# Fundamentals & Application of Medium Voltage Adjustable Speed Drives (ASD)

Manish
Verma
Senior Member IEEE
TMEIC

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# Safety Moment - Petextrians

After decades of decline, pedestrian fatalities are once again on the rise.
“Petextrians” — people who text while walking — may be partly to blame, according to the report.”
(ABC News Report)

# Quality Moment

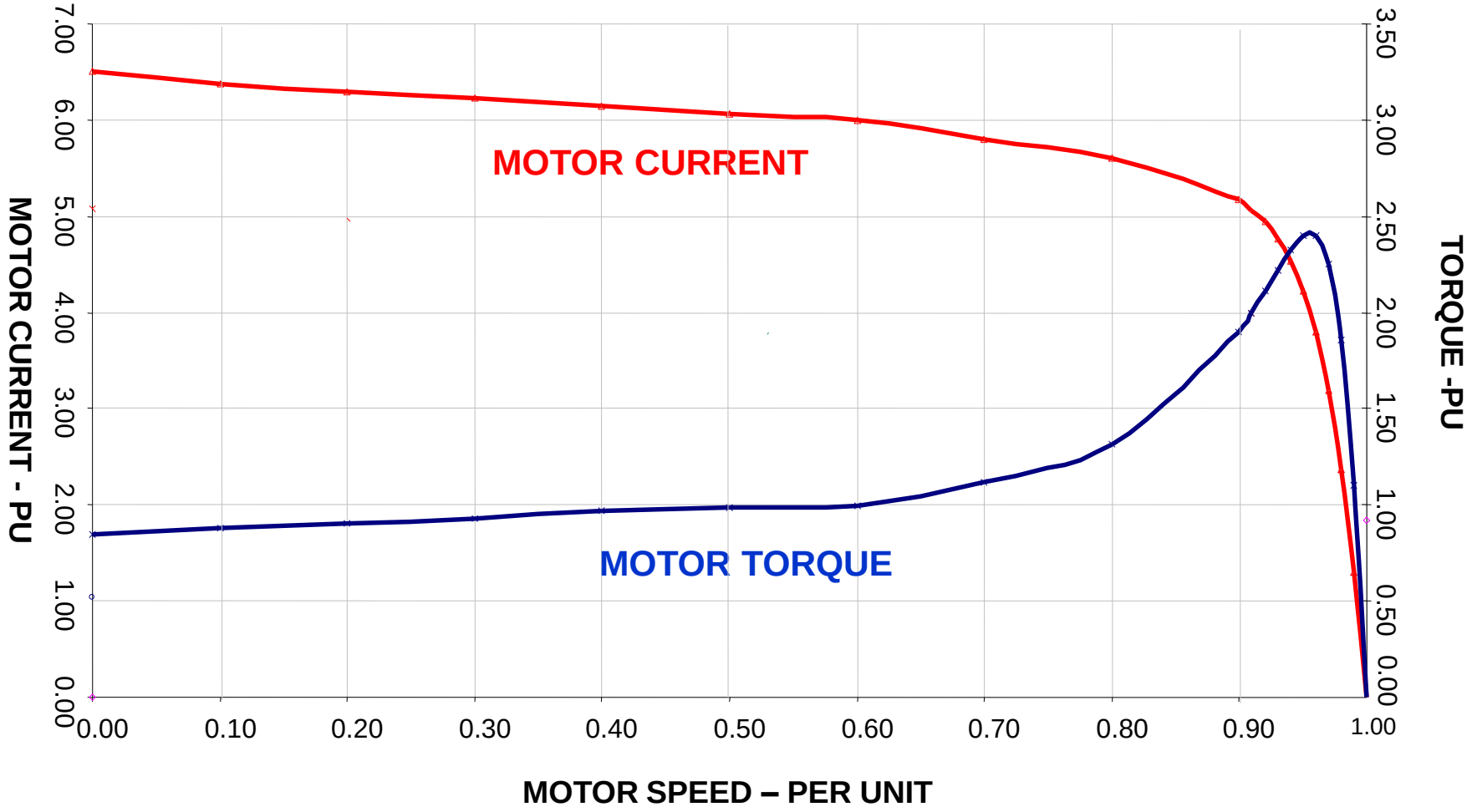
**Quality means doing it right when no one is looking.**

**- Henry Ford**

# Applicable dimension

| Parameter | Description |
|---|---|
| Service types | Rotating machinery such as pumps, compressors, extruders, fans, blowers, etc. |
| Power Level (HP) | 500HP – 130,000HP |
| Voltage range(kV) | Medium Voltage, > 1.0 kV |

# Typical Motor Starting Characteristics

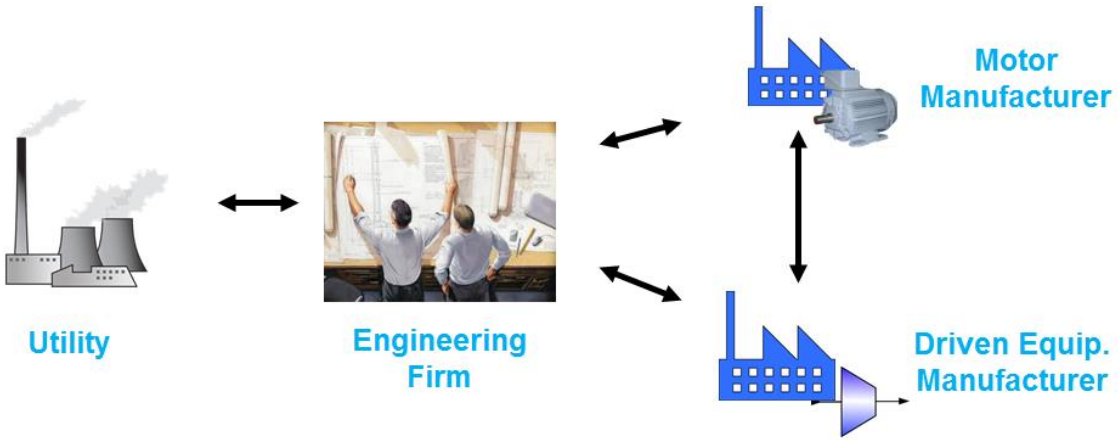


# Why is starting large motors stressful?

- Highest current is seen when shaft is still
- Starting currents create stresses and torques that can damage motor and attached load
- The motor and the load must breakaway and accelerate
- Remember current equals heat !

## Power System Challenge

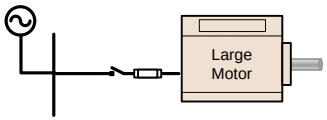
- Balance allowed inrush amps with Voltage drop
- Balance power system effects with torque demand of load



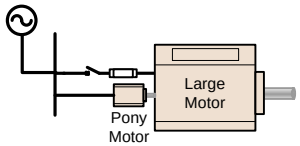
# Motor Speed Control Strategies

## Available Motor Speed Control Methods

**Direct-On-Line (DOL)**

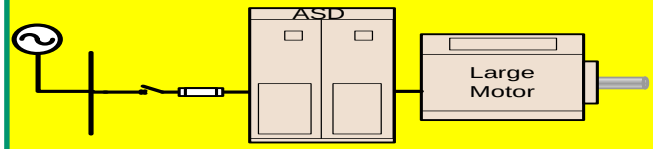



**Other Mech. Methods**




**Constant Utility Frequency (50 or 60Hz)**

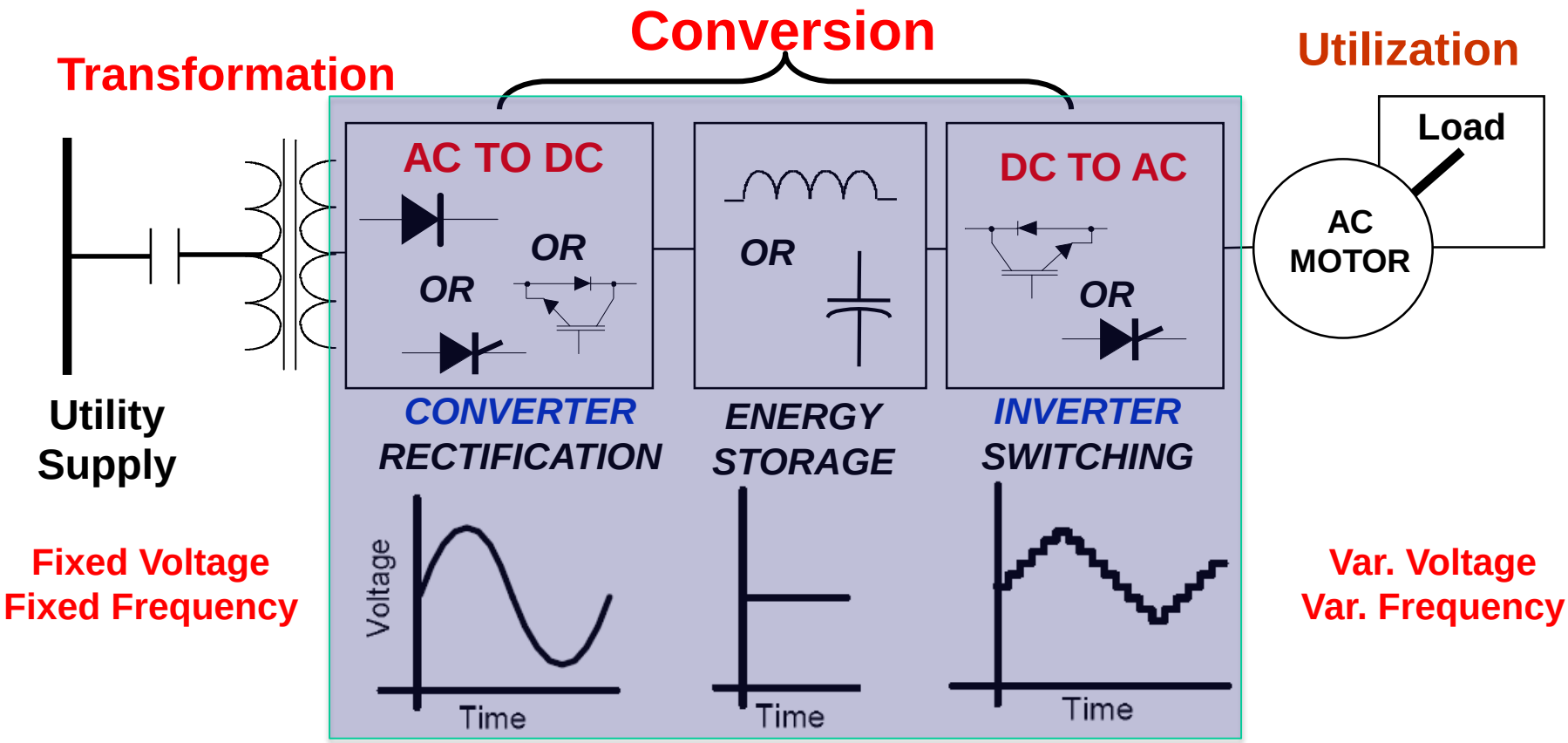
**Adjustable Speed Drives (ASD)**

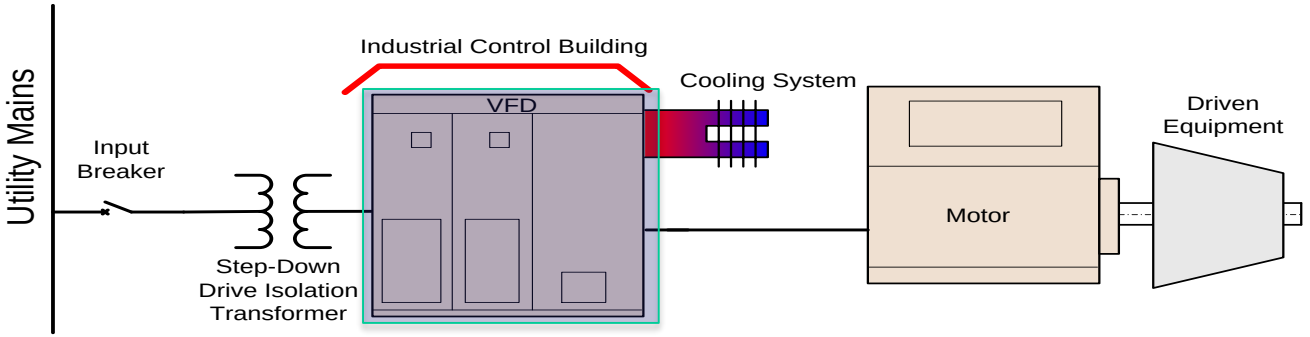



**Adjust Frequency**

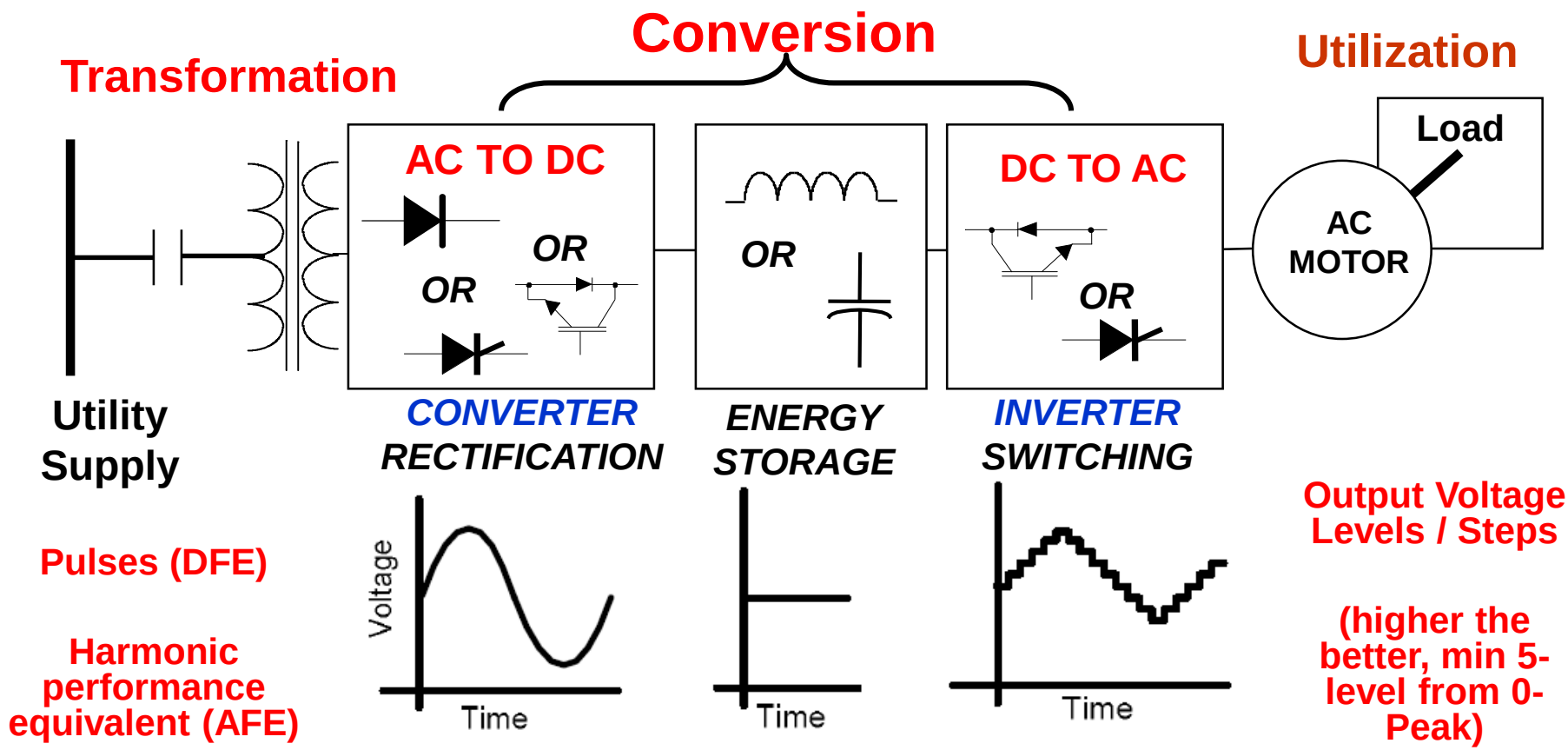
**Good Reference:** Larabee, J.; Pellegrino, B.; Flick, B., "Induction motor starting methods and issues," *Petroleum and Chemical Industry Conference, 2005. Industry Applications Society 52nd Annual* , vol., no., pp.217,222, 12-14 Sept. 2005

Nevelsteen, J.; Aragon, H., "Starting of large motors-methods and economics," *Petroleum and Chemical Industry Conference, 1988, Record of Conference Papers., Industrial Applications Society 35th Annual* , vol., no., pp.91,96, 12-14 Sep 1988


Transformation
Conversion
Utilization
AC TO DC
OR
OR
OR
DC TO AC
OR
Load
AC
MOTOR
Utility
Supply
CONVERTER
RECTIFICATION
ENERGY
STORAGE
INVERTER
SWITCHING
Fixed Voltage
Fixed Frequency
Voltage
Time
Time
Time
Var. Voltage
Var. Frequency


Utility Mains
Input
Breaker
Step-Down
Drive Isolation
Transformer
Industrial Control Building
VFD
Cooling System
Motor
Driven
Equipment

# What is an ASD? – Other common terminology



# What is an ASD?

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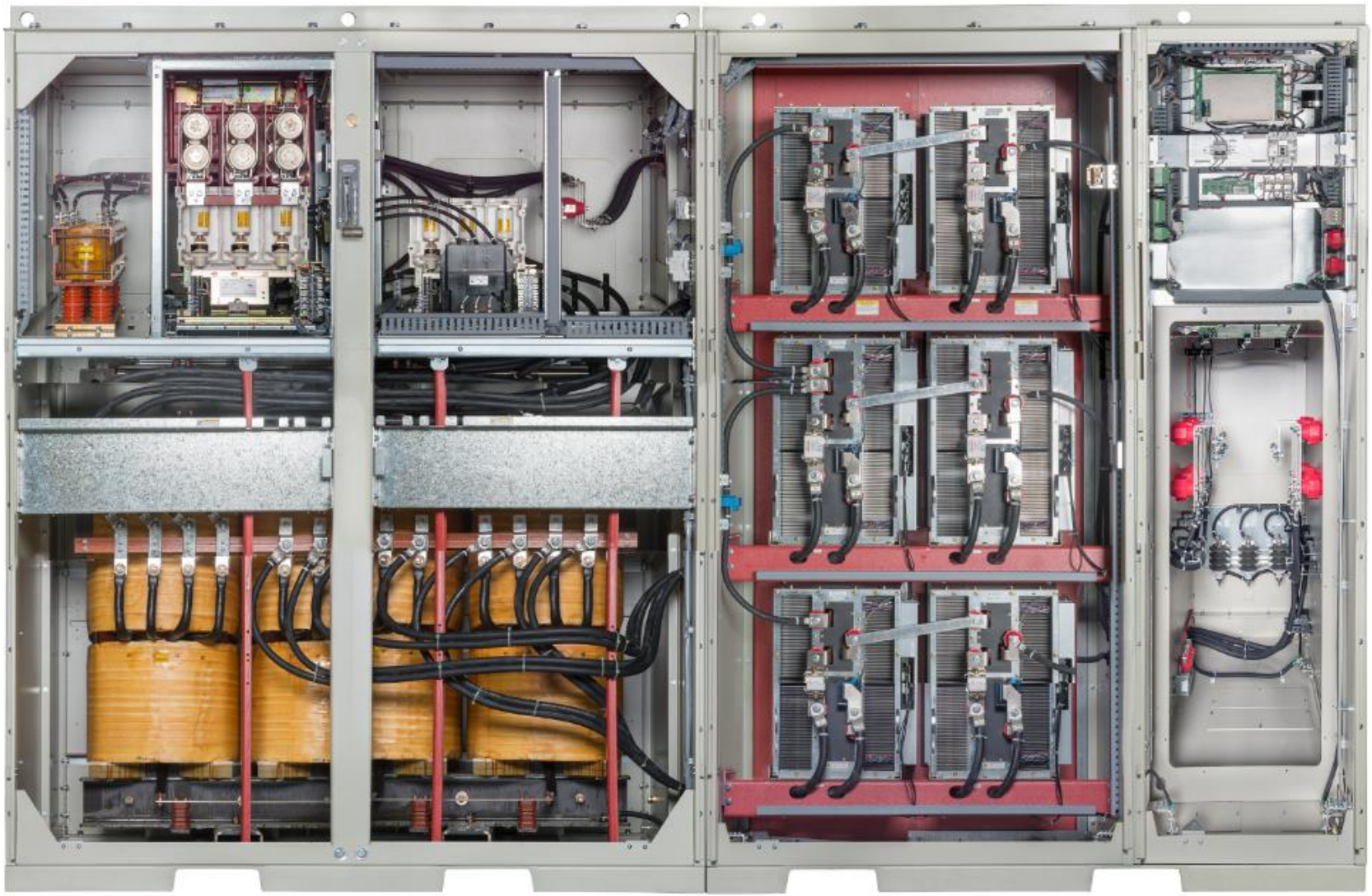
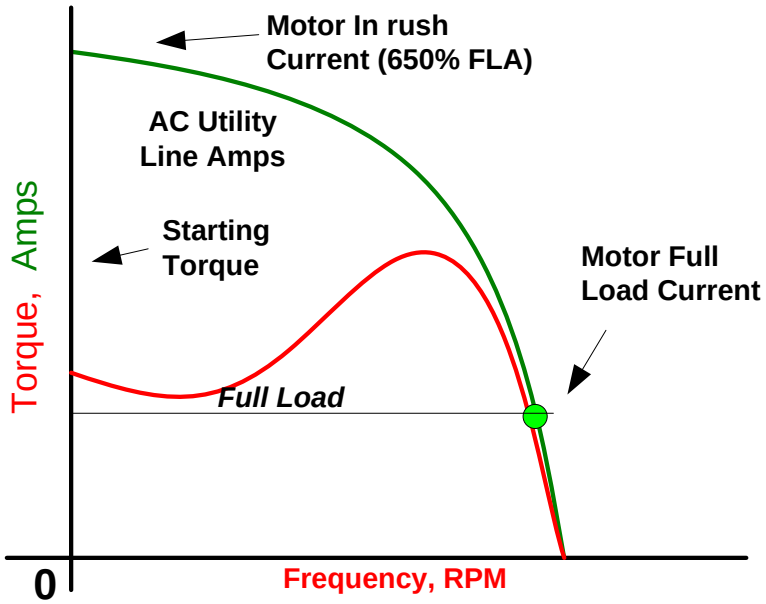
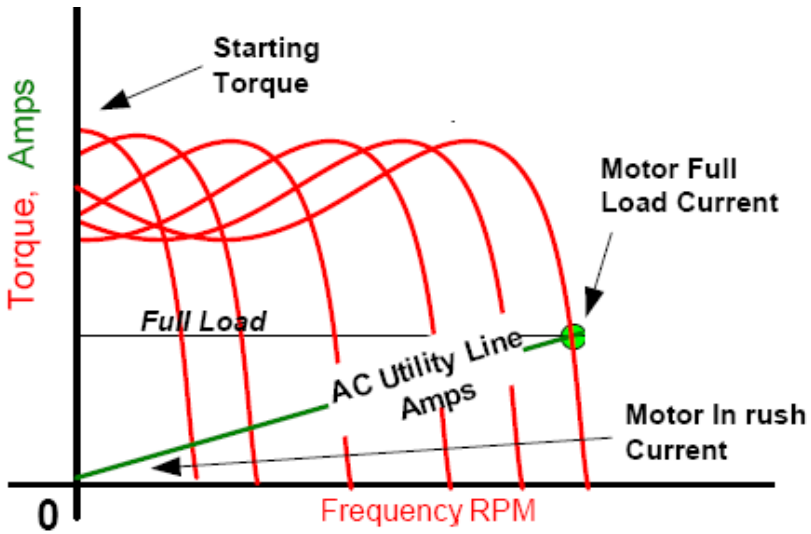


# What is an ASD?

# What does an ASD mean for the motor?

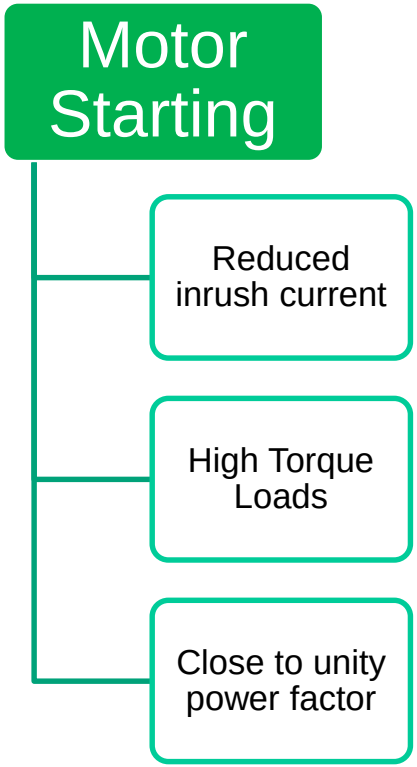



**Direct-on-line / Fixed Frequency**




**Variable Frequency**

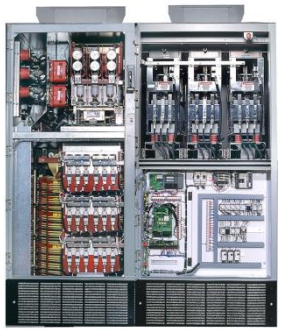
# What does an ASD mean for the motor?



# What do we mean by “Medium Voltage ASD”

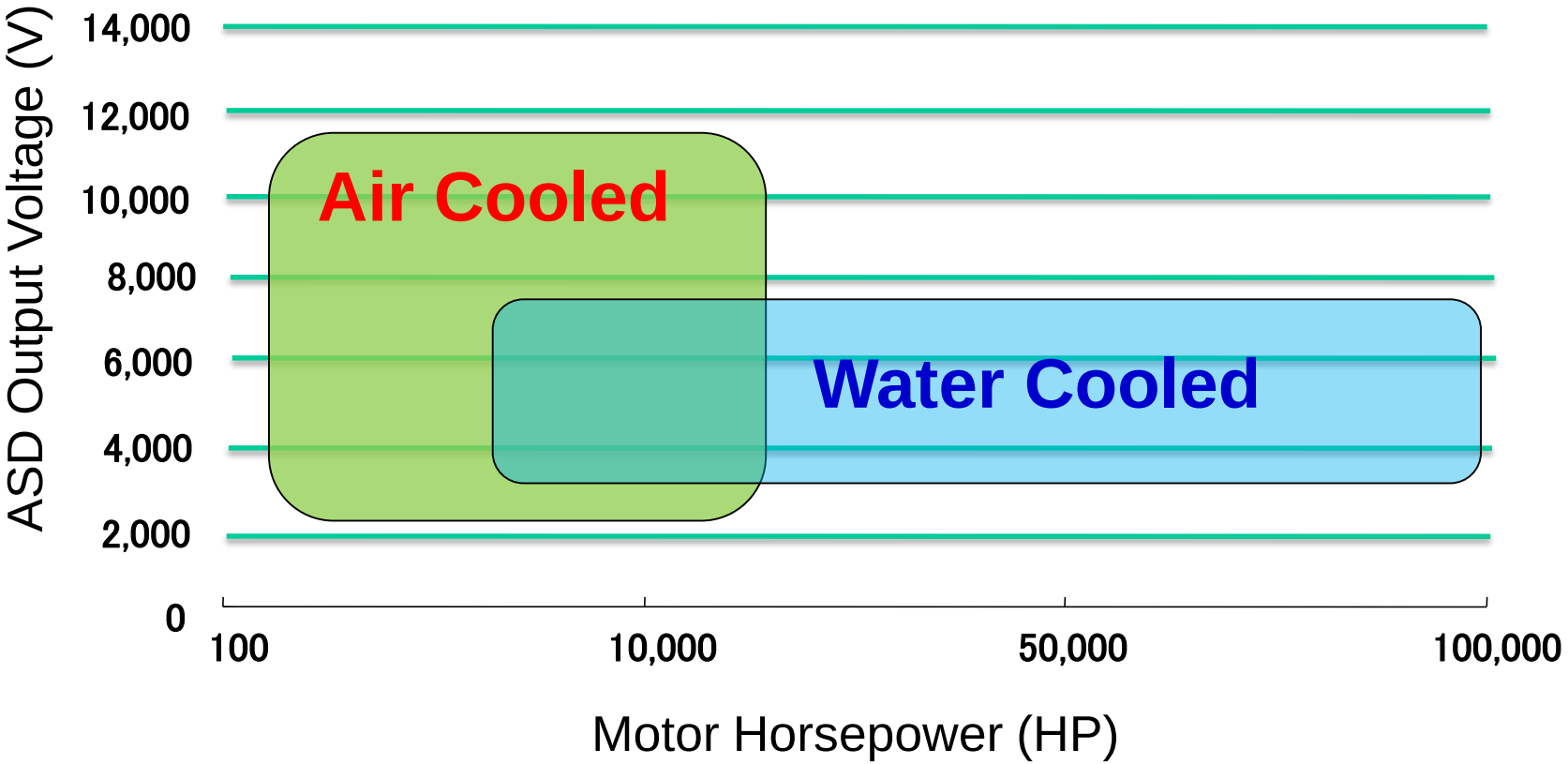
- Medium Voltage drives range from 2300V – 13800V.
- Voltage defined at output.
- Input voltage to the VFD between 2.3kV – 138kV
- ASD = VFD = EVFD = VVVF (can be used interchangeably)

Small Air-Cooled ASD

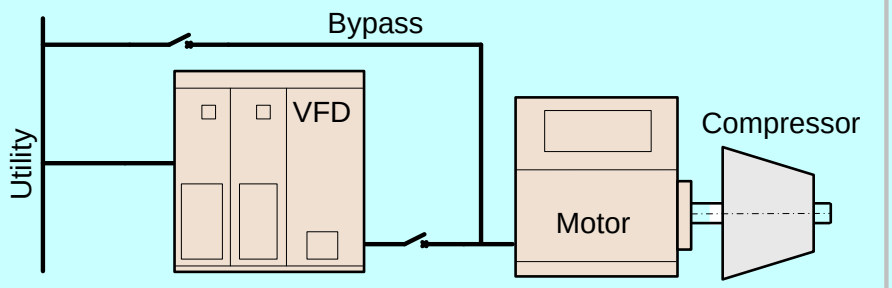
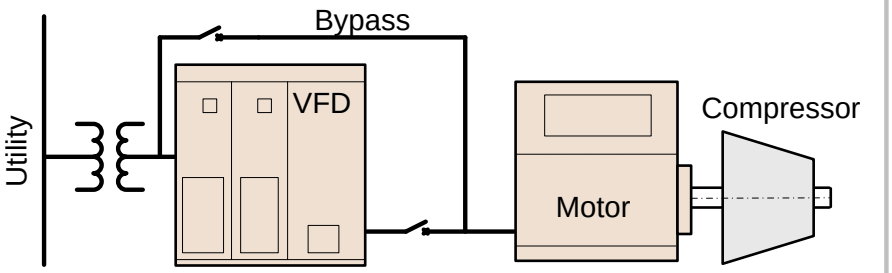
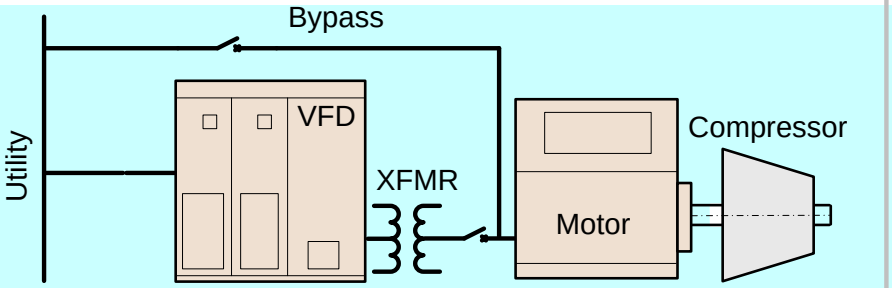


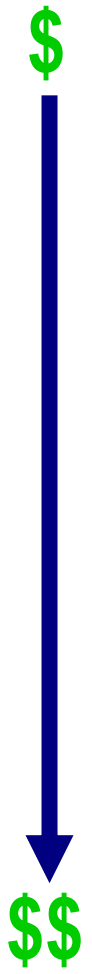
Large Water-Cooled ASD

# Typical Range of ASDs

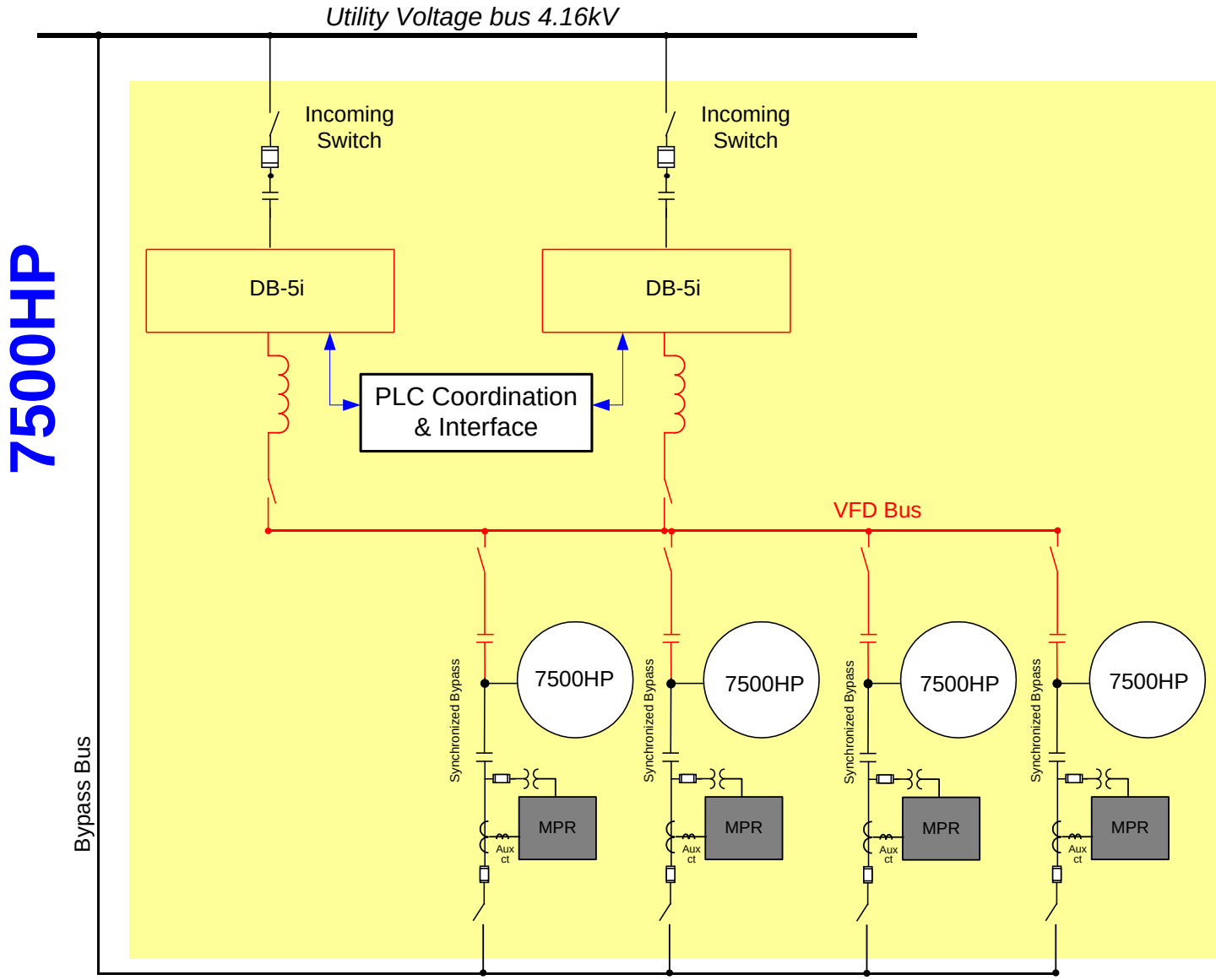


# Single VFD / single motor

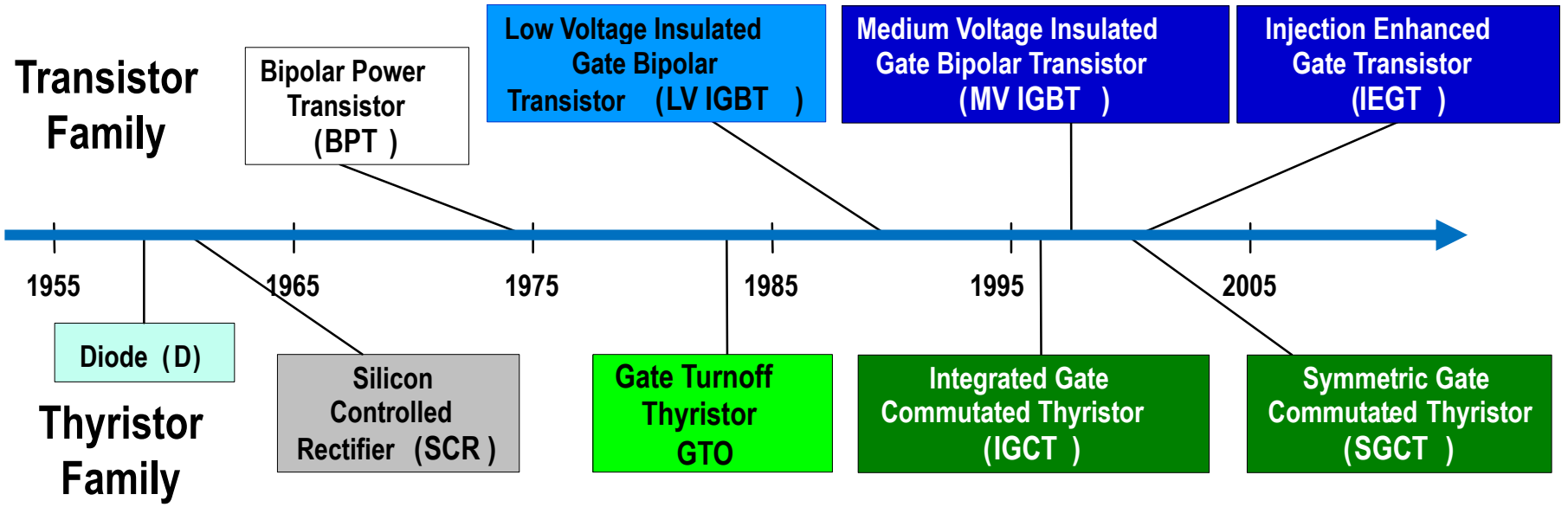
| Simple Electrical One-line | Voltage Level Scenario |
|---|---|
|  | Utility = VFD<br>VFD = Motor |
|  | Utility > VFD<br>VFD = Motor |
|  | Utility = VFD<br>VFD ≠ Motor |



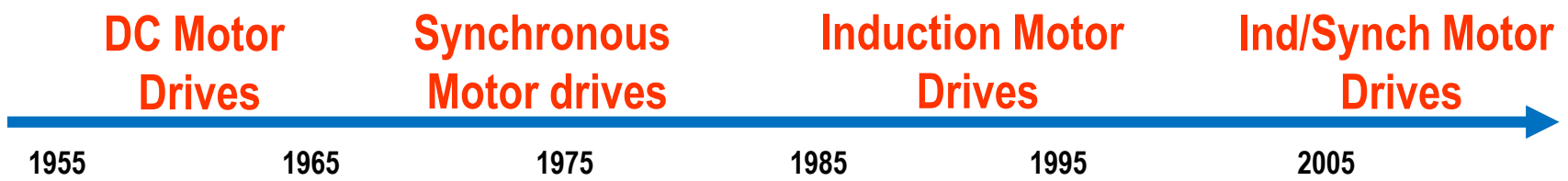
# Multi drive – Multi Motor



# Historical Overview




## Time Line of Adjustable Speed Drives



# ASD Topologies

- AC Drive Topology:

  *A map-like diagram showing the elements of an AC drive and the relationships between them.*

- The Common Threads:
  - All AC Drives rectify AC to DC.
  - All AC Drives use switches to create AC from DC.

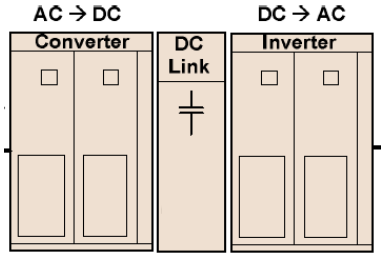
- Drive topologies were created as power rectifiers and switches grew in ratings and capabilities.

- Each new or uprated device opens up new applications

# Major ASD Topologies

## Voltage Source Inverters (VSI)

- Energy storage/DC Link is **Capacitor**

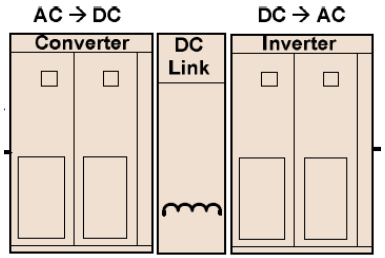



- Maintains constant Voltage at DC Link
- Converter (AC/DC) is either Passive (using diodes) or Active (using PWM)

## Current Source Inverters (CSI)

### Load Commutated Inverters (LCI)

- Energy storage/DC Link is **Inductor**




- Maintains constant current at DC Link
- Converter (AC/DC) is Active (using phase control or PWM)

### Pulse Width Modulated (PWM)

# Comparing Drives of All Topologies

- **Current Source Drives**
  - **LCI – Load Commutated Inverter**
  - **GTO/SGCT Current Source Induction Motor Drive**

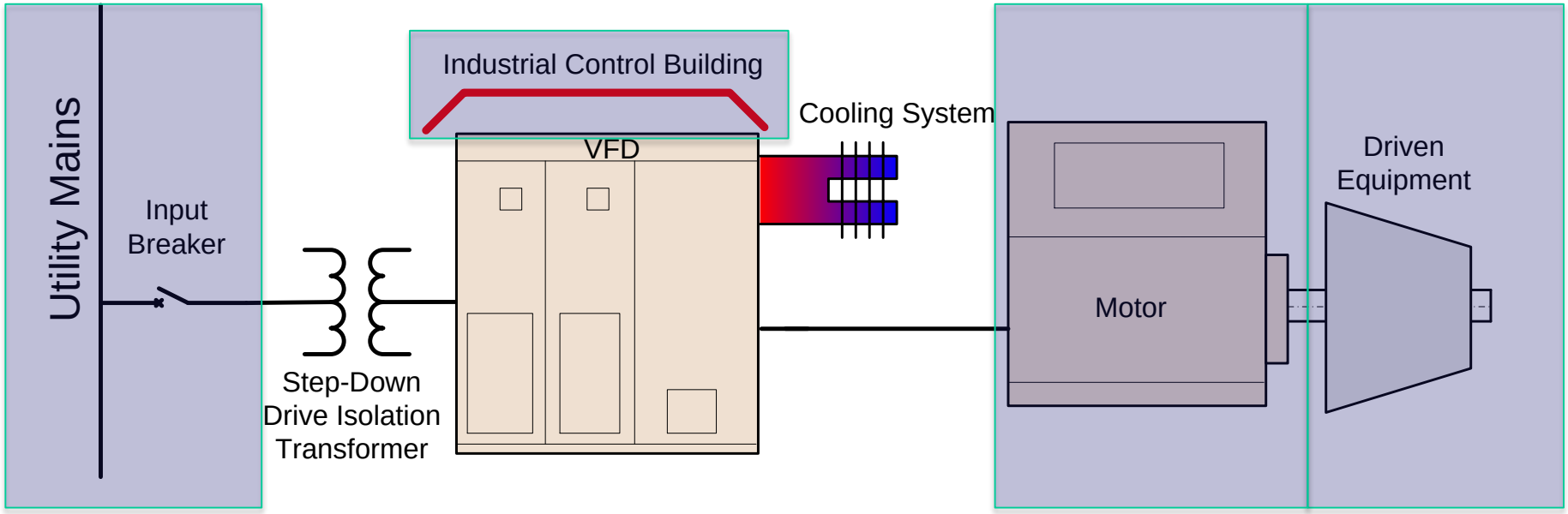
- **Voltage Source Drives**
  - **LV IGBT "Paice" Multilevel PWM**
  - **MV IGCT PWM – Diode or Active Source/Converter**
  - **MV IGBT PWM – Integrated package**
  - **MV IEGT PWM – Active or Diode Source/Converter**

**Good Reference for more details**: Lockley B, Paes, R. "What's new with MV Drives" http://sites.ieee.org/northern-canada-pesias/files/2014/02/Whats-New-with-MV-Drives-IEEE-NCS-2014-Final.pdf , Pages: 43 – 58.

# ASD System Considerations

Must consider the whole system in which the ASD will work

- From Utility to finished product or process
- Consider environment
- Consider effects on utility
- Consider the needs of the load
- Consider the effect of ASD on the motor and drive train



# ASD Overall Success Factors

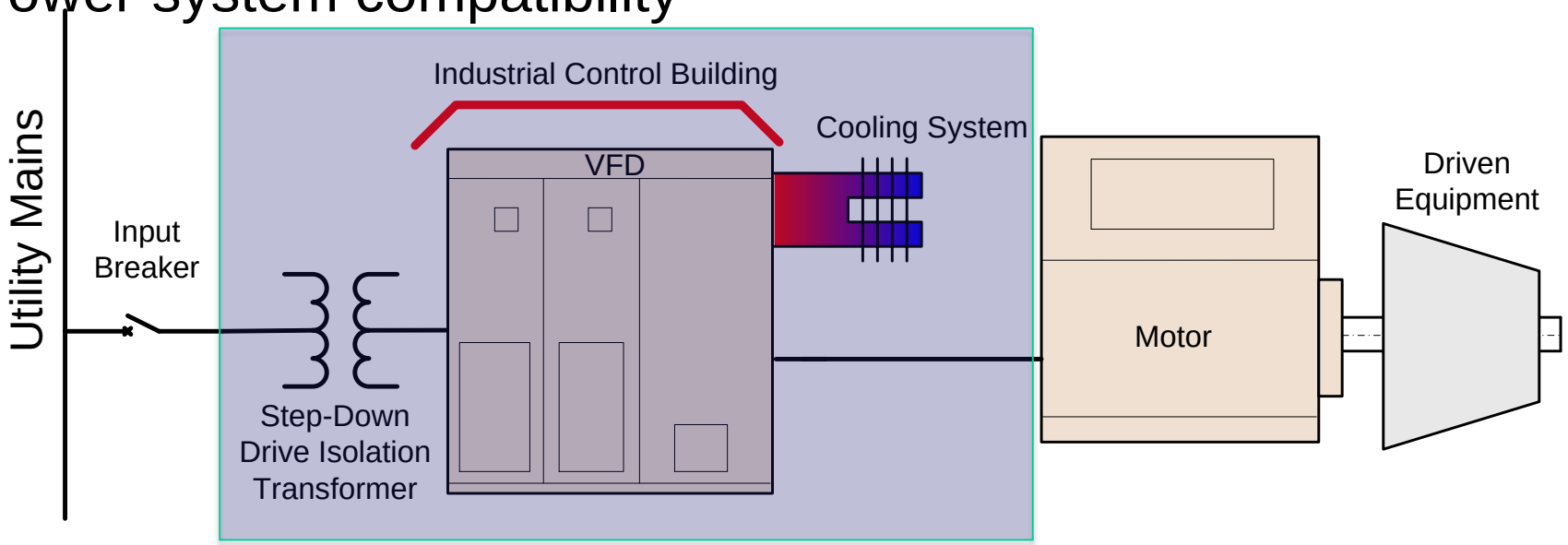
- Minimum first cost, including installation
- Maximum long-term payback.
- Good match to process & loads.
- Long equipment life.
- Ease of use for operators & technicians.
- Minimum impact on nearby equipment.
- Easy to maintain & repair.
- Smallest foot print

**Application considerations can divided into the <u>following</u>:**

- Electrical/Load Application Factors
- Installation Factors (E-house integration/Cabling)
- ASD Protection & Cooling methodology
- ASD standards and Factory Testing

# Electrical/Power Application Factors

- Continuous kW or HP & duty cycle
- Torque & Power Overload requirements
- Load factors:  CT, VT, CHP, regenerative, non-regenerative.
- Drive and Motor Voltage
- Power system compatibility




**#2 - Define the power system requirements**

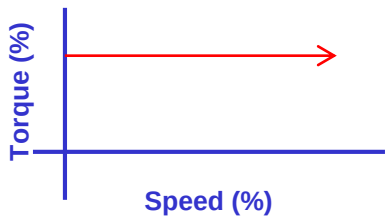
**#3 – Determine best drive solution!**

**#1 - Define the process loads and duty cycle**

# Load Type Examples

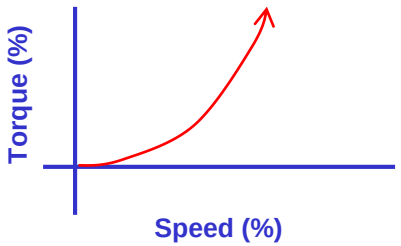
## Constant Torque

- Conveyors
- Grinding Mills
- Kilns
- Reciprocating Compressors
- Positive Displacement [Screw Type] pumps, compressors




## Variable Torque

- ID / FD Fans
- Centrifugal Pumps
- Centrifugal Compressors
- Pipeline booster pumps
- Axial Compressors

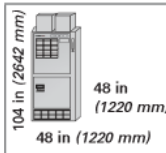
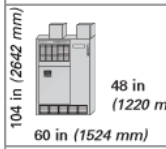
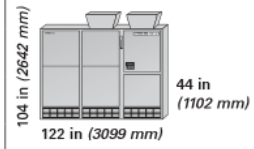
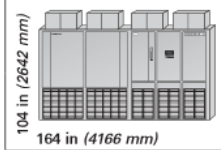
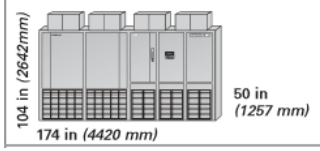


# Keep In Mind

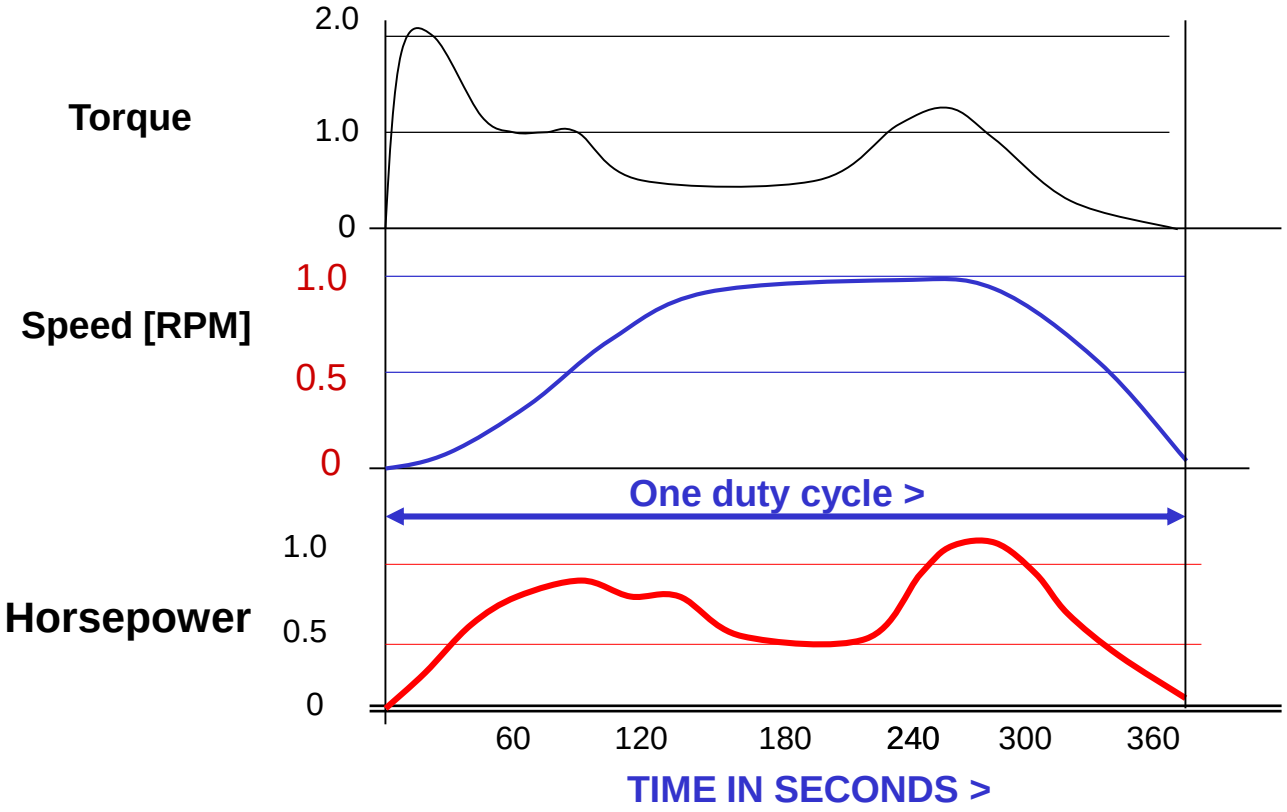
**Drives are sized & priced based on Motor Full Load Current AND Operating Envelope**

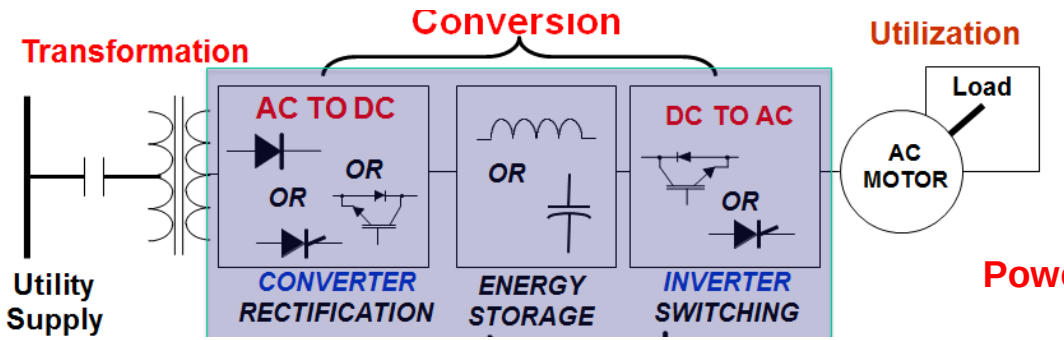
Example:

1. 7000 HP, 1800 rpm, 4000V, FLA 910A
   = 6300 kVA
2. 7000 HP, 450 rpm, 4000V, FLA 1240A
   = 8600 kVA

| | | 4000 Series 4160 Volts Out | |
|---|---|---|---|
| | | Motor Shaft hp (kW) | Output Amps $I_{Phase}AC$ |
|  | Frame A4µ | 600 (448) | 74 |
|  | Frame A4 | 800 (599) | 99 |
| | | 900 (671) | 112 |
| | | 1000 (746) | 124* |
|  | Frame 1 | 1000 (746) | 124 |
| | | 1250 (933) | 155 |
| | | 1750 (1306) | 217 |
| | | 2000 (1492) | 248* |
|  | Frame 2 | 2250 (1679) | 279 |
| | | 2500 (1865) | 310 |
|  | Frame 3 | 3000 (2238) | 372 |
| | | 3500 (2611) | 434 |

# Lets take an example




**Power = Speed x Torque**

# Drive Ratings and Torques

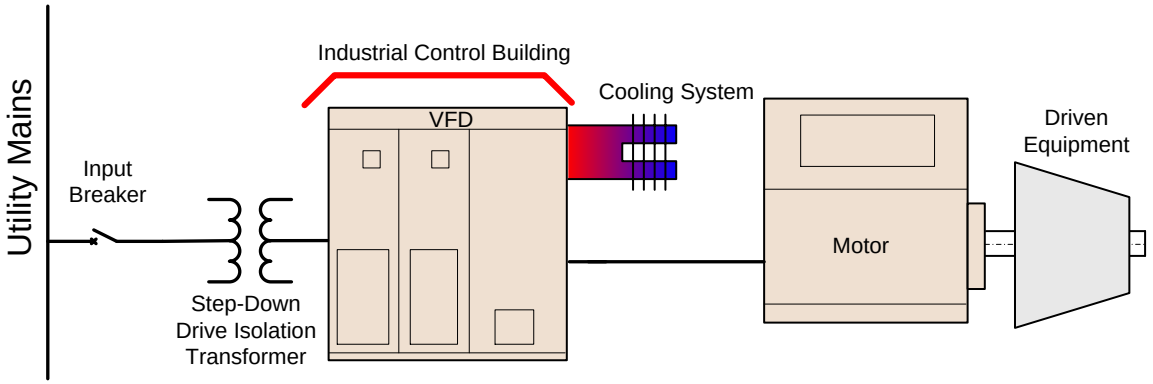
- Variable Torque (VT) ratings usually include 110 -115% OL rating for 60 seconds when starting from rated Temp

- Constant Torque (CT) rating usually includes 150% OL rating for 60 seconds when starting from rated Temp.

On Constant Torque applications, take a close look at the Speed Torque Curve for selecting the correct ASD size

# Power System Compatibility

- Power distribution (available utilization voltages)
- Protection.
- Harmonics limits.
- Power factor control.
- Efficiency.




- Breakers, transformers, and cable must be rated to carry full kVA & harmonics.

- Transformers need to be “drive isolation” rated with proper considerations for the drive type.

# Power system compatibility - Keep In Mind

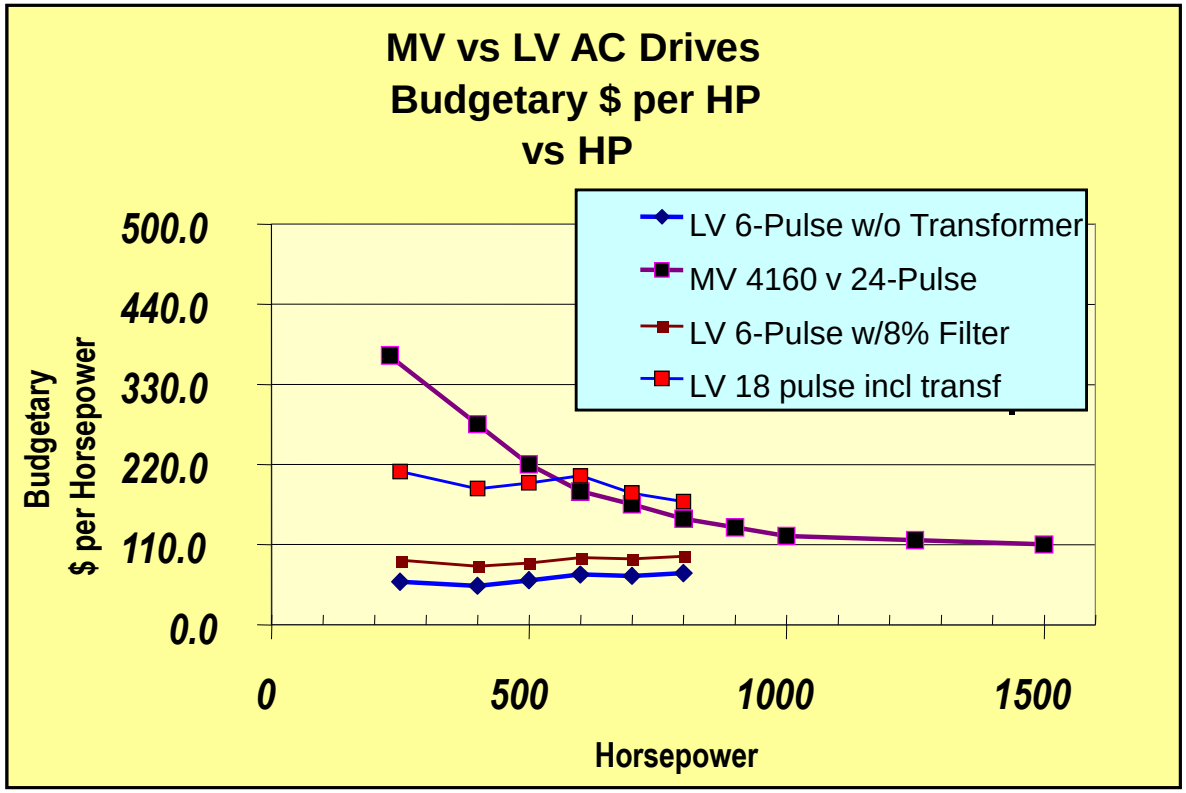
- Always provide and electrical one-line diagram
- Some tips for ASD voltage level selection

| Motor Power | ASD Input Voltage | Motor Voltage |
|---|---|---|
| • 250HP – 5000HP | 2.3, 4.16, 3.3, 6.6, 10, 11, 13.8 kV | 2.3, 4.16, 3.3, 6.6, 10, 11 kV |
| • 5000HP – 10,000HP | 4.16, 6.6, 10, 11, 13.8, 25, 34, 66 kV | Matched to ASD output voltage |
| • >10,000HP | 10, 11, 13.8, 25, 34, 66, 110, 138 kV | Matched to ASD output voltage |

**Note: if ASD is used for starting ONLY, then**
**Motor Voltage = Utility Voltage (Max 13.8kV)**

# Medium voltage versus low voltage – what to use??

- MV drive $ / HP decreases with HP
- Installed cost must be considered including:-
  - Harmonic mitigation requirements
  - Cabling costs
  - Installation costs
  - Reliability



# Drive Output Voltage & Motor Application

- Why Pick LV [<690v] Drive & Motor?
  - LV drives are lower cost / HP than MV
  - Reduces some safety & MV training concerns
  - HP range is small enough
  - Individual preference

- Why pick MV over LV?
  - Lower cost wiring, smaller cables
  - Lower power system harmonic impact
  - High HP LV require dual winding motors
  - Individual preference

**Recent Trend:** **Some users select MV >250 HP**
**Many users select MV > 500 HP.**

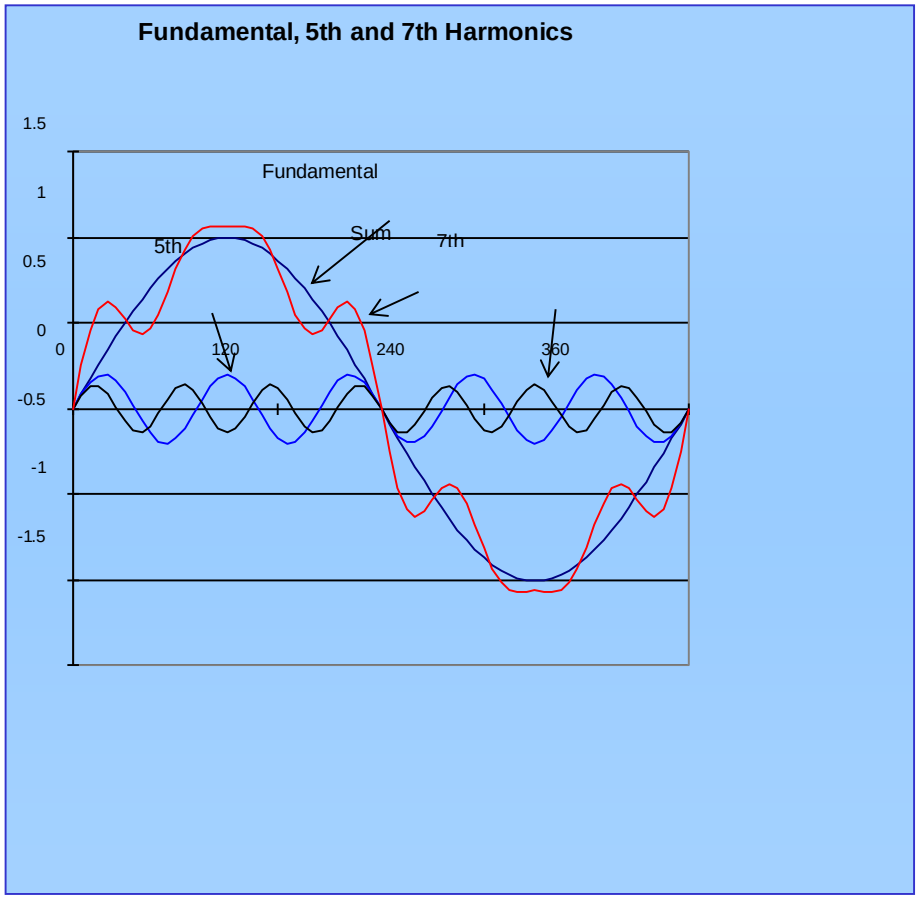
# Some MV vs. LV Conclusions

- For drives > 1000 HP, MV makes sense
- For long cable runs, MV makes sense
- For drives < 500 HP, LV makes sense.
- If low power system harmonics are required, LV filter or multi-pulse cost adders can favor MV over LV.
- In the range 500 to 1000 HP the various application & installation factors apply.

- Final choice may boil down to user preference.

# Power Line Harmonics

- "Harmonics" are voltages and currents at frequencies that are multiples of utility power frequency.
- Harmonic currents are drawn by loads such as drives, computers and ballasts that take their power in non-sine-wave format. These are so-called non-linear loads.



# IEEE 519-2014 Table 10.3 $I_{TDD}$ Limits

**Maximum Harmonic Curent Distortion in % of I-Load**

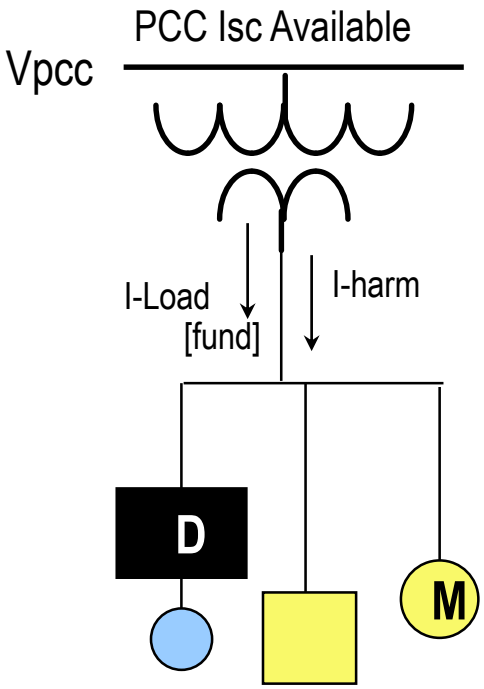
| Isc to I-load Ratio | h < 11 | h = 11 to <17 | h = 17 to <23 | h = 23 to <35 | h = 35 & up | TDD % |
|---|---|---|---|---|---|---|
| < 20 | 4.0 | 2.0 | 1.5 | 0.6 | 0.3 | 5.0 |
| 20 < 50 | 7.0 | 3.5 | 2.5 | 1.0 | 0.5 | 8.0 |
| 50 < 100 | 10.0 | 4.5 | 4.0 | 1.5 | 0.7 | 12.0 |
| 100 < 1000 | 12.0 | 5.5 | 5.0 | 2.0 | 1.0 | 15.0 |
| >1000 | 15.0 | 7.0 | 6.0 | 2.5 | 1.4 | 20.0 |

**Notes:** Even Harmonics limited to 25% of the harmonic level

**TDD** = Total Demand Disortion %, based on maximum demand current at the point of common coupling [PCC].

**Isc** = Maximum Short Circuit current or kVA at the PCC

**I-load** = Fundamental freqency load current or kVA at the PCC




**Specifying a min. 24-Pulse VSI VFDs or Active Front End VFD is safest option for harmonic mitigation**

# Power System & Drive Efficiency

- Drive itself is typically 98% or more efficient
  - With all fans, transformers, pumps, etc, efficiencies of 96-97% are common
  - Efficiency impact of drive varies with speed

- Efficiency effect of the drive can be eliminated at full speed by synchronous bypass.

**For Air-cooled Versus Water-cooled Overall system efficiency use:**

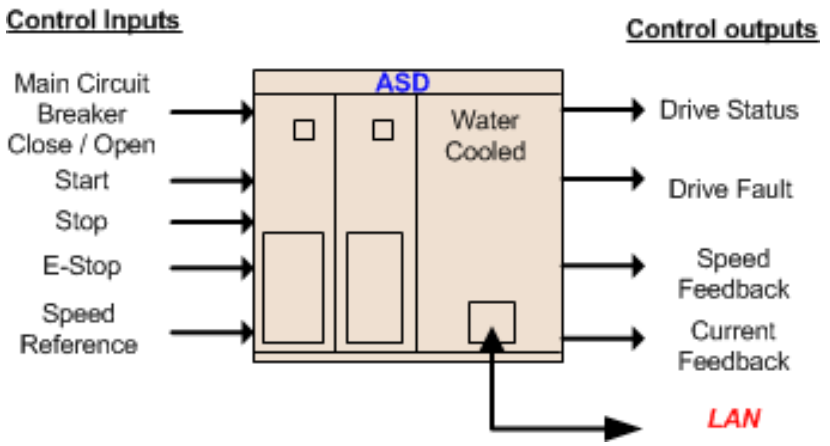
**92% for air-cooled (Includes VFD and E-house HVAC)**
**96% for water-cooled (Includes VFD and E-House HVAC)**

# Speed & Torque Control Requirements

- Each application is unique
  - Simple, free-standing pumps
  - Complex – e.g. sync to utility, multiple motors per drive, multiple drives on same load
- Process control – usually 4-20 mA for speed
- Go Tachless if possible
  - Precise speed control rare with MV drives and high kW level drives
  - High load torques (>150% OL) may require tachometer

# Operator Control and Communication

- Interface with larger process
  - Controls for operator –
    - Simple start-stop contacts
    - More complex HMI
  - Process equipment controls – system PLC

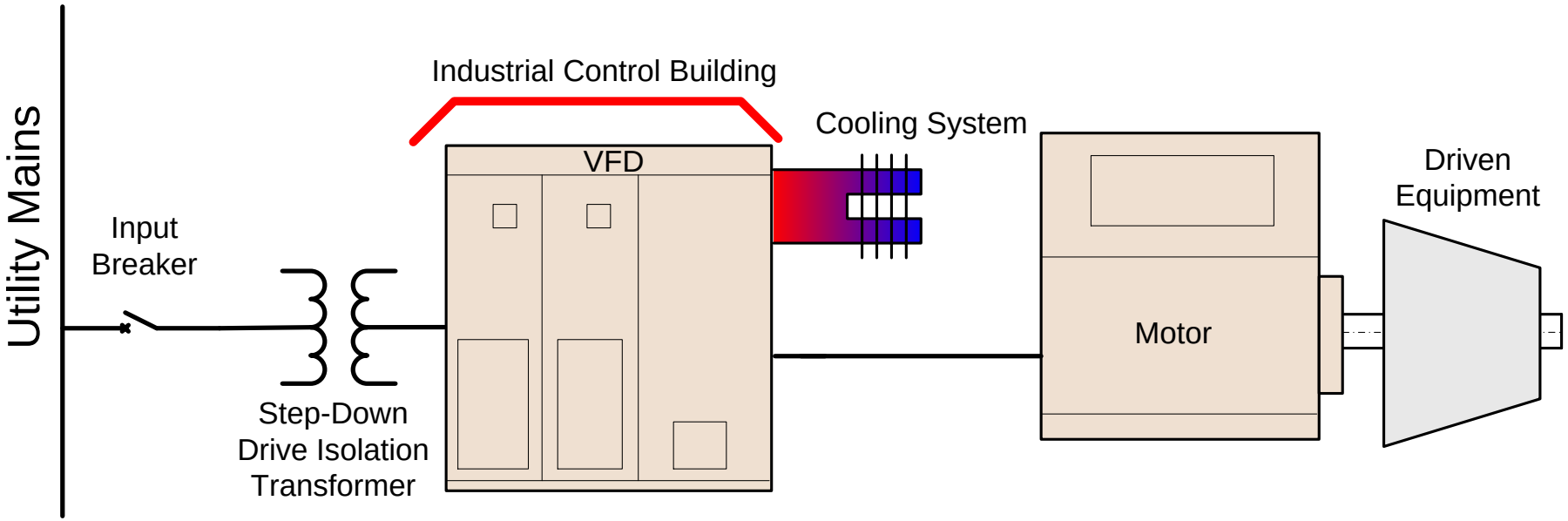



- LAN communication of drive status if/as needed to plant PLC or DCS

- Plan for remote diagnostics capability

# Drive Design For Reliability

- Minimum parts – fewest power components, and simplest firing circuits
- No “Weak links” like marginally rated capacitors, switching devices, etc
- Conservatively rated, fully qualified components
  - Quality built in not “burn-in tested”
  - Quality tracked



# ASD Operational / Environmental limitations

- Altitude:  De-rate current rating 2-3% per 1000 ft above 3000 feet. May have to de-rate voltage for very high altitudes.
- Temperature De-rate: 1.5% per degree C above base rating (usually 40C) up to max (usually 50 C).

- Drives put out heat – must be removed or vented to outside

- ASDs are designed to be installed in a relatively clean, dry environment

Operation

- 0 to 40 or 50 C with a relative humidity of 95% maximum, non-condensing.

Storage

- Equipment is generally designed for a non-operating (storage) temperature range of –25 C to 70 C.

# Specifying E-houses – Key to reliability

- Good standard to use is PIP ELSSG11, Electrical power center specification

If End User / EPC / OEM is supplying the ASD building

ASD Vendor to supply:-
- Heat Dissipation in kW
- Max. ASD Operating Temp.
- ASD Humidity & Air Quality Req.
- Weights & Dimensions
- Air flow requirement

Outline ultimate responsibility of the entire system

If End User / EPC / OEM splits the scope of building and ASD

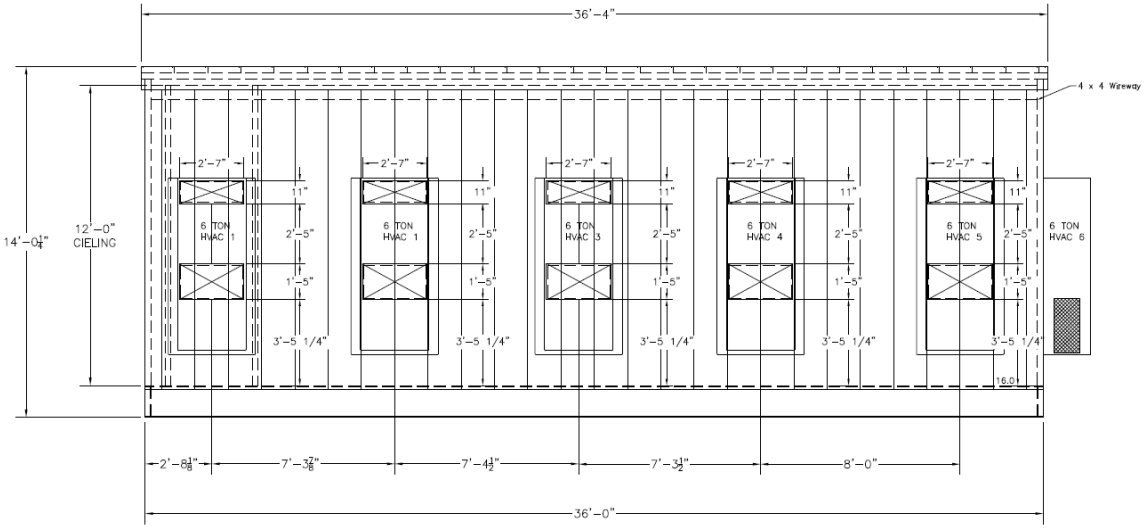
ASD Vendor ⟷ Building Vendor

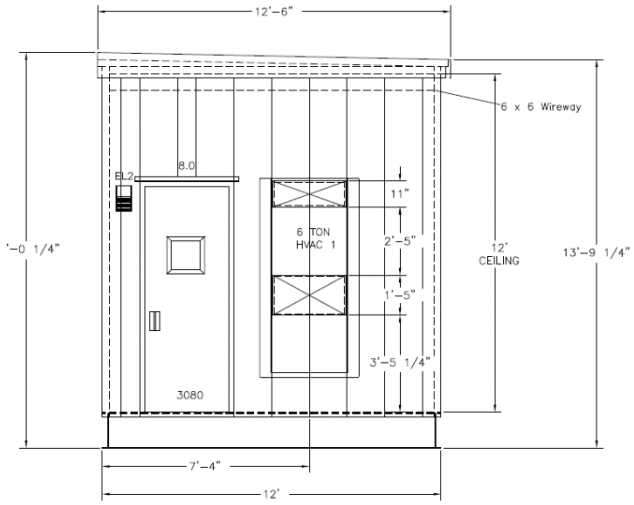
Heat Dissipation in kW
Max. ASD Operating Temp.
ASD Humidity & Air Quality Req.
Weights & Dimensions
Air flow requirements
Clarify responsibility ASD hook-up, plumbing, wiring, check-out

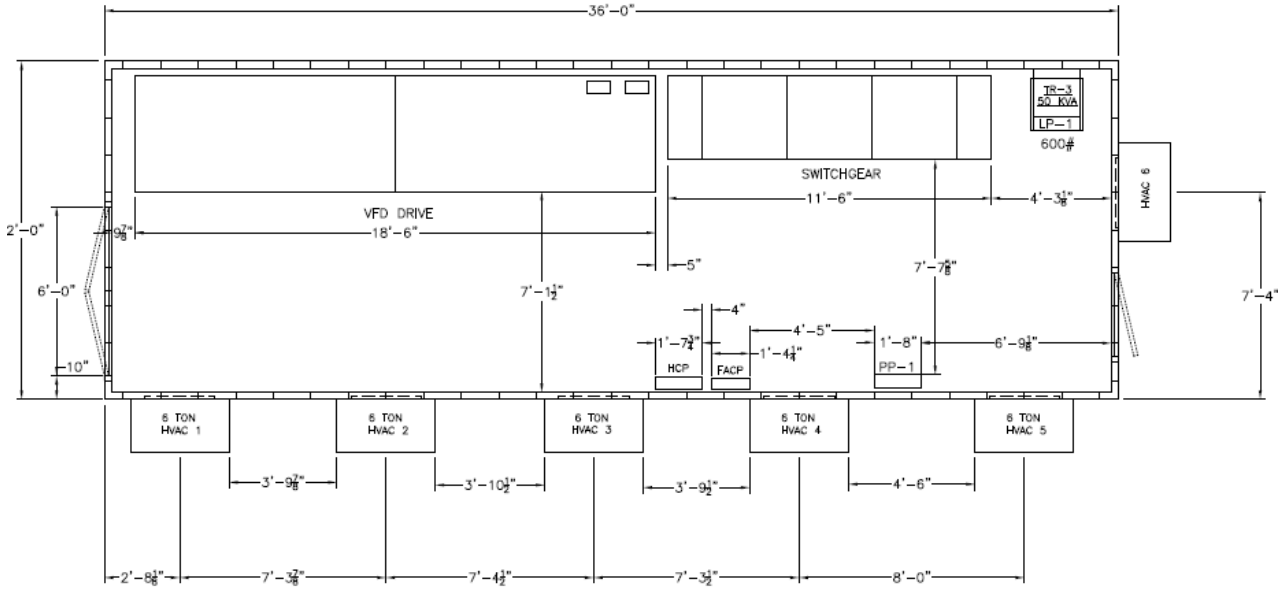
# E-house requirements

- Minimum requirements for ASD E-houses are:-
  - E-House NEMA rating, Typically 3R
  - Fire/Smoke detection
    - Note: Fire suppression is usually not provided and is optional (like FM200 waterless suppression)
  - N+1 HVAC based on ASD heat loss
  - 480V, 120V Panel boards for lights, control, ASD Aux
  - Bus Ducts or cable trays
  - PE stamp, certifications (if any), access restrictions
  - Local codes. Default is NEC
  - Location of E-house final destination – For E-house estimating shipping splits

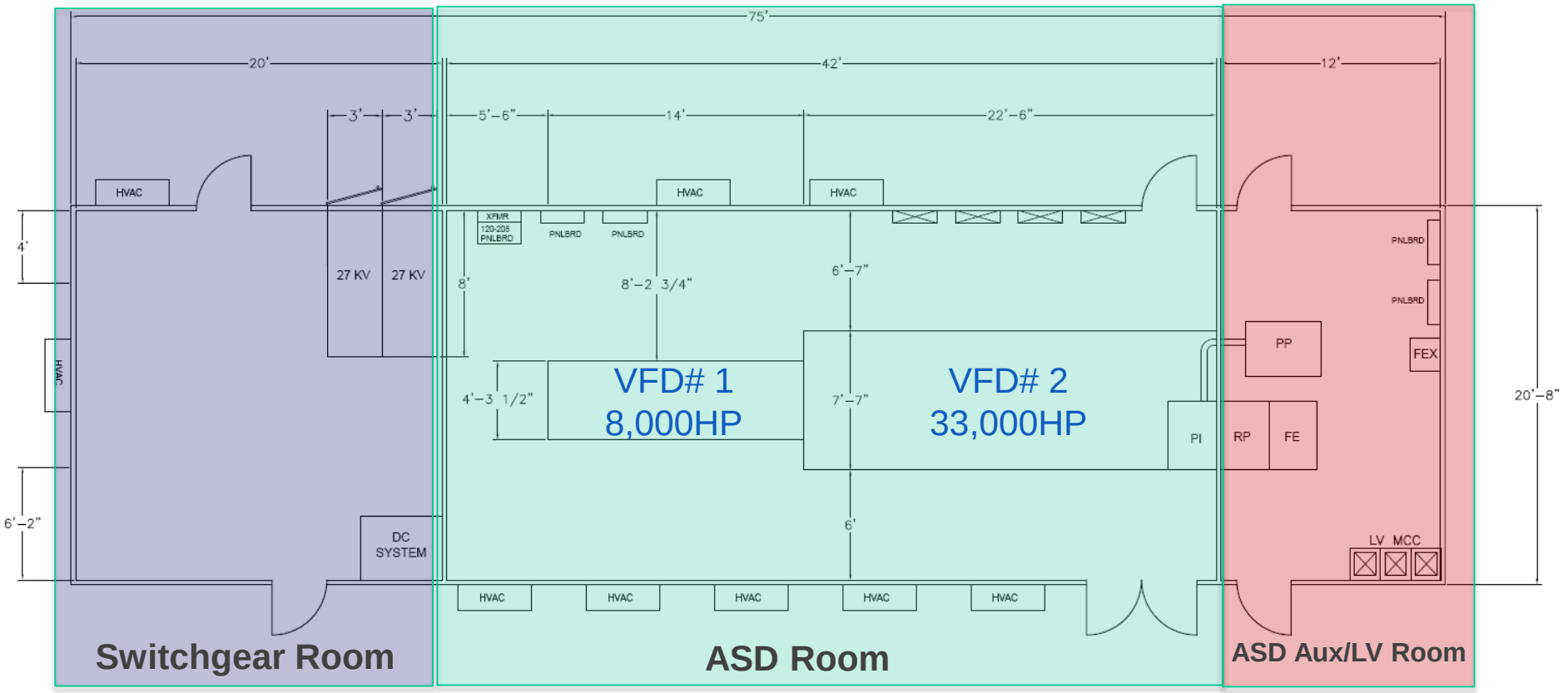
# Sample E-house layouts



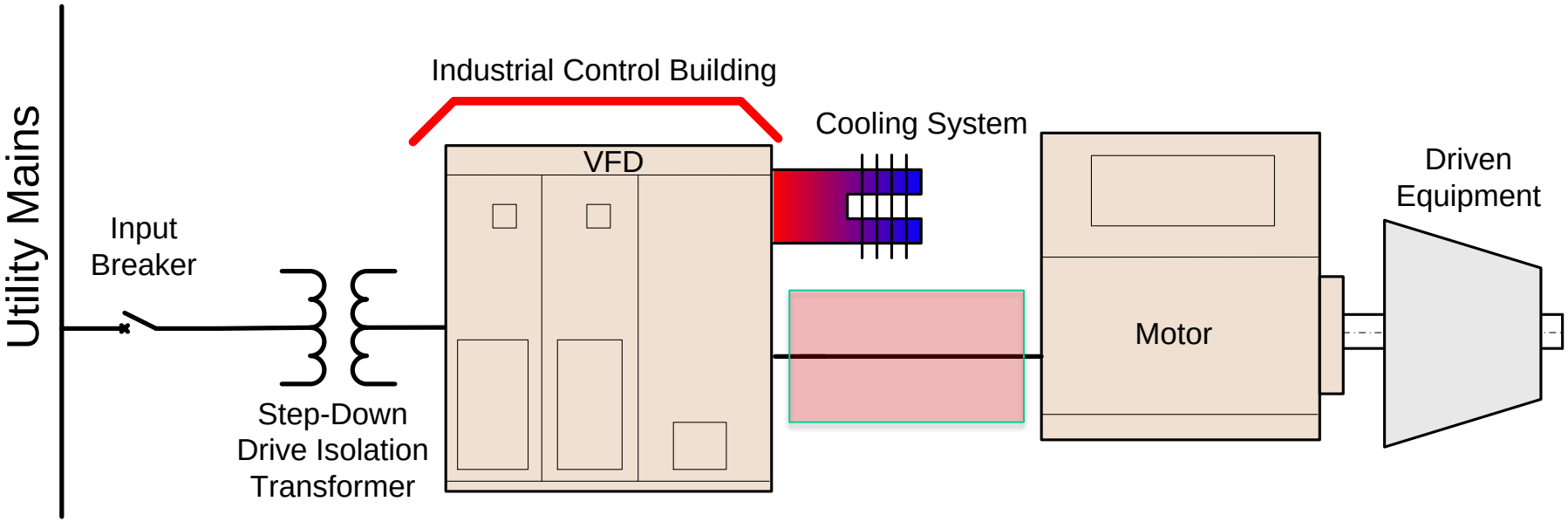
# Sample E-house layouts




**Preferable for ASD vendor to take responsibility of E-house specially for large ASDs**

# Cables From ASD to Motors

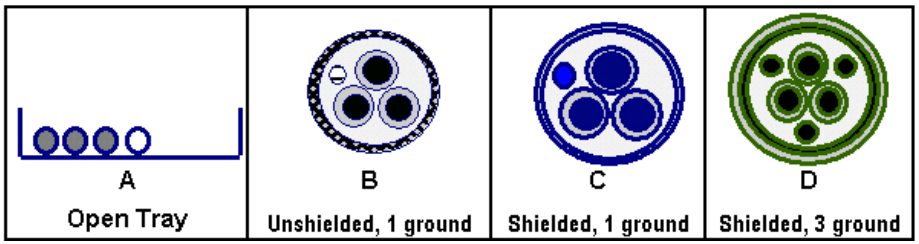
- Drives themselves are usually tolerant of most cable types & methods
- BUT, Cabling affects EMI radiation or motor.
- Cables > 500 meters need special attention [cable capacitance]



# Motor-Drive Cable Methods And Tradeoffs

| | | Relative Performance Area | | Usefulness by Drive Type | | | |
|---|---|---|---|---|---|---|---|
| Ref | Cable Type or Method | EMI Propagation & Cross-Talk from PWM | Minimizing Bearing Voltages & Currents | 2-Level < 690 volts | 3 Level, NPC* | 5 level or More, NPC* | Comments |
| A | **Open Tray, individual conductors** | Poor | Poor | **Not recommended** | Marginally acceptable | Marginally acceptable | **Use caution** by separating other conductors from inverter to motor cables by 300 MM [12 inches] or more |
| B | **3-conductor unshielded with 1 ground** | Poor | Better | **Not recommended** | Acceptable | Acceptable | **Use caution** by separating other conductors from inverter to motor cables by 300 MM [12 inches] or more |
| C | **3-conductor shielded with 1 non-centered ground.** | Good | Better | Marginally acceptable | Acceptable | Good | Shield should be grounded at both drive power-common and motor frame |
| D | 3-conductor shielded with 3 symmetrical grounds, continuous extruded aluminum armor | Good | Good | Good | Good | Good | Shield should be grounded at both drive power-common and motor frame |

* NPC = Neutral Point Clamped Inverter Power Circuit



# Questions?

## The Curse of Knowledge