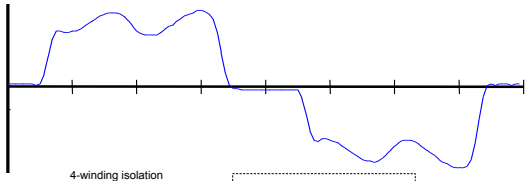
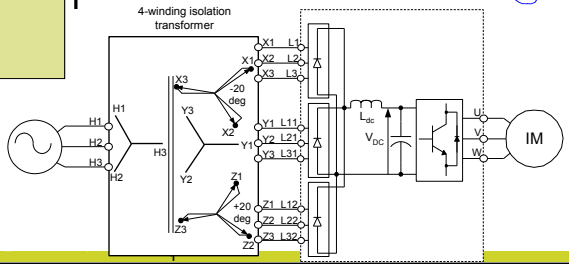
YASKAWA
Tony Anthony
Eastern OH. Western Pa, and WV

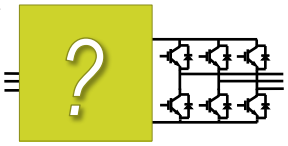
Basics of Harmonics





Overview

- *Review of VFD's for HVAC Applications*
  - *Energy Savings*
- *Review of Harmonics*
  - *What are harmonics?*
  - *What causes harmonics?*
  - *Why should we care?*
- *Review of IEEE-519*
- *Review the difference between active and passive front ends*
  - *Review most common harmonic correction techniques*
  - *THD vs. Eff. Vs. cost impact*



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Energy Savings: Centrifugal Loads

- *How can a VFD save money*
  - *Motor is sized for maximum demand volume at a constant speed*
  - *Maximum demand volume is required for small percentage of total operating time*
  - *Majority of operating time is spent providing 40 - 70% volume*
  - *Affinity Laws*

$Volume_1 / Volume_2 = RPM_1 / RPM_2$

$Pressure_1 / Pressure_2 = (RPM_1 / RPM_2)^2$

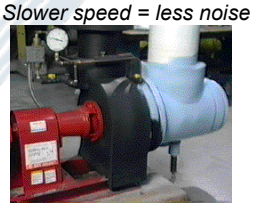
$HP_1 / HP_2 = (RPM_1 / RPM_2)^3$

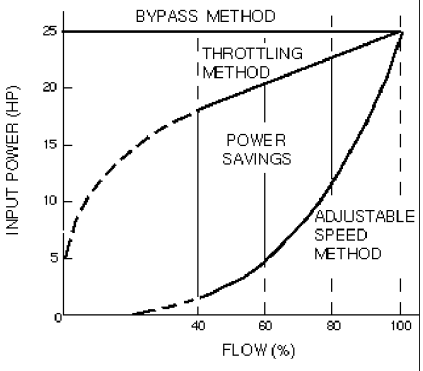
Dropping Motor Speed Increases Energy Savings!

Benefits to Applying VFD to Centrifugal Loads

- *Energy Savings*
  - *Savings depends on static head of system*
  - *Maximize Eff. Of driven equipment (pump curve)*
  - *Soft Start (no inrush)*
  - *Reduces water hammers*
  - *Less stress on belts and seals*
  - *Noise Reduction*

Slower speed = less noise

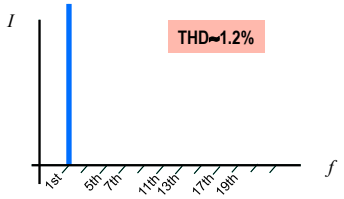


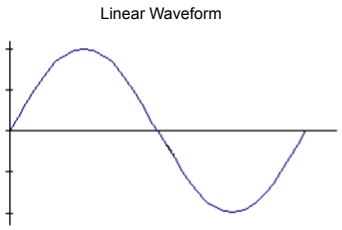


More Benefits Than Just Energy Savings!

What are harmonics?

- Harmonics
  - *Harmonics are components of a waveform that are integral multiples of the fundamental component of a non linear waveform.*
  - *In a Power System, voltage and current harmonics exists – current harmonics causes system losses while voltage harmonics adversely affects reliable operation of electrical equipment*
  - *Lower harmonic content in a waveform corresponds to a more linear waveform*





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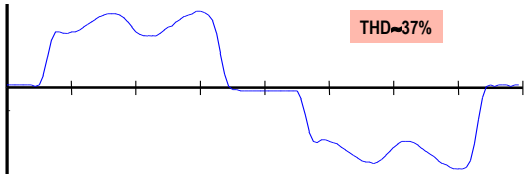
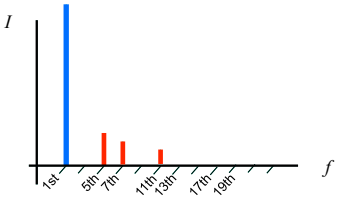
What are harmonics?

- Harmonics
  - *In a balanced three-phase system, harmonic components typically correspond to non triplen and odd multiples of the fundamental – For e.g.*
    - *5th harmonic is a sine wave at 5 times the frequency of the fundamental,*
    - *7th harmonic is a sine wave at 7 times the frequency of the fundamental,*
    - *11th harmonic is a sine wave at 11 times the frequency of the fundamental,*
    - *13th harmonic is a sine wave at 13 times the frequency of the fundamental,*
    - *Etc.*
  - *Each harmonic component either adds or subtracts a small amount to the fundamental*
  - *In a typical AC to DC rectifier with significant DC inductor, current waveform is close to a rectangular waveform. In this waveform:*
    - *The 5th harmonic is about 1/5 of the fundamental current*
    - *The 7th harmonic is about 1/7 of the fundamental current*
    - *Etc.*





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What causes harmonics?

- *What systems create harmonics*
  - *Lighting Equipment*

  - *Equipment with AC-to-DC power supplies*
    - *Computers*
    - *Uninterruptable Power Supplies*

  - *VFDs (Highest percentage of non-linear load)*
- *What thing will affect harmonic performance*
  - *System impedance (Supply and Input)*
  - *Voltage balance*
  - *Percent loading (non-linear load vs. linear load)*
  - *Types of rectification*

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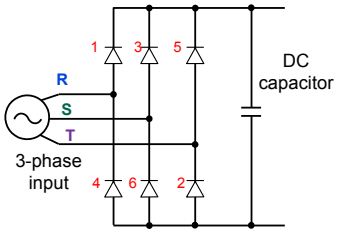
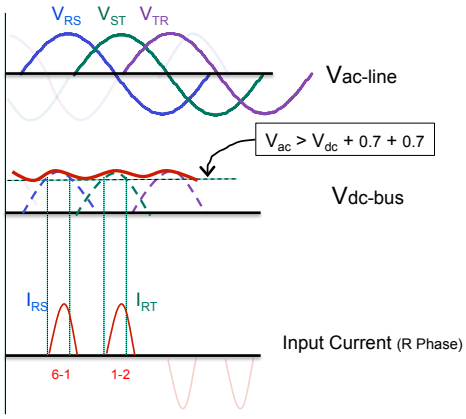
VFD Input Types

- *AC Drive Front End sections*
  - *Diodes*
    - *Voltage Source Inverter (VSI)*
    - *Energy storing devices - capacitors*



THD≈70 to 80%



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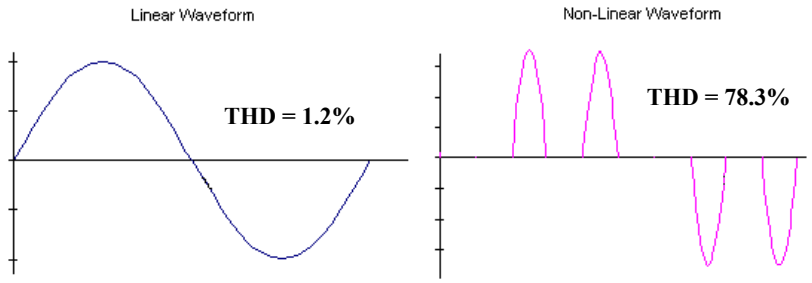
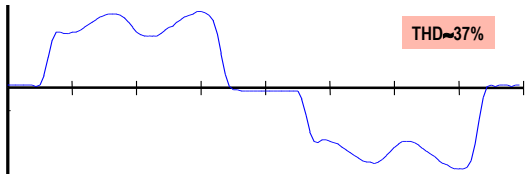
Sample Waveforms



Every Wave shape has Harmonic Distortion!



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Definition of THD

- Ratio of the square root of the sum of squares of the rms value of harmonic component to the rms value of the fundamental component is defined as Total Harmonic Distortion (THD)
- If the waveform under discussion is current, then the THD definition is called Current Harmonic Distortion. If the waveform under discussion is voltage, then the THD definition is called Voltage Harmonic Distortion

$$THD_I = \frac{\sqrt{\sum_{n=2}^{n=\infty} I_n^{\,2}}}{I_1} \qquad THD_V = \frac{\sqrt{\sum_{n=2}^{n=\infty} V_n^{\,2}}}{V_1}$$

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Why should we care?

- Why worry about created harmonics?
  - They lower overall system efficiency
    - Power that is required is not used to energize the load
      - Waste of energy and money
    - Example – 10,000 Amp load (@ $0.10 kWhr)
      - 20% THD at PCC creates 2% eff. Loss (200Amps) ($80,000/yr)
      - 10% THD at PCC creates 0.5% eff. Loss (50Amps) ($20,000/yr)
      - 5% THD at PCC creates 0.125% eff. Loss (12Amps) ($5,000/yr)
  - Greater losses/more heating in power delivery equipment
    - Equipment wear and tear
  - Effects other equipment
    - Current distortion leads to voltage distortion
    - Current distortion is localized but voltage distortion is not
      - Voltage distortion will affect the performance of other equipment near the VFD
      - May cause nuisance tripping
    - Voltage distortion will effect Utility customers on the same grid
    - To limit the voltage distortion – curb the harmonics!

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Why should we care?

- Why worry about created harmonics?
  - Sizing of main distribution Equipment
    - Transformers
    - Wiring
    - Generators
  - Power Factor
    - Though not the same thing, high harmonic content is linked to lower power factor
    - True PF is part displacement PF (Leading or Lagging) and part harmonic distortion.
    - Reactive power (unusable,) is necessary to draw actual power (usable,)
    - Poor PF taxes the local utility so they penalize you
  - The best way to improve poor power factor caused by non-linear loads it to reduce current distortion
    - Get closer to a sine wave
    - Cancel largest harmonic components

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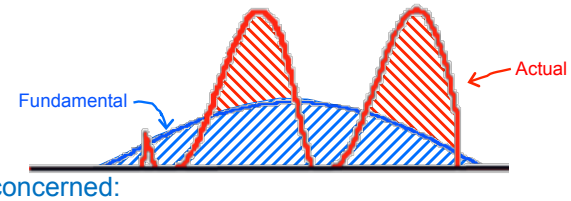
Why should we care?

- *Why worry about created harmonics?*
  - *High Crest Factor*
    - *Crest factor is the ratio between the instantaneous peak current required by the load and the RMS current*
    - *The source must supply the peak currents*
    - *Peak currents cause voltage distortion in weak AC systems*
    - *Increased wear and tear on the power delivery components*



Where should we be concerned:

- Hospitals
- Airports
- Universities
- Large Data Centers
- Central Utility Plants

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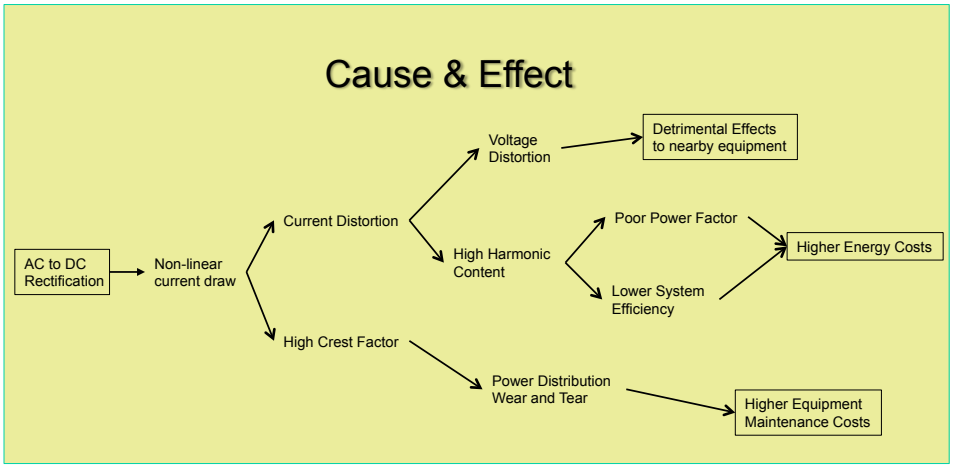
Final Harmonic Summary



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Harmonic Mitigation Techniques For VFDs

What We Can Do About It

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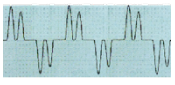
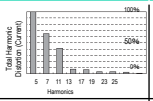
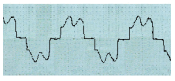
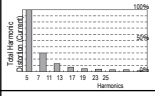
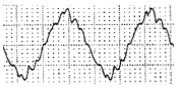
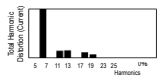
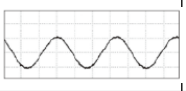
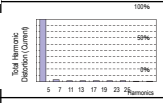
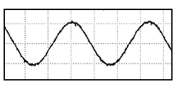
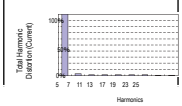
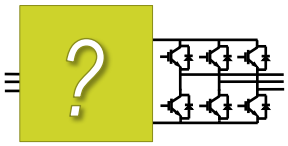
Harmonic Performance Comparison

	Current Waveform	Current Spectrum	System Eff.	iTHD
AC drive without reactor			97%	~ 80%
AC drive with DC reactor			96-97%	~ 35%
AC drive with multi-pulse or filter			94%	5 - 12%
AC drive with AFE			94-96%	4-5%
Matrix AFE			98%	3-4%

Active vs. Passive

- Review?
  - Harmonics exist in non linear waveforms
    - Current waveform will have current harmonics
    - Voltage waveform will have voltage harmonics
    - Harmonic components correspond to losses in a power system
  - Harmonics are often created by VFD front ends that are performing AC to DC rectification



  - Harmonic distortion lowers system efficiency, affects the performance of nearby equipment, lowers input power factor (which may cost you penalties), and the high crest factor can cause extra strain on power delivery equipment
- What can we do about it?
  - Change the front end topology to limit harmonic distortion
    - Passive Techniques that include AC and DC inductors
    - Passive Techniques also include Multi-pulse Front Ends that are configured for 12 pulse or 18 pulse inputs, and L-C Series and Shunt Filters
    - Active Front Ends

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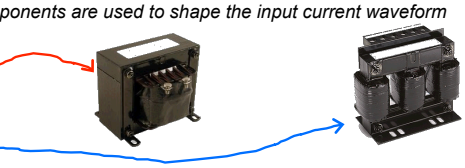
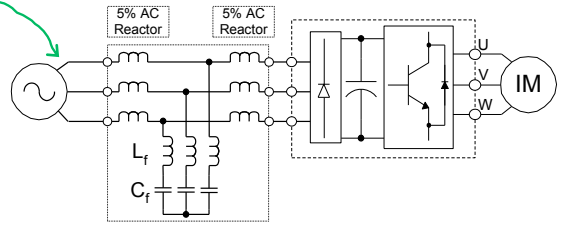
Passive

- What does passive front end mean?
  - How
    - Passive Front End Converters do not rely on manipulating the input current using Power Semiconductor Switches
    - Inductive and Capacitive components are used to shape the input current waveform
  - What
    - DC Link Chokes
    - AC Line Reactors
    - Harmonic Filters
    - 12-Pulse Rectification
    - 18-Pulse Rectification





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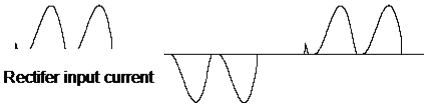
Reactors

Can be standard in some VFD or inexpensive opttions
Total system Eff. – 96-97%



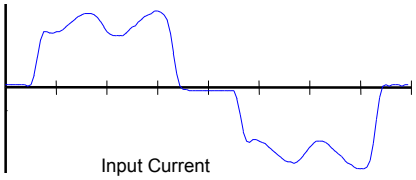
6-pulse diode rectification
w/o mitigation

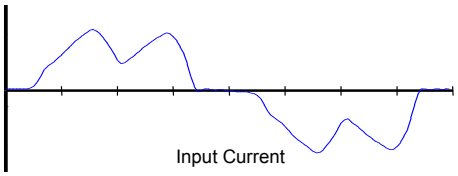
w/ DC Link Choke

THD≈35 to 45%

w/ AC Line Reactor

THD≈35 to 45%





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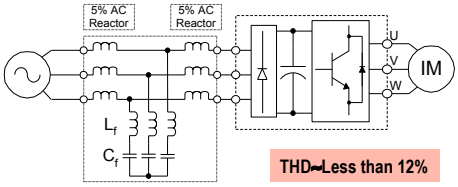
Passive

- *Passive Front End*
  - *Harmonic Filter*
    - » *Series, shunt, and hybrid*
      - – *Series Filter – tuned to offer high impedance to select harmonic frequencies*
      - – *Shunt Filter – tuned to shunt (trap) select harmonic frequencies*
      - – *Hybrid Filters – combination of above*
    - » *Large, bulky, expensive, and often ineffective*
      - – *Power Loss, and higher stresses on DC Bus Caps*
      - – *Generally multiple sections needed to capture enough harmonic orders*
      - – *Can cause system resonance (Affect the whole system)*
    - » *Total Eff. – 94%*



THD≈Less than 12%

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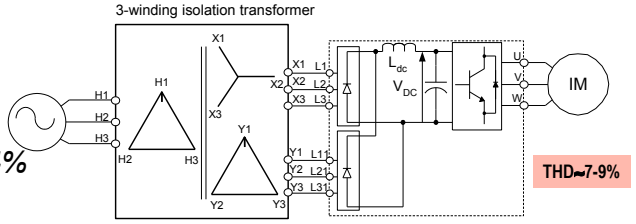
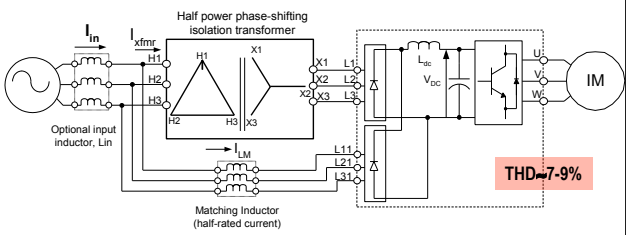
Passive

- *Types of Passive Front Ends*
  - *Standard 12-Pulse*
    - *Higher the order of harmonic in a waveform, lower is the amplitude of the harmonic*
    - *Multi-pulse technique helps in increasing the lowest harmonic order*
    - *h=kq±1; For a six pulse system, q=6 and lowest pair of harmonics is 5th and 7th*
    - *For a twelve pulse system, q=12 and lowest pair of harmonics is 11th and 13th*
  - *What*
    - ***3-winding 12 pulse transformer – Flux Cancellation Technique***
    - *Half Power 2-winding transformer plus a "matching" inductor – Current Cancellation Technique*
  - *Why*
    - *More robust*
  - *Why not*
    - *Bulky*
  - *Total Eff. – 94%*



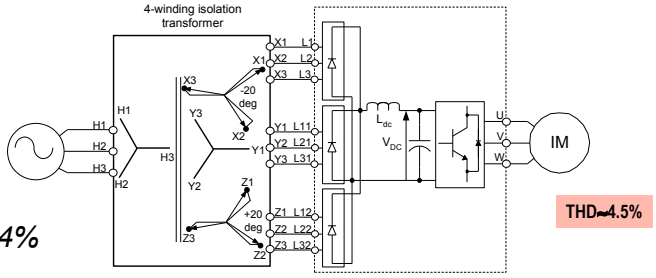
Passive

- *Types of Passive Front Ends*
  - *Hybrid 12-Pulse*
    - *Higher the order of harmonic in a waveform, lower is the amplitude of the harmonic*
    - *Multi-pulse technique helps in increasing the lowest harmonic order*
    - *h=kq±1; For a six pulse system, q=6 and lowest pair of harmonics is 5th and 7th*
    - *For a twelve pulse system, q=12 and lowest pair of harmonics is 11th and 13th*
  - *What*
    - *3-winding 12 pulse transformer – Flux Cancellation Technique*
    - ***Half Power 2-winding transformer plus a "matching" inductor – Current Cancellation Technique***
  - *Why*
    - *More robust*
  - *Why not*
    - *Expensive*
    - *Bulky*
  - *Total Eff. – 94%*



Passive

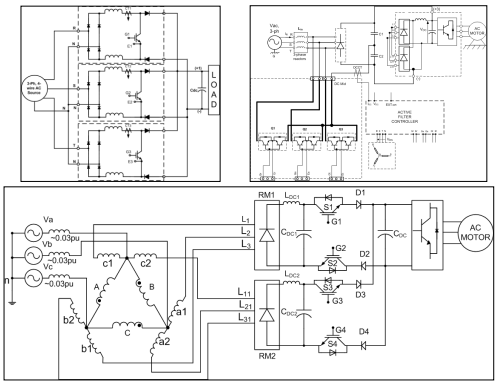
- *Types of Passive Front Ends*
  - *Standard 18-Pulse*
    - *h=kq±1; For a six pulse system, q=6 and lowest pair of harmonics is 5th and 7th*
    - *For an eighteen pulse system, q=18 and lowest pair of harmonics is 17th and 19th*
  - *What*
    - ***4-winding 18 pulse transformer – Flux Cancellation Technique***
    - *Two-thirds Power 3-winding transformer plus a "matching" inductor – Current Cancellation Technique*
  - *Why*
    - *Meet IEEE-519*
  - *Why not*
    - *Expensive*
    - *Bulky*
  - *Total Eff. – 94%*



18 pulse 75HP package

Active vs. Passive

- *What does active front end mean?*
  - *How*
    - *In Active Front End Converters input current is shaped using Power Semiconductor Switches to a desired waveform so as to have low harmonic content*
    - *Typically energy is stored in Inductive components and is retrieved at appropriate times to regulate the dc bus and make the input current continuous*
  - *What*
    - *Semiconductor switches*
    - *Energy storage devices*
  - *Why*
    - *Less bulky*
  - *Why not*
    - *May create unwanted EMI*
    - *May increase common mode current*



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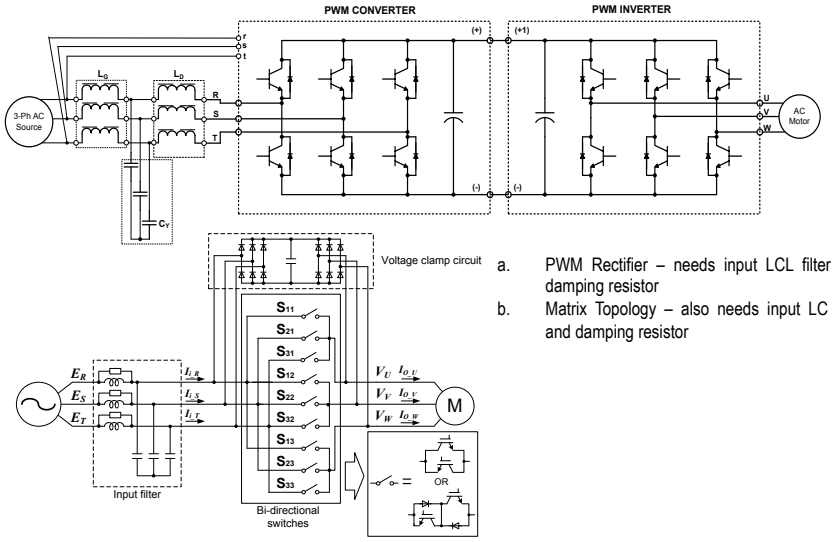
Active Converters

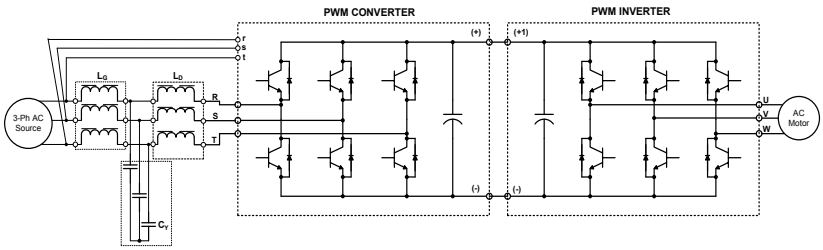


a. PWM Rectifier – needs input LCL filter and damping resistor
b. Matrix Topology – also needs input LC filter and damping resistor

Active Front End (AFE)

- *What is Active Front End (AFE)?*
  - *Good Efficiency (96%)*
  - *Better Power Factor*
  - *Low Harmonics (4-5% THD)*
  - *Smaller space, less bulky and lower cost*

  What about regeneration?
    - » *Not all AFEs are regenerative*



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Matrix AFE Technology

- *What is the Matrix (Z1000U) Technology*
  - *AC to AC power conversion*

    (without DC-bus)

  - *3-4% THD*
  - *Excellent Eff. - 98%*
    - » *98% vs 94% eff. - 100HP (@$0.10 kWhr) - $2000/yr savings*
  - *Fully Regenerative*
  - *Smaller package*
  - *Low Harmonics (IEEE-519 Compliant –from TDD viewpoint)*
  - *Unity Power Factor @ 80% or higher load*
  - *"ECO-mode" at 60Hz operation (99.5% eff. – 0% THD)*

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Matrix 75HP package

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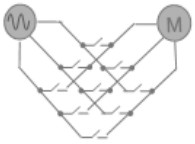
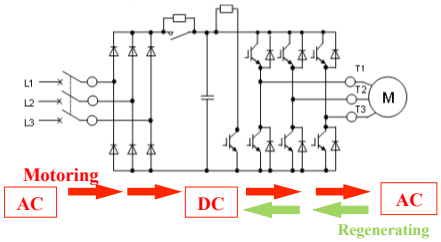
Matrix Theory

- The Matrix Drive creates precise control of voltage and frequency from 3ph AC power by connecting 9 bi-directional switches like a matrix.
- Differing from conventional drives, the Matrix Drive has no DC link circuit with diode and main capacitor, thus resulting higher efficiency.
- Typical harmonics associated with charging and discharging of DC link capacitors is not present with the Matrix drive.
- The Matrix Drive can return power during regeneration which can be re-used by loads connected to the same power source.

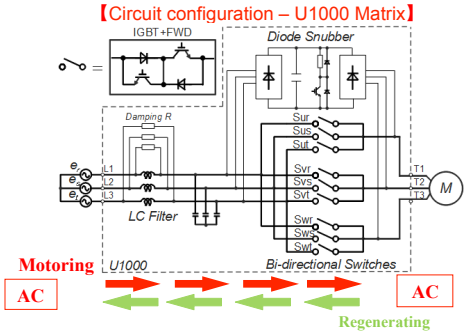


【9 bi-directional switches】

【Circuit configuration - general-purpose drive】



【Circuit configuration – U1000 Matrix】



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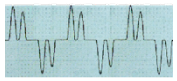
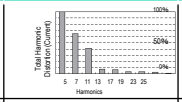
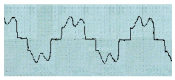
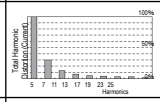
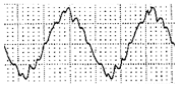
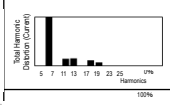
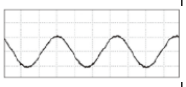
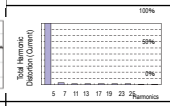
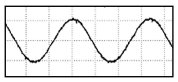
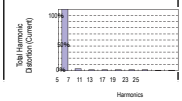
Harmonic Performance Comparison

	Current Waveform	Current Spectrum	System Eff.	iTHD
AC drive without reactor			97%	~ 80%
AC drive with DC reactor			96-97%	~ 35%
AC drive with multi-pulse or filter			94%	5 - 12%
AC drive with AFE			94-96%	4-5%
Matrix AFE			98%	3-4%

Driving Value

Yaskawa America, Inc.

YASKAWA

