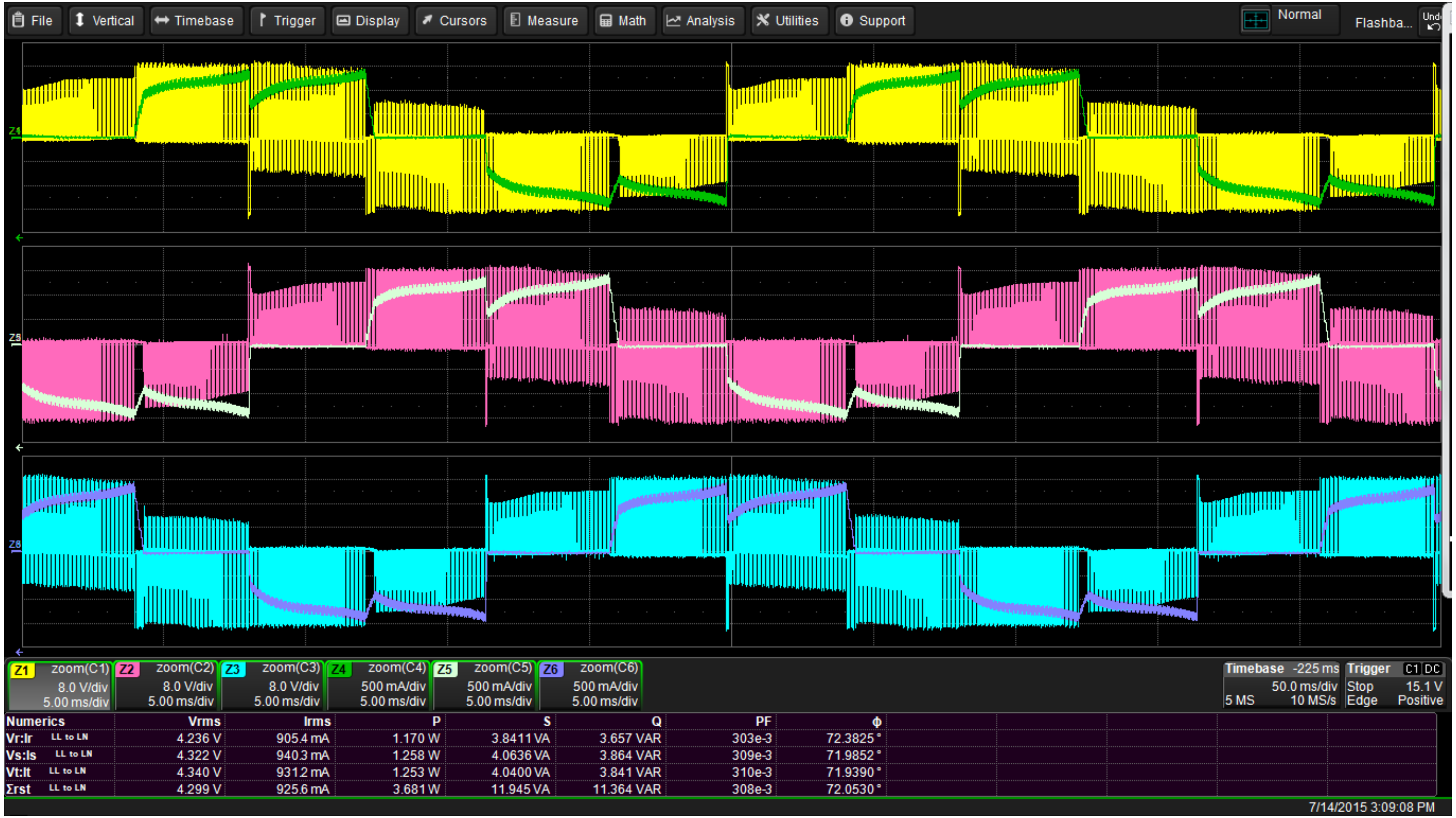
Example – BLDC Three-Phase Voltage and Current

These have even more inherent distortion than PMSM waveforms…



	zoom	V/div or mA/div	ms/div
Z1	zoom(C1)	8.0 V/div	5.00 ms/div
Z2	zoom(C2)	8.0 V/div	5.00 ms/div
Z3	zoom(C3)	8.0 V/div	5.00 ms/div
Z4	zoom(C4)	500 mA/div	5.00 ms/div
Z5	zoom(C5)	500 mA/div	5.00 ms/div
Z6	zoom(C6)	500 mA/div	5.00 ms/div

Timebase -225 ms
50.0 ms/div
5 MS 10 MS/s

Trigger C1 DC
Stop 15.1 V
Edge Positive

Numerics		Vrms	Irms	P	S	Q	PF	Φ
Vr:Ir	LL to LN	4.236 V	905.4 mA	1.170 W	3.8411 VA	3.657 VAR	303e-3	72.3825 °
Vs:Is	LL to LN	4.322 V	940.3 mA	1.258 W	4.0636 VA	3.864 VAR	309e-3	71.9852 °
Vt:It	LL to LN	4.340 V	931.2 mA	1.253 W	4.0400 VA	3.841 VAR	310e-3	71.9390 °
Σrst	LL to LN	4.299 V	925.6 mA	3.681 W	11.945 VA	11.364 VAR	308e-3	72.0530 °

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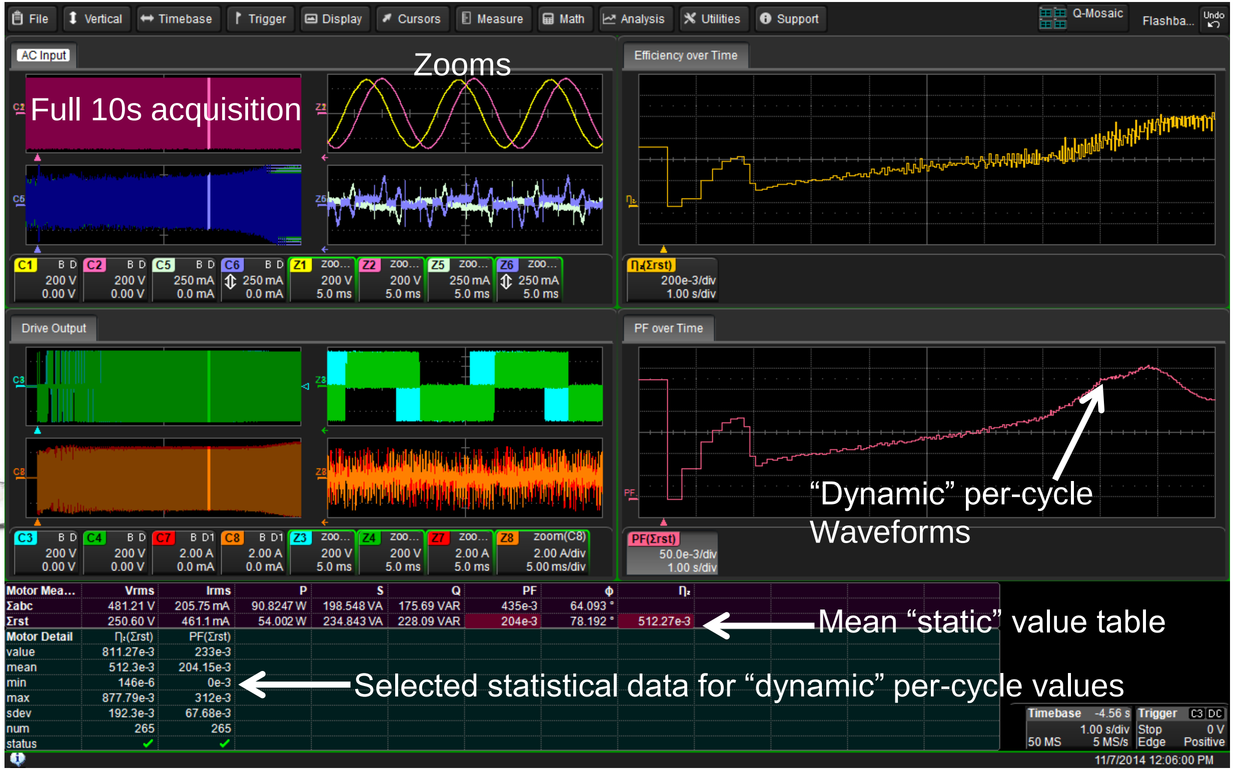
Teledyne LeCroy Motor Drive Analyzer

Ideal for measuring three-phase power in non-linear (distorted) power systems

- Teledyne LeCroy MDA810 Motor Drive Analyzer
  - 8ch, 12-bit, 1 GHz
  - 3-phase electrical and mechanical power analysis

- Input voltage and current, and it calculates static and dynamic power values



Zooms

Full 10s acquisition

“Dynamic” per-cycle Waveforms

Motor Mea...	Vrms	Irms	P	S	Q	PF	φ	η_2
Σabc	481.21 V	205.75 mA	90.8247 W	198.548 VA	175.69 VAR	435e-3	64.093 °	
Σrst	250.60 V	461.1 mA	54.002 W	234.843 VA	228.09 VAR	204e-3	78.192 °	512.27e-3

Mean “static” value table

Motor Detail	η_2(Σrst)	PF(Σrst)
value	811.27e-3	233e-3
mean	512.3e-3	204.15e-3
min	146e-6	0e-3
max	877.79e-3	312e-3
sdev	192.3e-3	67.68e-3
num	265	265
status	✓	✓

Selected statistical data for “dynamic” per-cycle values

Devices used to measure high voltages

The “right” device to use depends on the application

- High Voltage Differential Probes
  - 1kV, 2kV, 6kV safety-rated (isolated)
  - 1% accuracy
  - Excellent CMRR performance
  - DC to 100+ MHz
- High Voltage Passive Probes
  - DC to ~500 MHz
- Differential Amplifiers
  - DA1855A (Teledyne LeCroy)
  - CIC Research
- Potential Transformers
  - Not DC rated
  - Limited high frequency response

Devices used to measure currents

These devices have frequency response from DC

- Current Probes
  - 30A, 150A, 500A
  - 1% accuracy
  - DC up to 100 MHz
  - Expensive, but multi-purpose f a wide range of oscilloscope probing requirements
- Specialty Current Transducers
  - e.g. Danisense
  - <1% accuracy
  - DC to ~100 kHz
- Why DC?
  - Low frequencies present at start-up events

Devices used to measure currents, cont'd

These devices have AC frequency response only

- Rogowski Coils (e.g. PEM-UK)
  - Frequency response depends on model (lowest ~5-15 Hz typical)
  - Lowest cost
  - Split-core
  - Very small to very high loop sizes
- Pearson Current Transformers (CT)
  - Frequency response depends on model (lowest ~5 Hz typical)
  - Split-core (typical)
  - Built-in shunt resistors for scaled voltage output
- Conventional Turns Ratio CT*
  - Frequency response typically covers line frequency range with a little margin
  - Scaled output current
  - Need shunt resistor on output to convert to voltage output

*Note: dangerous open-circuit voltages can occur at the output of these devices – use extreme caution, and avoid operating open-circuited

Current Sensor Adapter to Teledyne LeCroy Oscilloscope

Enables simple use of 3rd party current measurement solutions

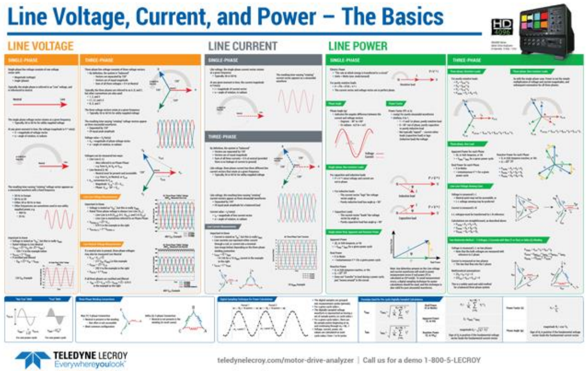
- Provides ability for third-party current sensor to operate like a Teledyne LeCroy “probe”
  - Programmable
  - Customizable
    - Bandwidth filtering
    - Shunt resistor
  - Converts any linear voltage or current input to output scaled in Amperes
- Simplifies the setup

Summary – Distorted Waveform Power Measurements

- Textbook descriptions of power calculations typically assume sinusoidal waveforms for single-phase systems (one voltage, one current).
  - Knowledge of phase angle between sinusoidal voltage and current waveforms is then used for power calculations
- The output of a power electronics converter/inverter is a distorted waveform that requires different power calculation methodologies than most engineers are familiar with
  - There is no practical way to measure phase angle between distorted voltage and current waveforms
  - Digital sampling techniques are required
  - These digital sampling techniques also work for pure sinusoids

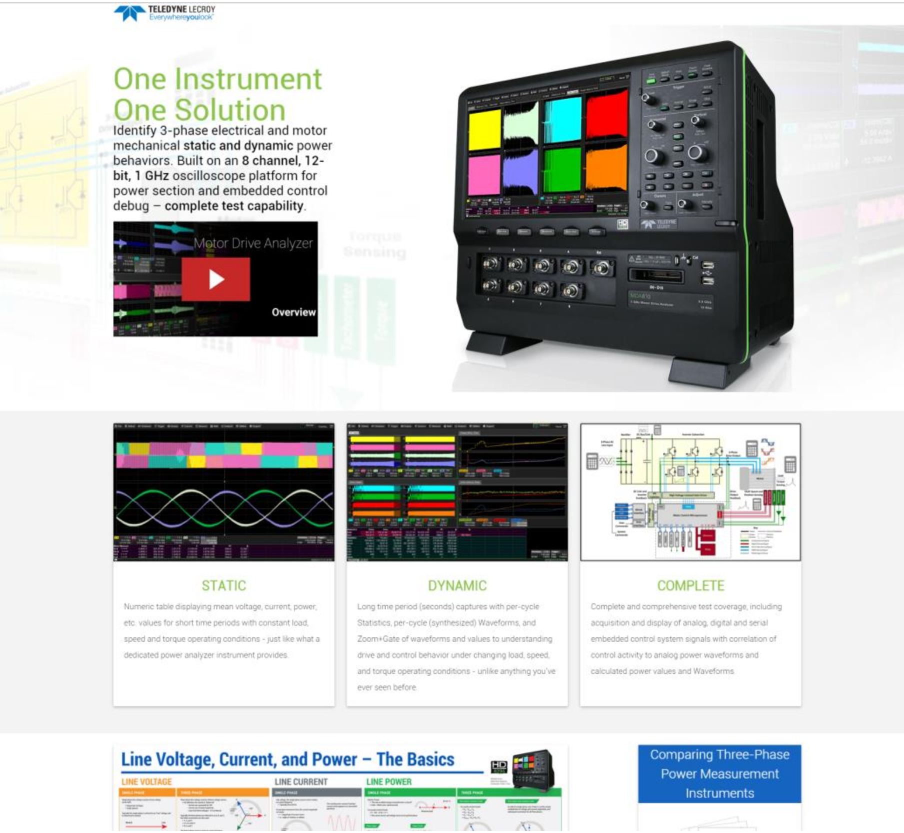
Visit Us At: teledynelecroy.com/static-dynamic-complete

- Complete information on our Motor Drive Analyzer
  - Videos
  - Application Notes
  - Request a Power Poster



Line Voltage, Current, and Power – The Basics

teledynelecroy.com/motor-drive-analyzer | Call us for a demo 1-800-5-LECROY



One Instrument One Solution

Identify 3-phase electrical and motor mechanical **static and dynamic** power behaviors. Built on an **8 channel, 12-bit, 1 GHz** oscilloscope platform for power section and embedded control debug – **complete test capability**.

STATIC

Numeric table displaying mean voltage, current, power, etc. values for short time periods with constant load, speed and torque operating conditions - just like what a dedicated power analyzer instrument provides.

DYNAMIC

Long time period (seconds) captures with per-cycle Statistics, per-cycle (synthesized) Waveforms, and Zoom+Gate of waveforms and values to understanding drive and control behavior under changing load, speed, and torque operating conditions - unlike anything you've ever seen before.

COMPLETE

Complete and comprehensive test coverage, including acquisition and display of analog, digital and serial embedded control system signals with correlation of control activity to analog power waveforms and calculated power values and Waveforms.

Line Voltage, Current, and Power – The Basics

Comparing Three-Phase Power Measurement Instruments

Questions?

TELEDYNE LECROY
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