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Fundamentals of Medium Voltage Adjustable Speed Drives

Manish Verma

TMEIC

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TEXAS A&M UNIVERSITY

TEES | TURBOMACHINERY LABORATORY
TEXAS A&M ENGINEERING EXPERIMENT STATION

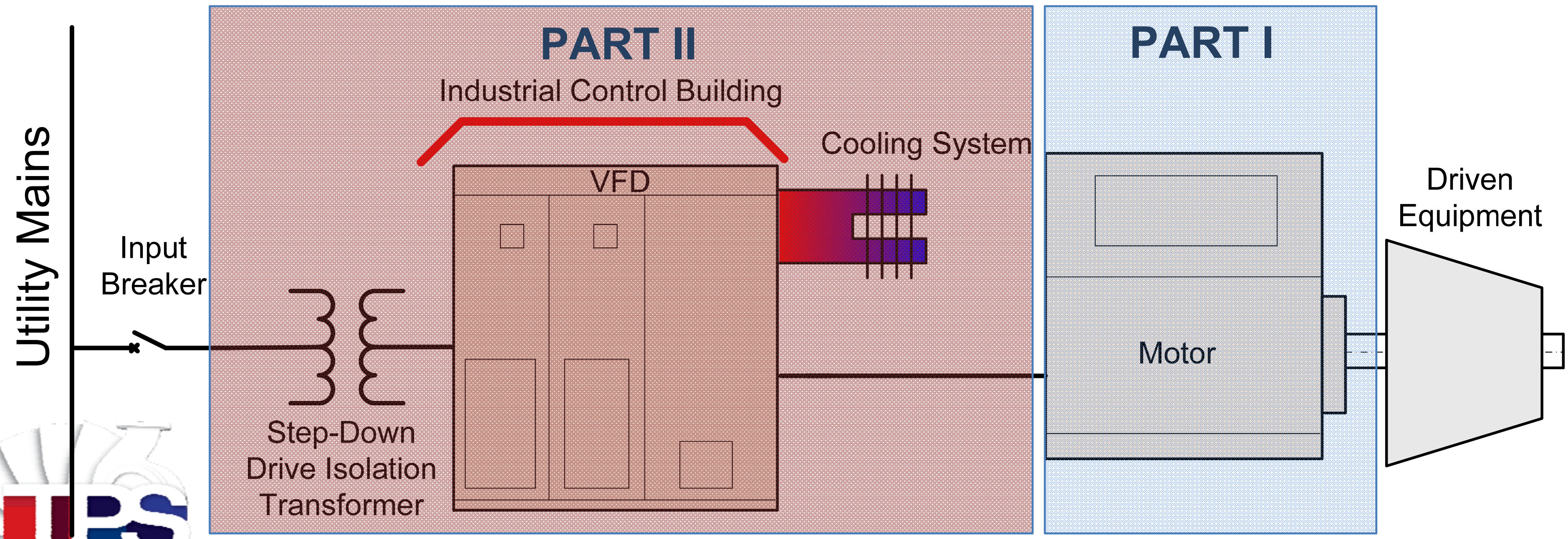
Manish Verma bio

Senior Sales Application Engineer
TMEIC

Manish Verma is a senior sales application engineer with TMEIC. He graduated in 2006 from Virginia Tech with BSEE. He began his career with TMEIC in 2006 while continuing his professional education. In 2009 he completed his MSEE with concentration in power. After a broad exposure and education in the various TMEIC business units, he joined the global drives division, with concentration on sales and application engineering. His responsibilities include providing solutions-based engineered adjustable speed drives and motors, reviewing specifications, and technical and sales training for a wide variety of industrial clients and channel partners. He is a senior member of IEEE and has authored and presented more than 20 technical papers and tutorials for several nationally recognized conferences and seminars.

Agenda

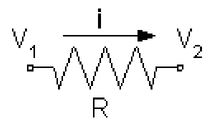
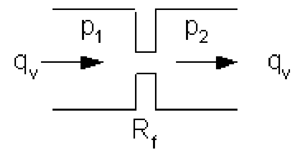
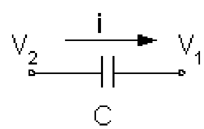
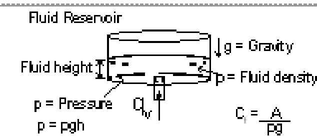
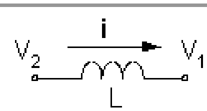
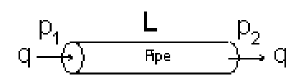
- Basic Electrical fundamentals & Mechanical Equivalents
- Starting strategies for large capacity motor / compressors
- What is an ASD, how does it work & its benefits for compression/pumping
- ASD application overview & installation considerations
- ASD cooling methods and standards



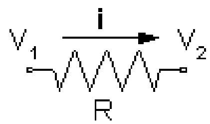
Applicable dimension of today's tutorial

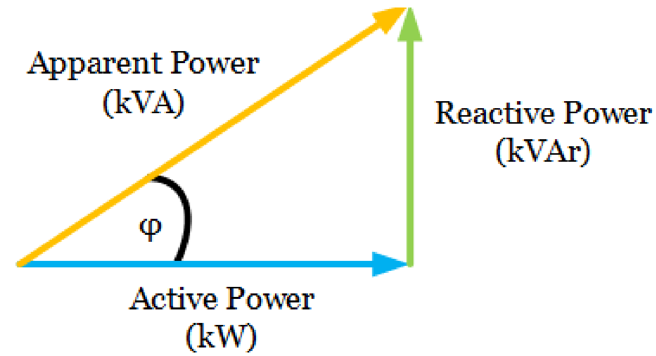
Parameter	Description
Service types	Rotating machinery such as pumps, compressors, extruders, fans, blowers, etc.
Power Level (HP)	500HP – 130,000HP
Voltage range(kV)	Medium Voltage, > 1.0 kV

Electrical Equivalents

Variable / Function	Electrical Element	Fluid Equivalent
Across Variable	Voltage (V)	Pressure (p)
Through Variable	Current (**i**)	Flow Rate (q_v)
Resistor	 $V_1 - V_2 = iR$	 $p_1 - p_2 = q_v R_f$
Capacitor	 $i = C \frac{dV_{21}}{dt}$	 $q_v = C_f \frac{dp}{dt}$
Inductor	 $V_{21} = L \frac{di}{dt}$	 $p_{21} = L \frac{dq}{dt}$

Electrical Equivalents

Variable / Function	Electrical Element
Across Variable	Voltage (V)
Through Variable	Current (i)
Energy Consumption	 $\text{Power} = \frac{V_{21}\,\mathbf{i}\ \text{Joules}}{\text{sec}}\quad \text{Watts}$

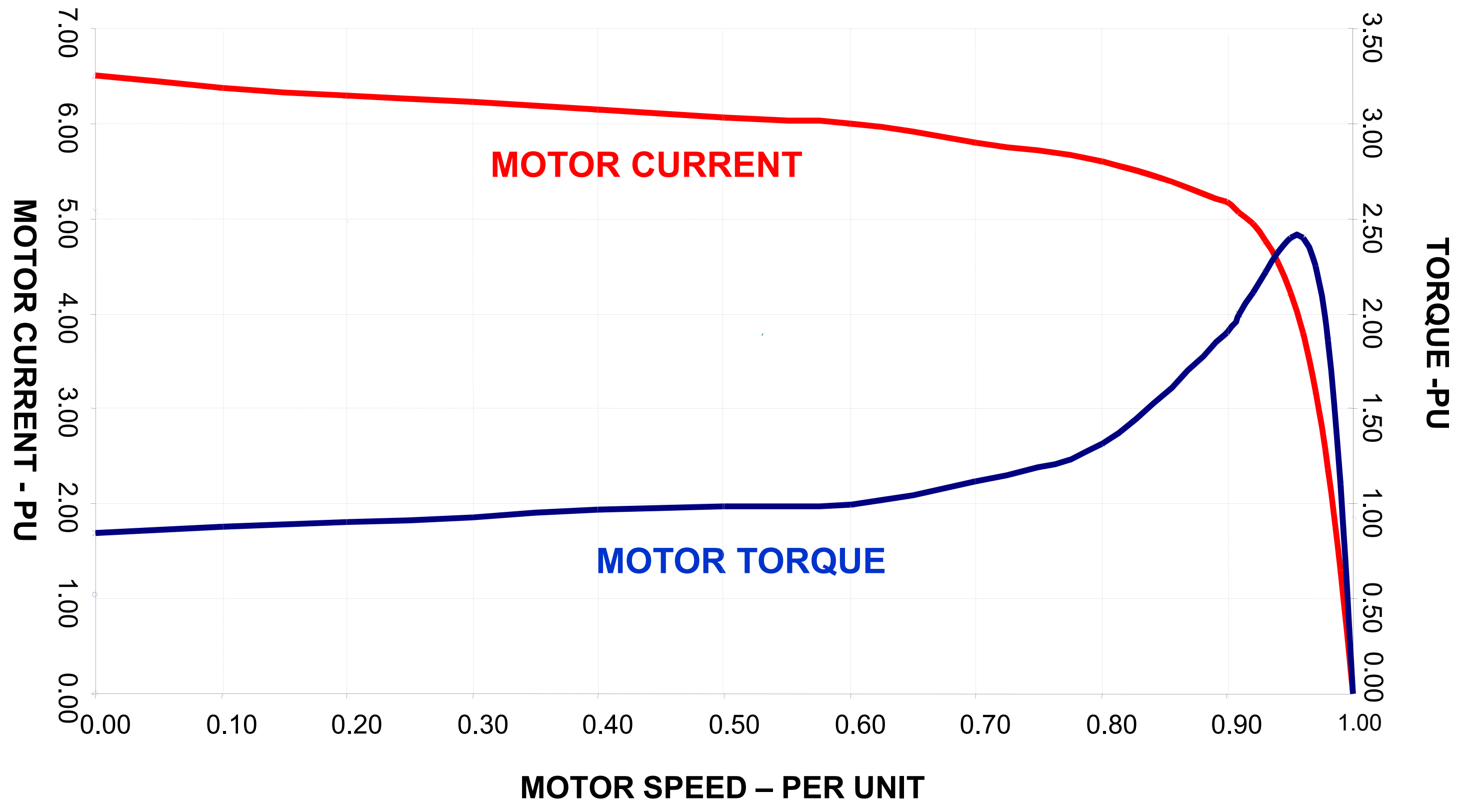


Power Factor = cos (Φ) = kW / kVA

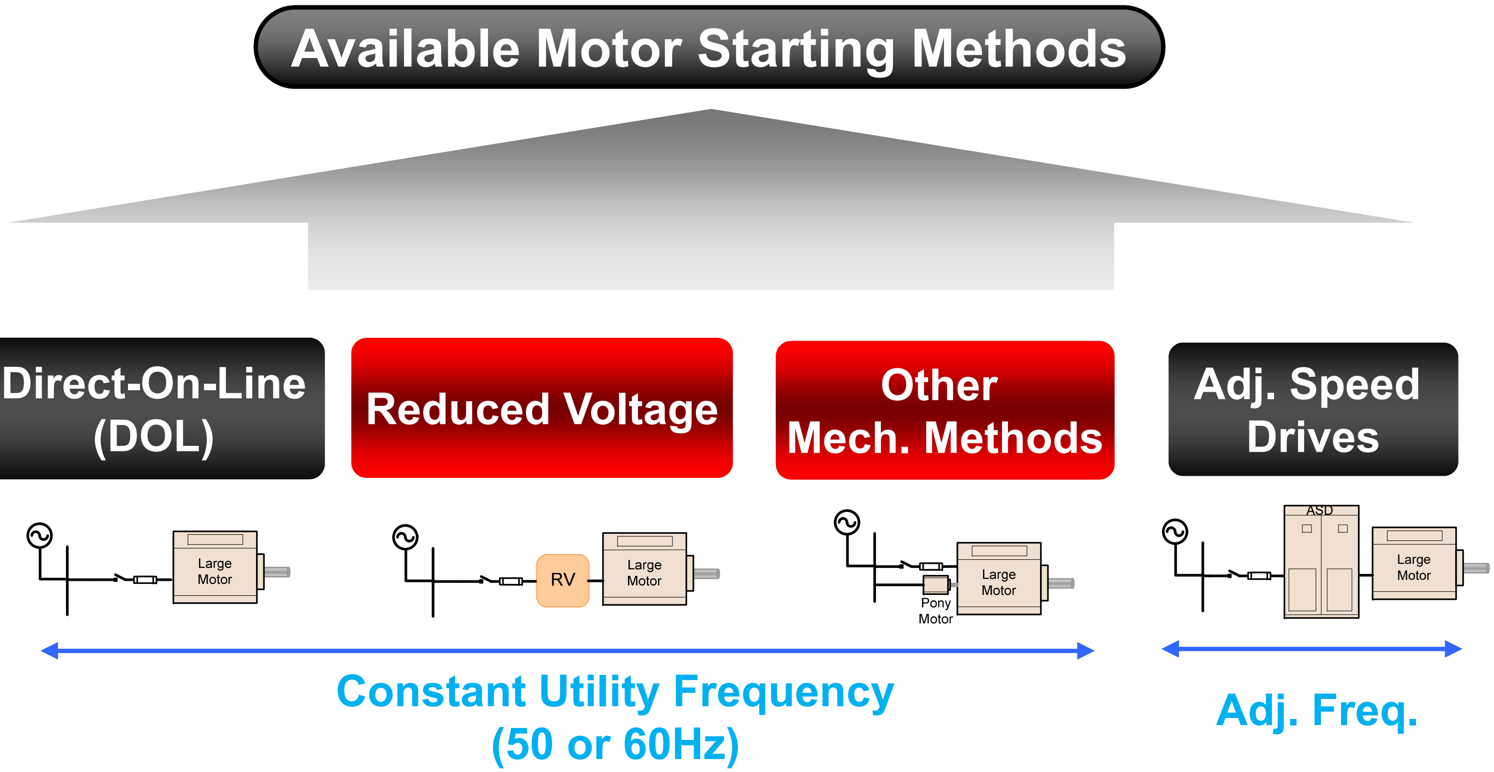
1000hp = 746kW

1hp = 746 watts

Typical Motor Starting Characteristics



Motor starting strategies

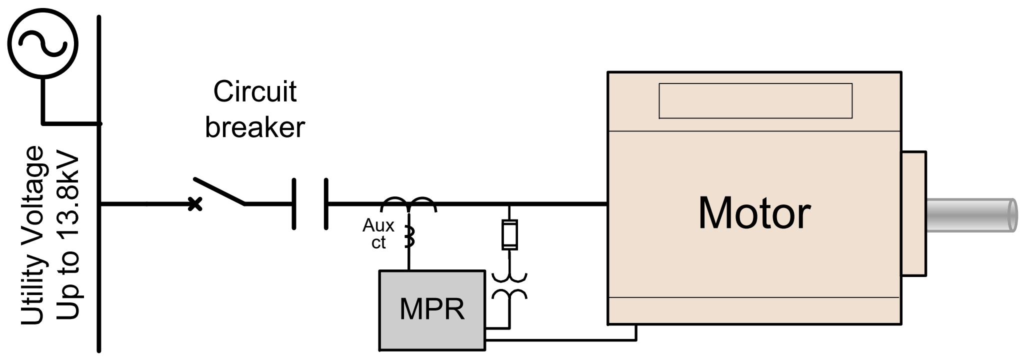


Good Reference: Larabee, J.; Pellegrino, B.; Flick, B., "Induction motor starting methods and issues," *Petroleum and Chemical Industry Conference, 2005. Industry Applications Society 52nd Annual* , vol., no., pp.217,222, 12-14 Sept. 2005

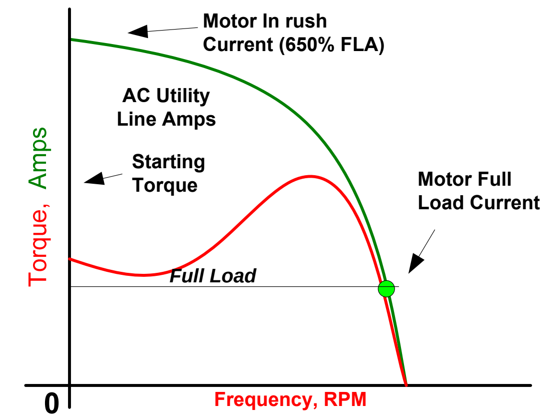
Nevelsteen, J.; Aragon, H., "Starting of large motors-methods and economics," *Petroleum and Chemical Industry Conference, 1988, Record of Conference Papers., Industrial Applications Society 35th Annual* , vol., no., pp.91,96, 12-14 Sep 1988

Direct-on-line Starting

System Configuration



Motor Speed – Torque Curve



Reduced Voltage Starting

Method of operation (applicable to all RV starting methods):

- Motor voltage is reduced
- With reduced voltage
  - Motor current is reduced by a proportional factor
  - BUT, available motor torque is also reduced

Remember

$(V_{motor})^2 \propto T_{motor}$

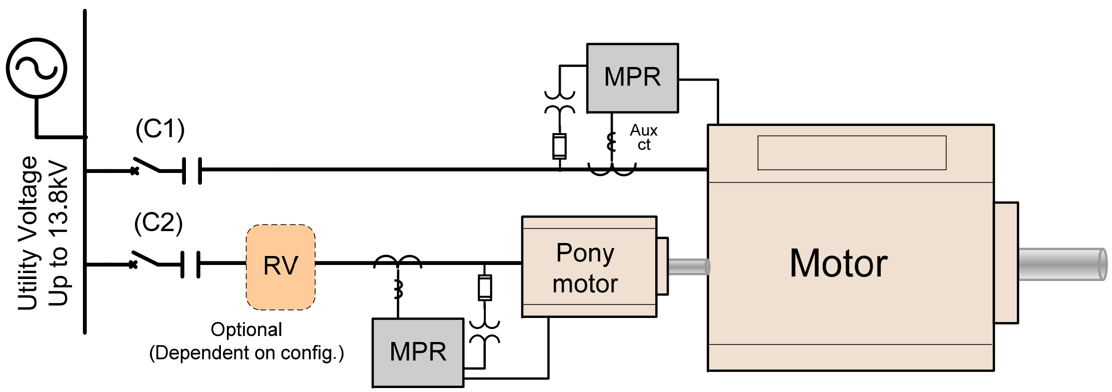
$V_{motor} \propto I_{motor}$

- *For Eg:*
  - *At 80% Motor Voltage only 64% Torque is available (0.8 x 0.8 = 0.64).*
  - *At 80% Motor Voltage 480% inrush amps (assume 600% Start Current).*

Reduce Voltage starters DO NOT change the motor frequency

Pony Motor Starting (Mech.)

System Configuration

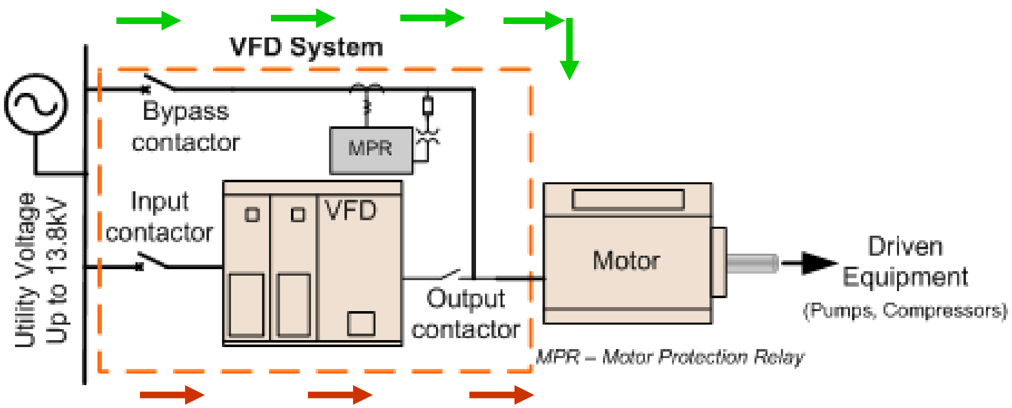


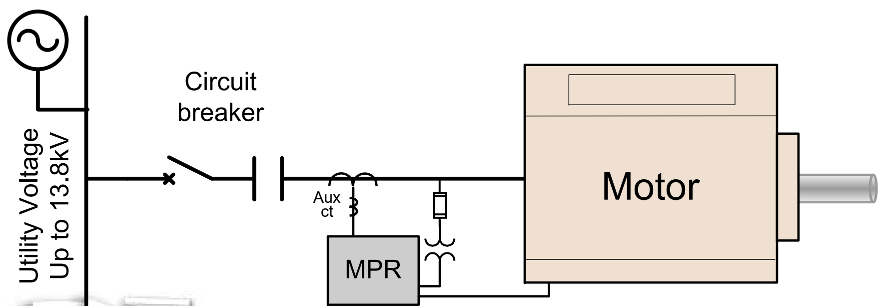
Motor Speed – Torque Curve

- Dependent on starting conditions, mechanical configuration

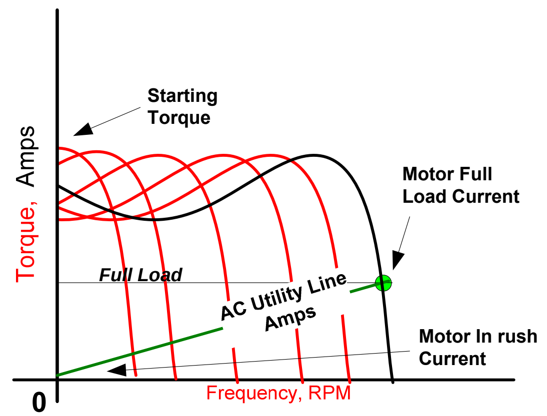
Reduced Voltage Starting

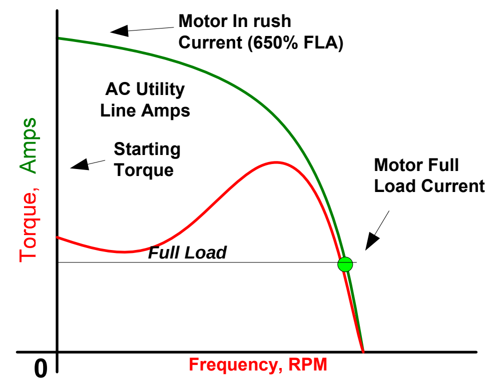
System Configuration





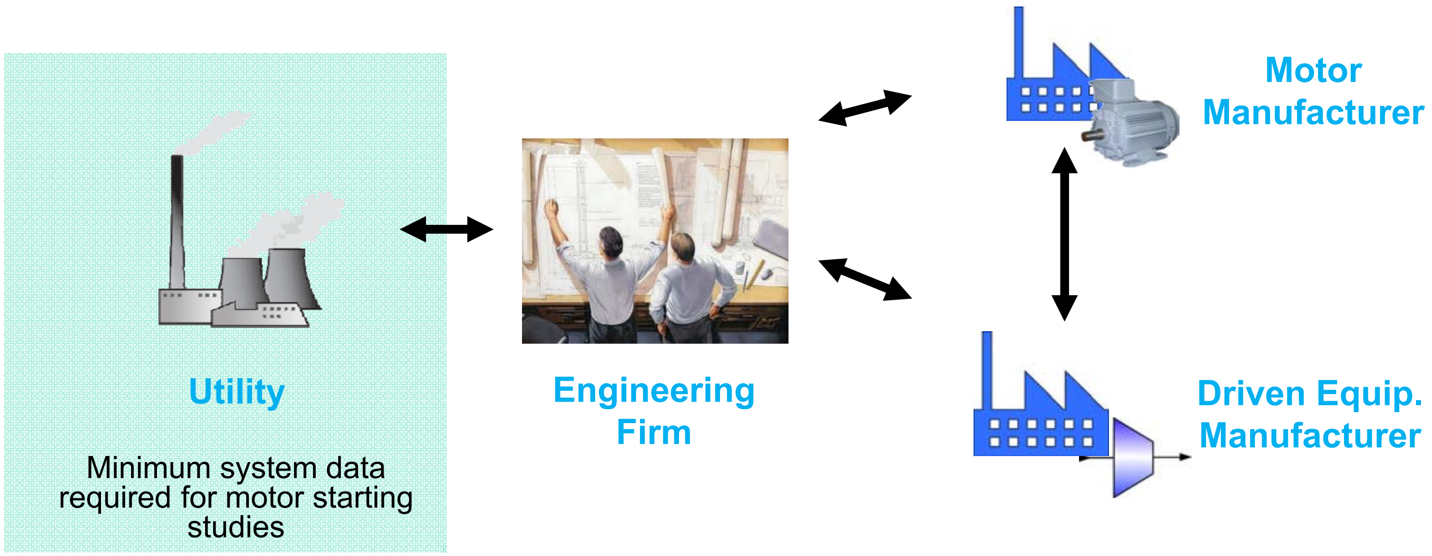
Motor Speed – Torque Curve





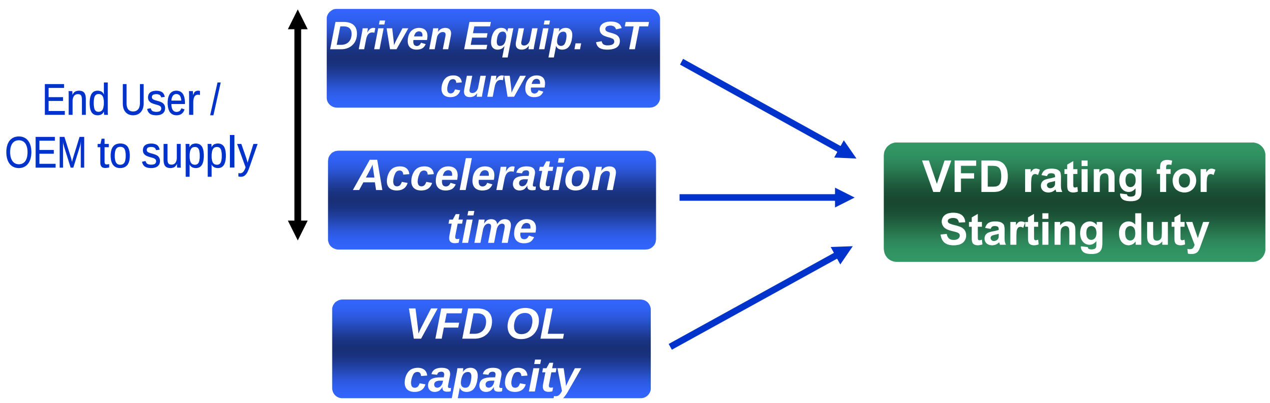
General application considerations

- Evaluate load speed torque curve
- Process requirements and need for variable speed
- Based on power decide whether air or liquid cooled VFD
- Cost benefit analysis
- Review details with OEM, motor and VFD vendor

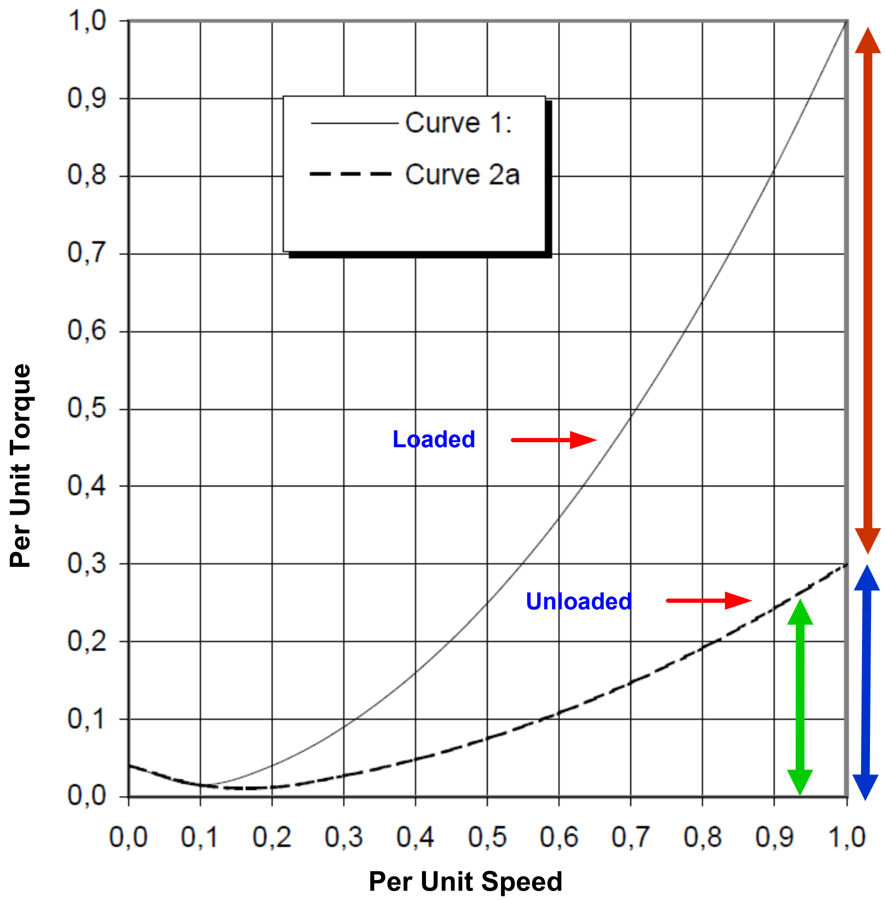


How are drives sized for starting duty?

- Virtually all VFDs have a short term (min 60 seconds) overload (OL) rating
- Common OL ratings are 110%, 115%, 150%, 200%, 300%
- Most variable loads require 110% or 115% OL rating
- Most constant torque loads require 150% OL rating



How are drives sized for starting duty?



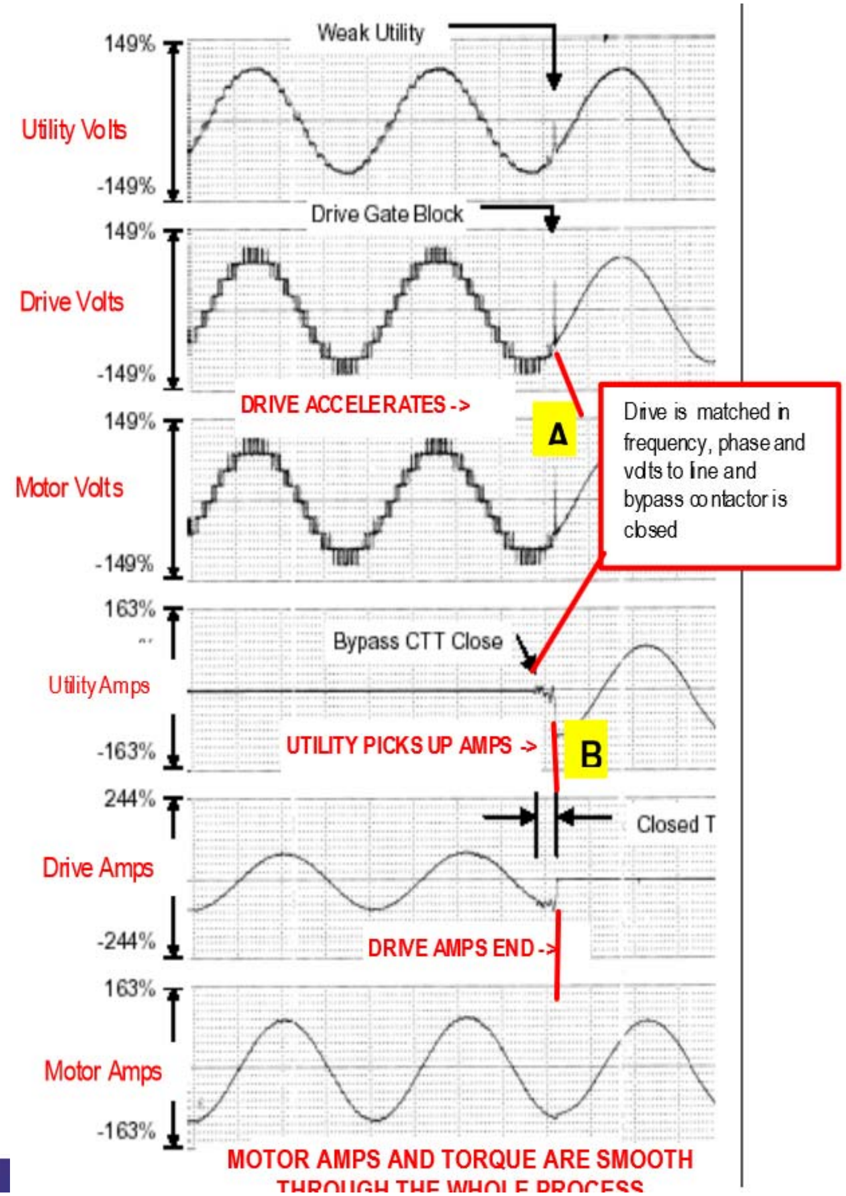
~ 70% Difference in Torque

VFD expected to be sized for 30% of compressor full rating

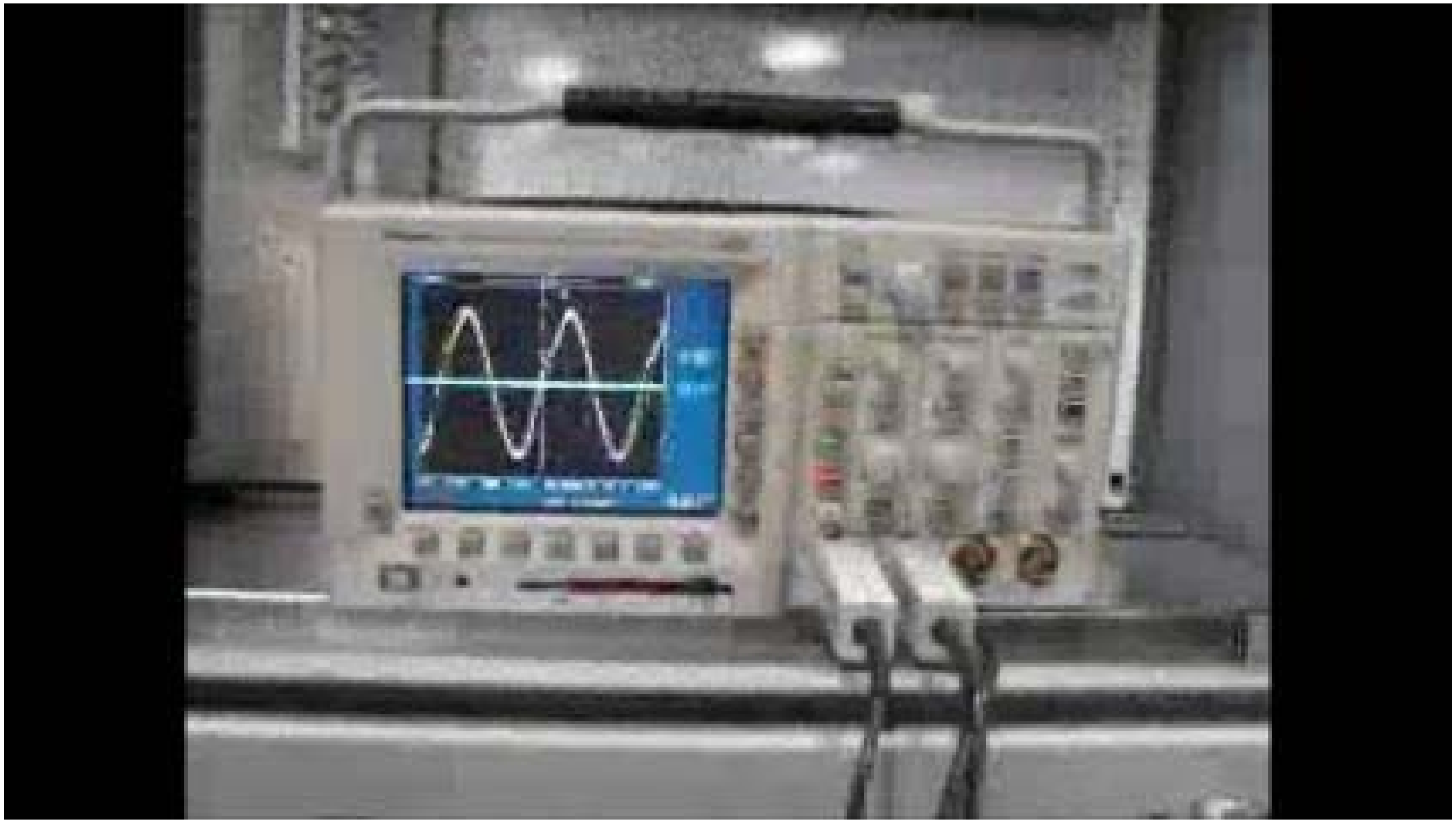
Actual VFD size = 25.5% Compressor Full Load Rating Using 115% VFD OL

Operating Sequence

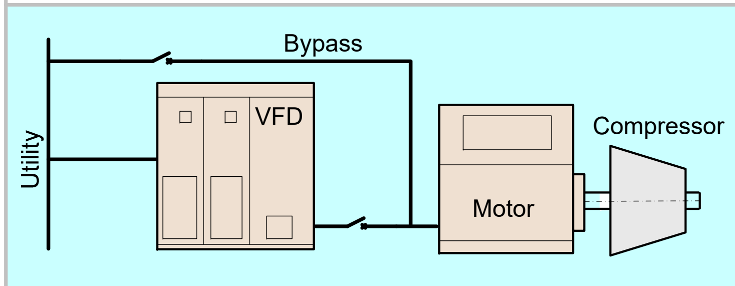
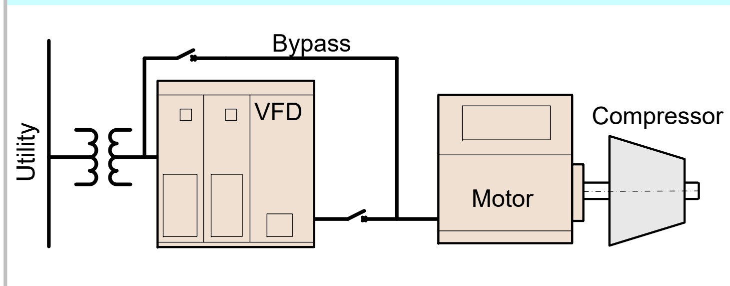
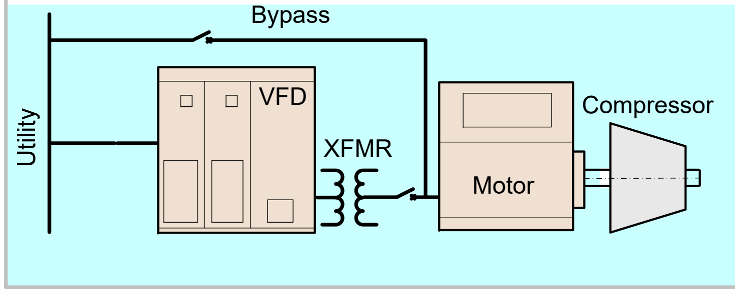
1. VFD Ready →
2. VFD accelerates the motor & load up to speed set-point →
3. Operator requests VFD to transfer motor to the line →
4. VFD accelerates the motor to the exact power grid voltage and frequency →
5. The grid and VFD output: Voltage Frequency and Phase angle are matched →
6. VFD control activates the closing of the bypass contactor →
7. VFD monitors the current flowing through the bypass contactor →
8. VFD opens the output contactor & stops



Motor Sync-to-line video demonstration



Single VFD / single motor

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

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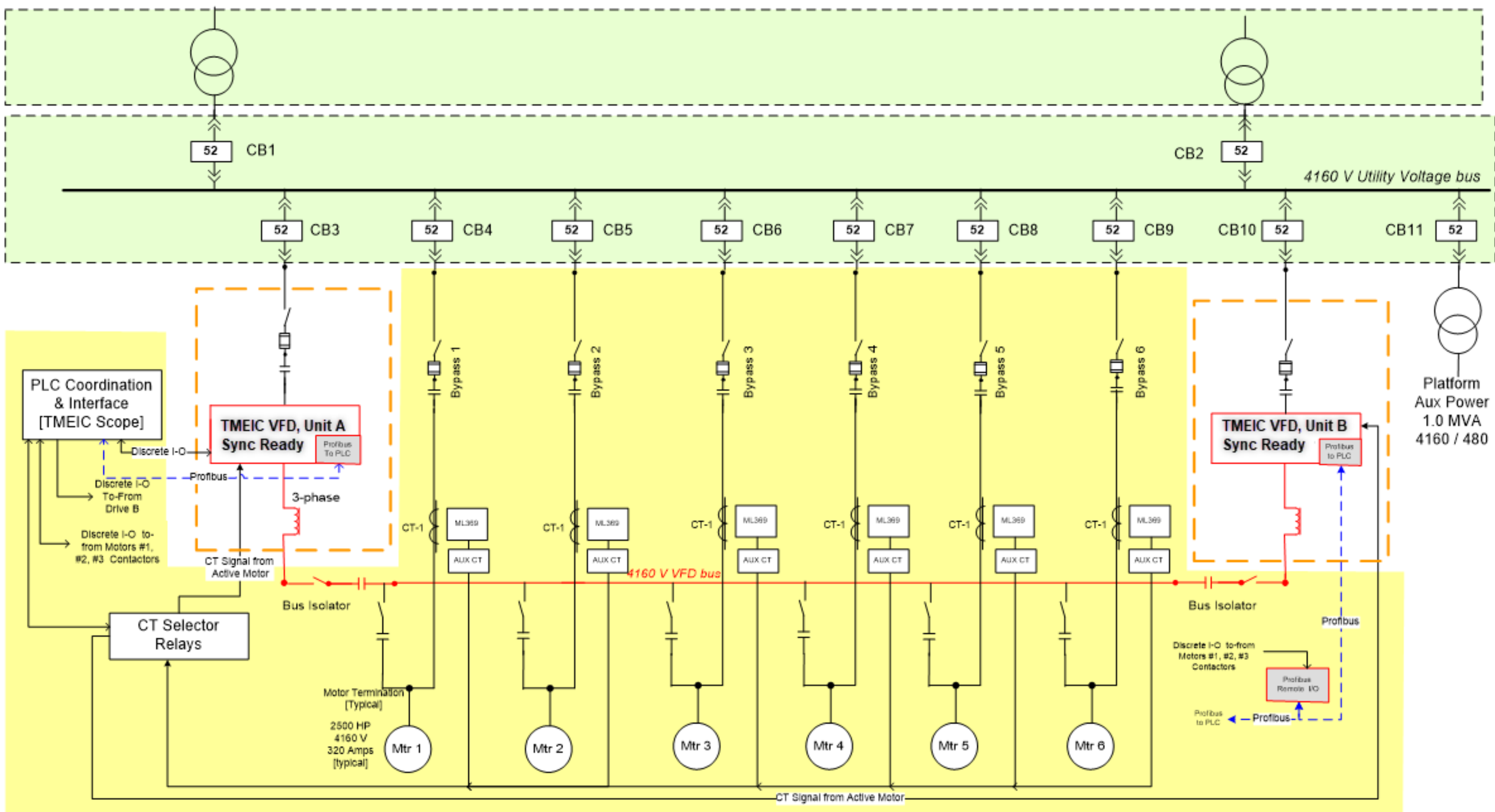
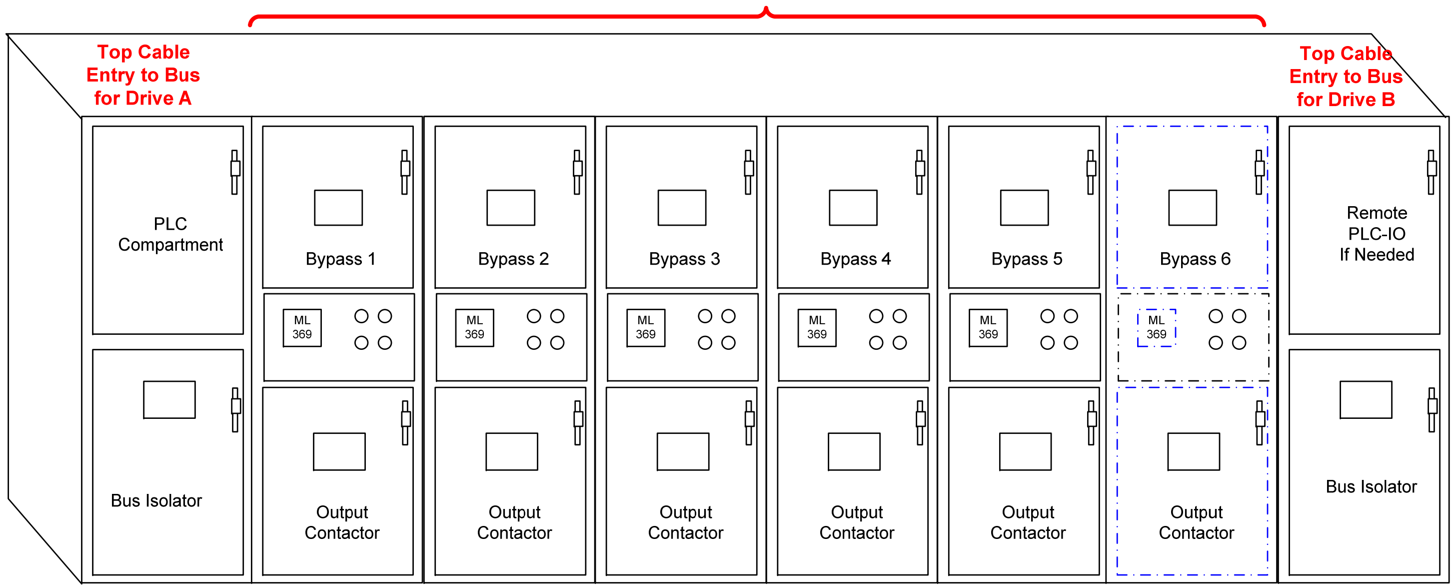
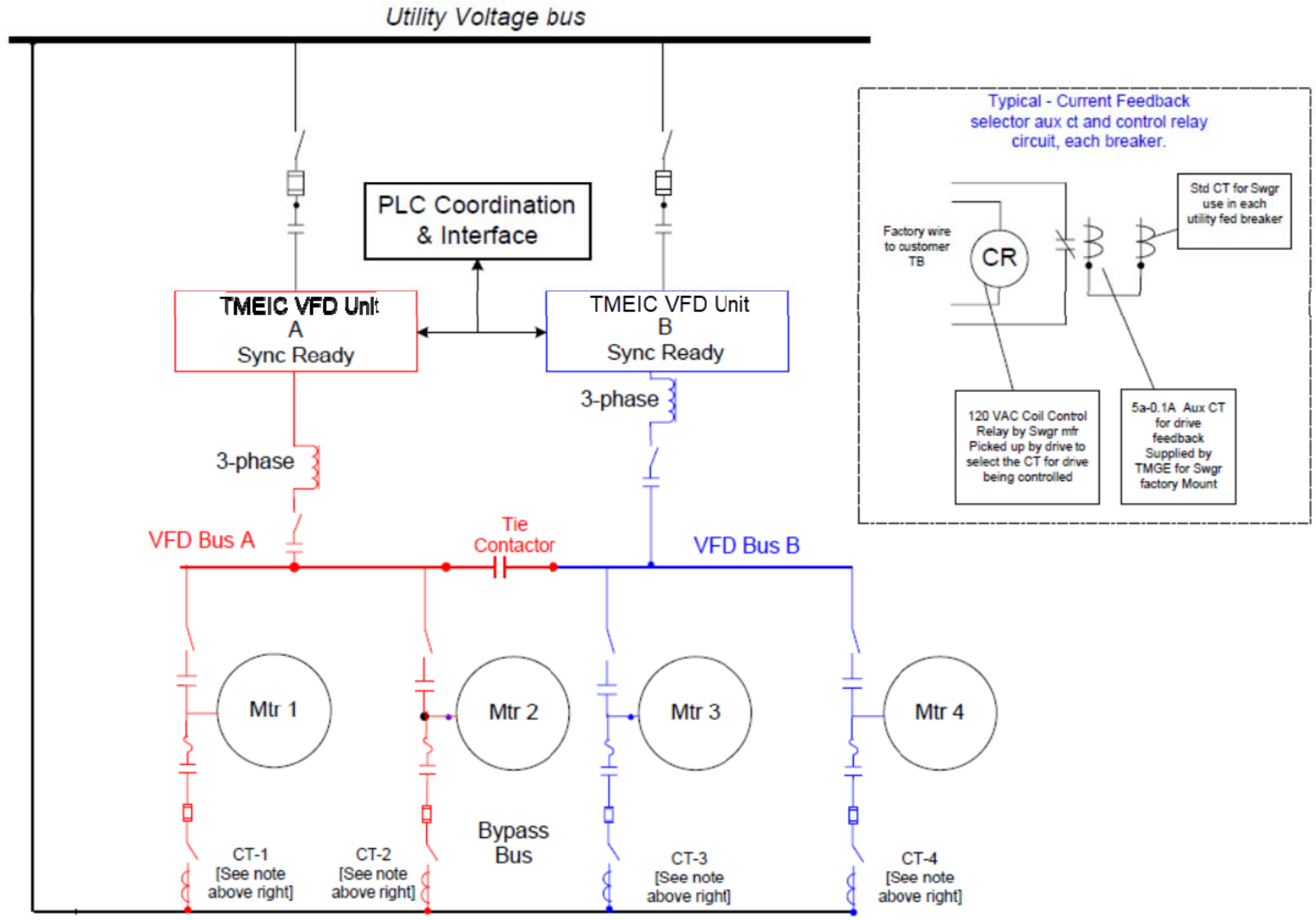
Redundant Starter – Representative configuration



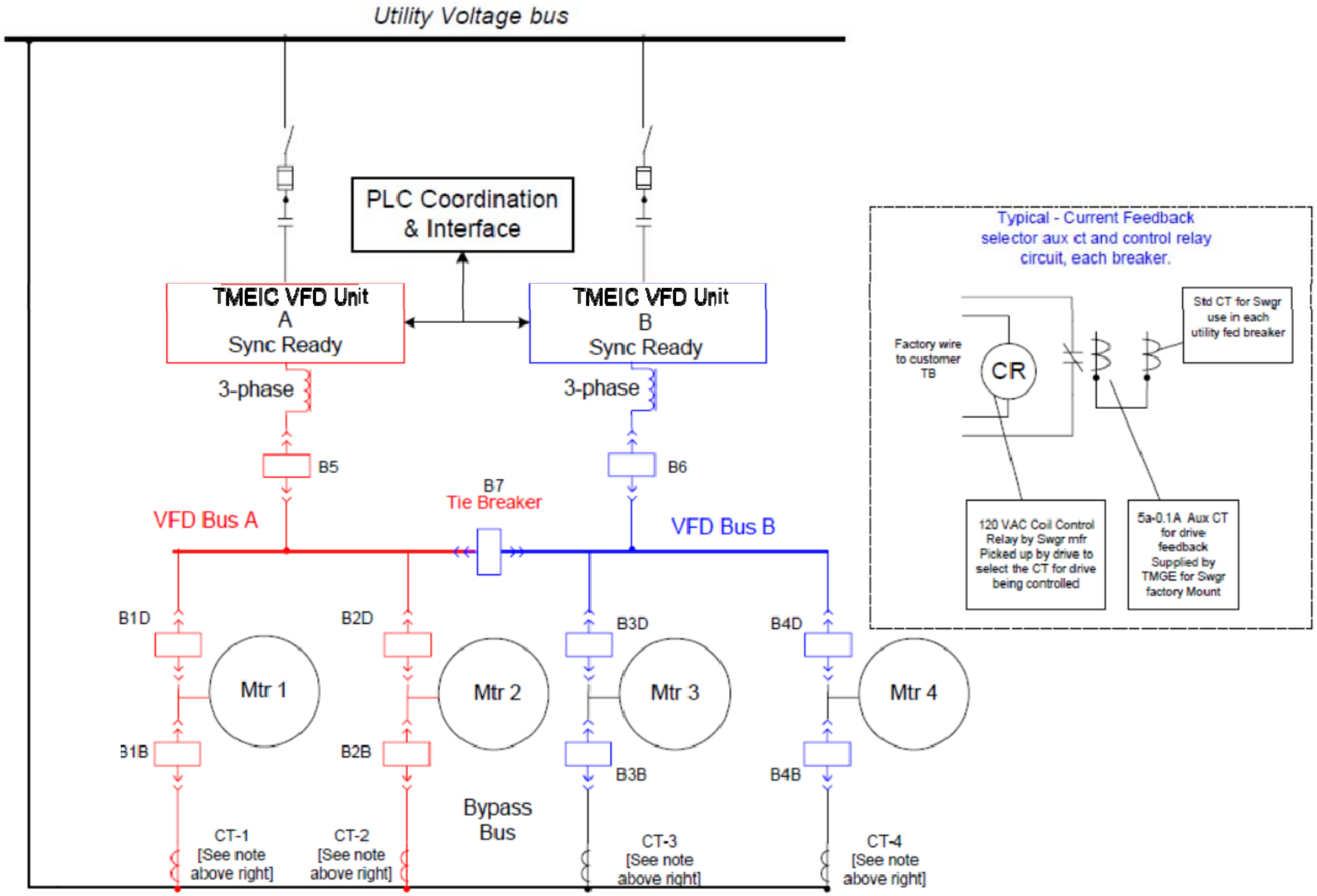
Redundant Starter – Representative configuration



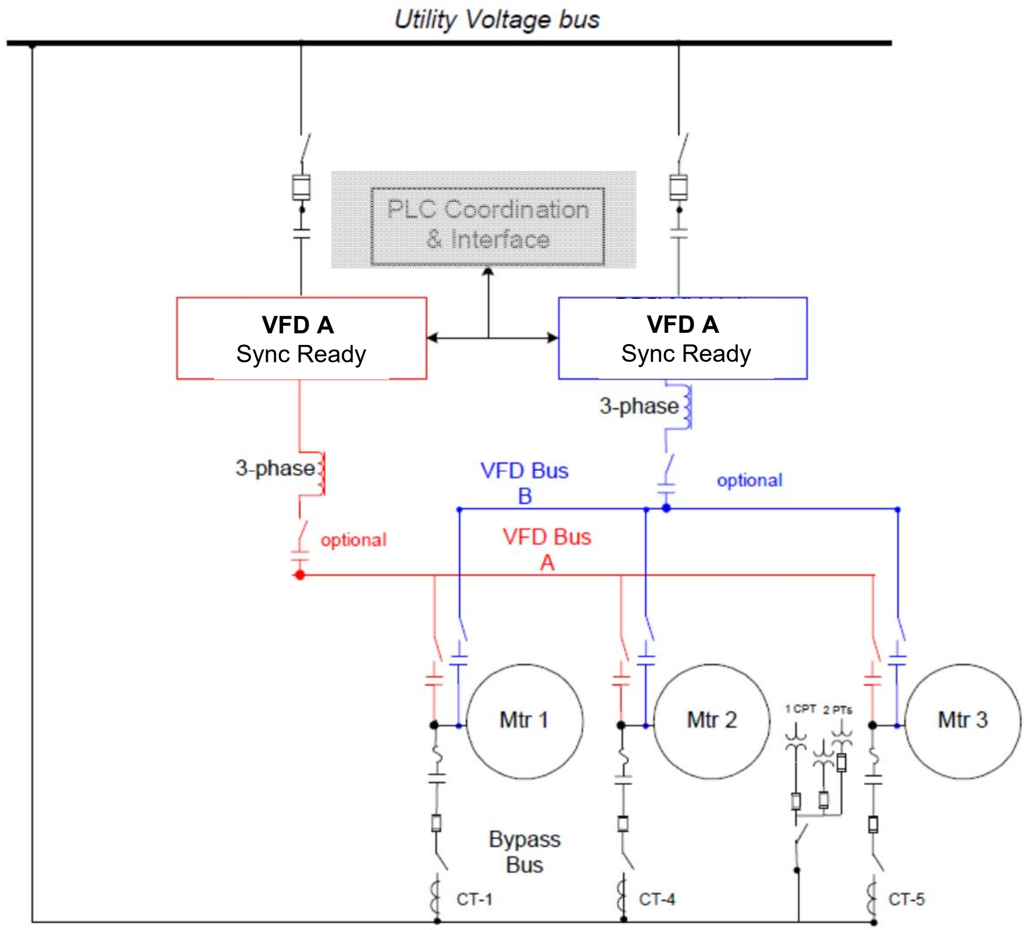
Redundant Starter – with Tie Contactor



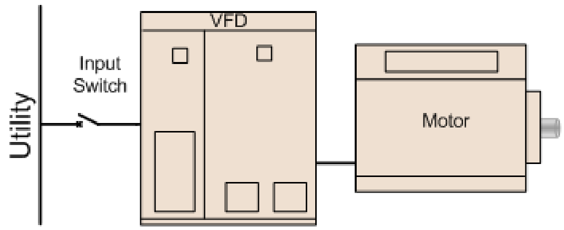
Representation starter – with tie breakers



Representation starter – with two starting bus



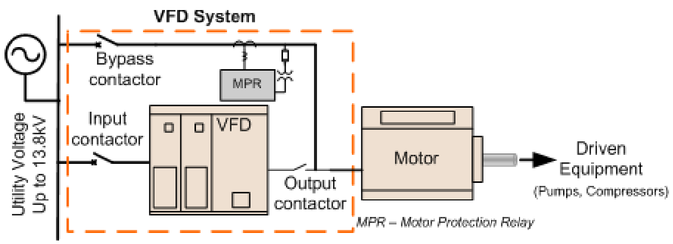
Motor protection guidance - Sync-transfer systems



- Primary protection for the motor is contained within the drive itself
- No need of Motor protection relays (MPR) for motor or ASD
- MPR protection may be added in addition for:-
  - Differential Current Protection
  - RTD

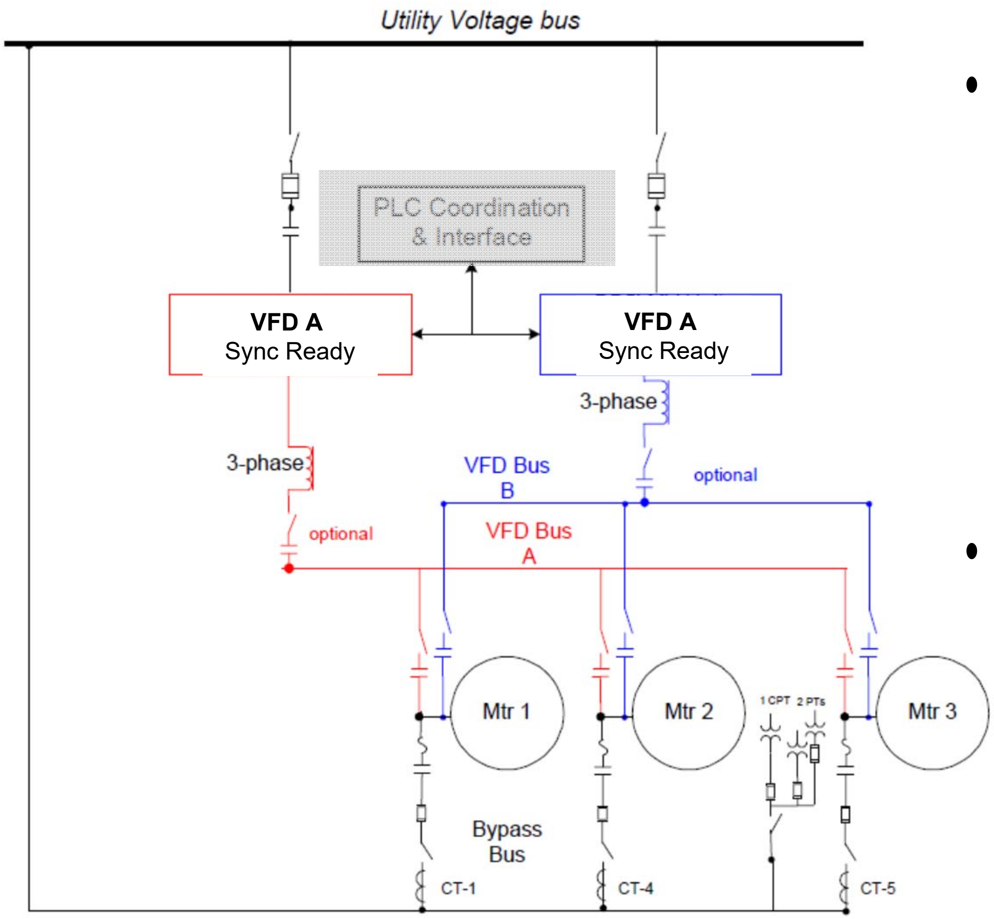
  <u>Considerations:-</u>
  - Check if MPR can work at all freq.
  - MPR protection is inhibited

  Typically very little added benefit & Philosophical decision



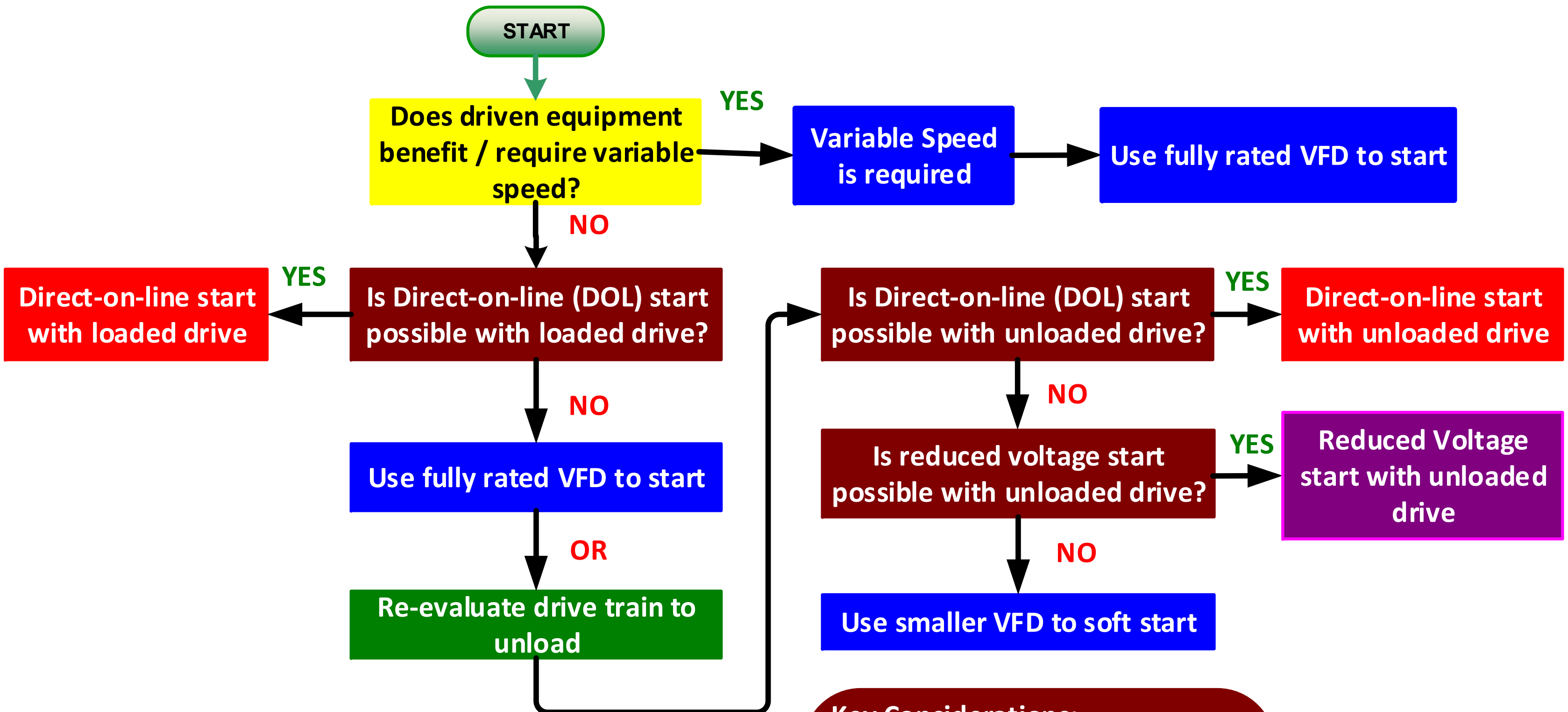
- Initial protection for the motor is contained within the drive itself
- MPR's needed for bypass circuit
- MPR operation is inhibited when motor is running on ASD
- Thermal Overload relay can also be used as inexpensive option

Procurement guidance



- VFD Vendor (minimum)
  - VFD
  - PLC Co-ordination
  - Switchgear specification guidance
- Others
  - Switchgear
  - Motors
  - Installation, etc

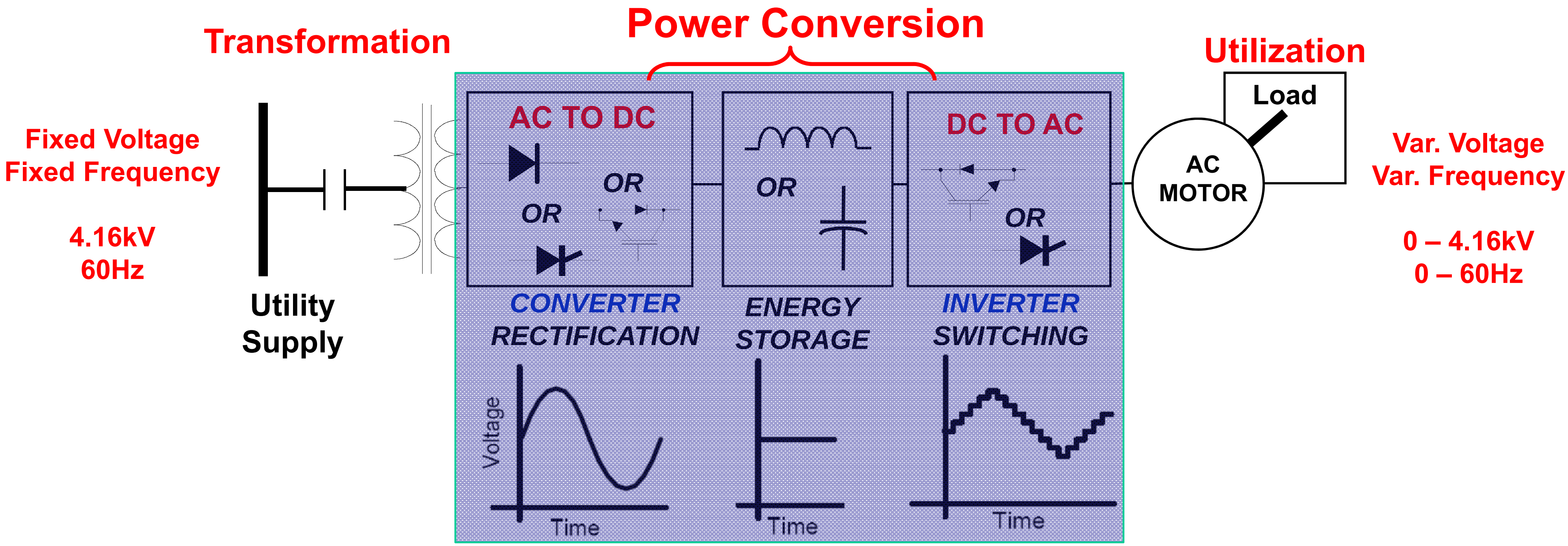
How to select motor starting strategy??

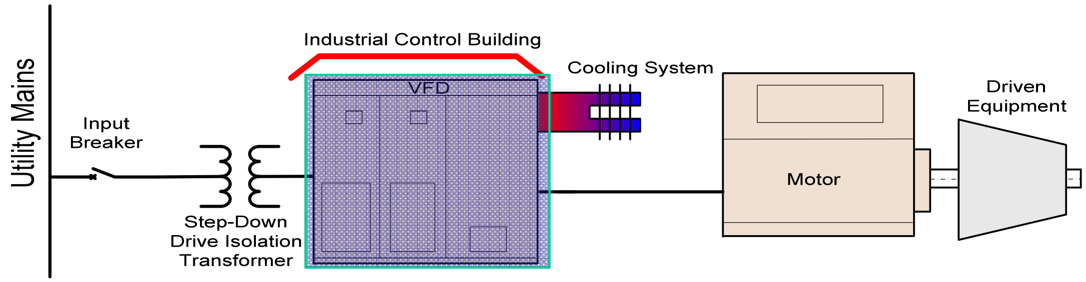


Key Considerations:-

- Available Short Circuit Amps
- Allowable Voltage drop on Utility
- Motor vs. Compressor ST Capabilities
- Max allowable Motor Starts / Hour
- Torstional effect on drive train
- Cost of DOL motor vs. VFD motor
- Motor power factor as seen by utility

What is an ASD?

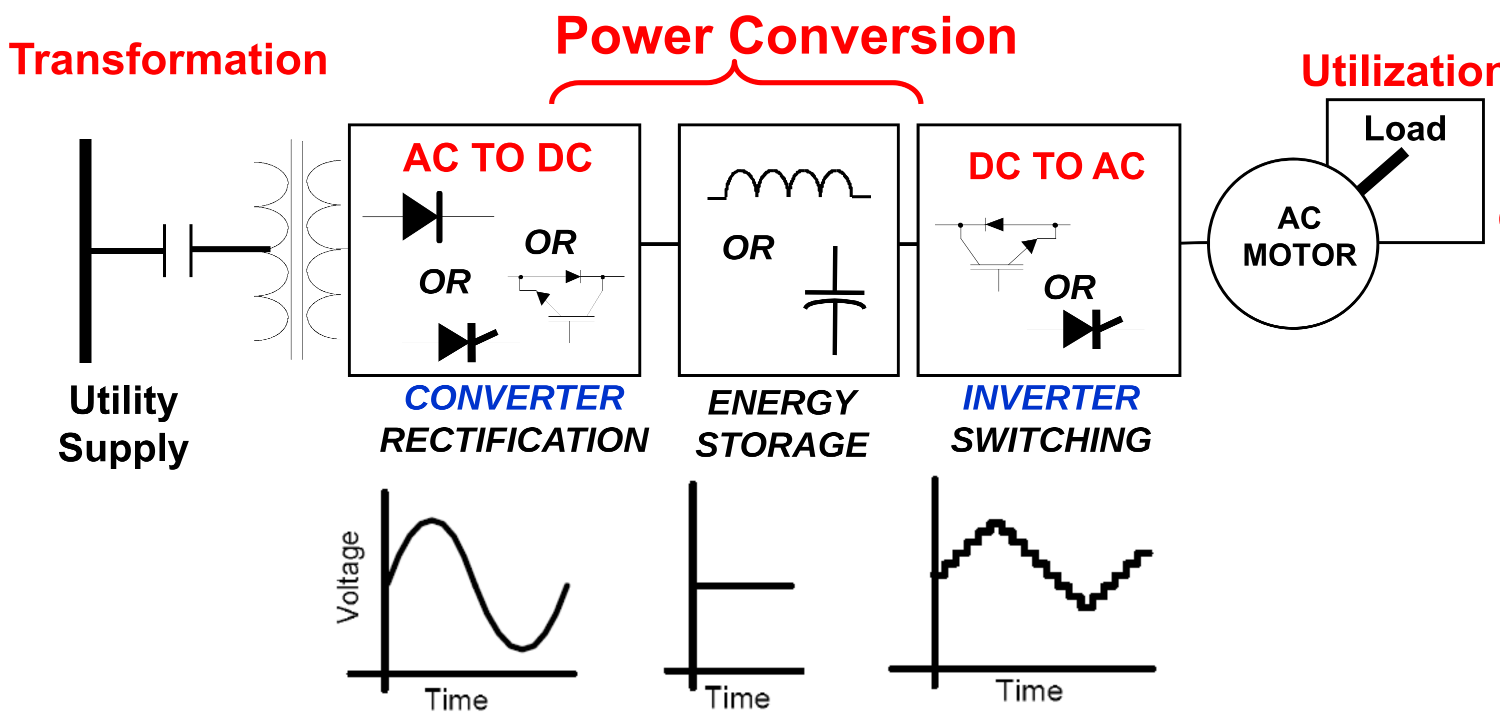




What is an ASD? – Other common terminology

Pulses (DFE)

Harmonic performance equivalent (AFE)



Output Voltage Levels / Steps

(higher the better, min 5-level from 0-Peak)

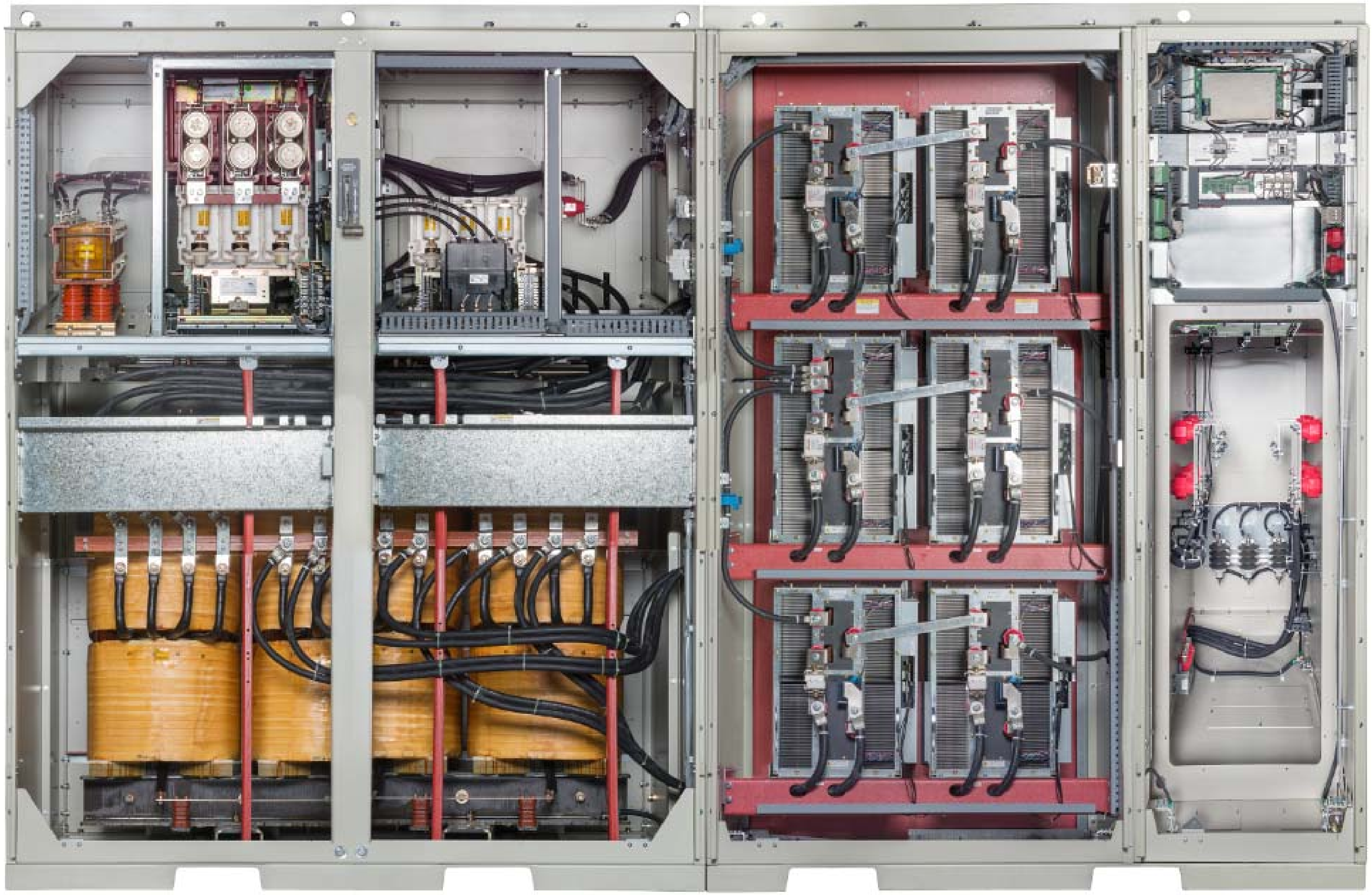
What is an ASD?

- Typical air cooled ASD
- 4.16kV, 60 Hz
- ~2,200 HP

TPS

What is an ASD? A look inside

- Typical air cooled ASD
- 4.16kV, 60 Hz
- ~2,200 HP

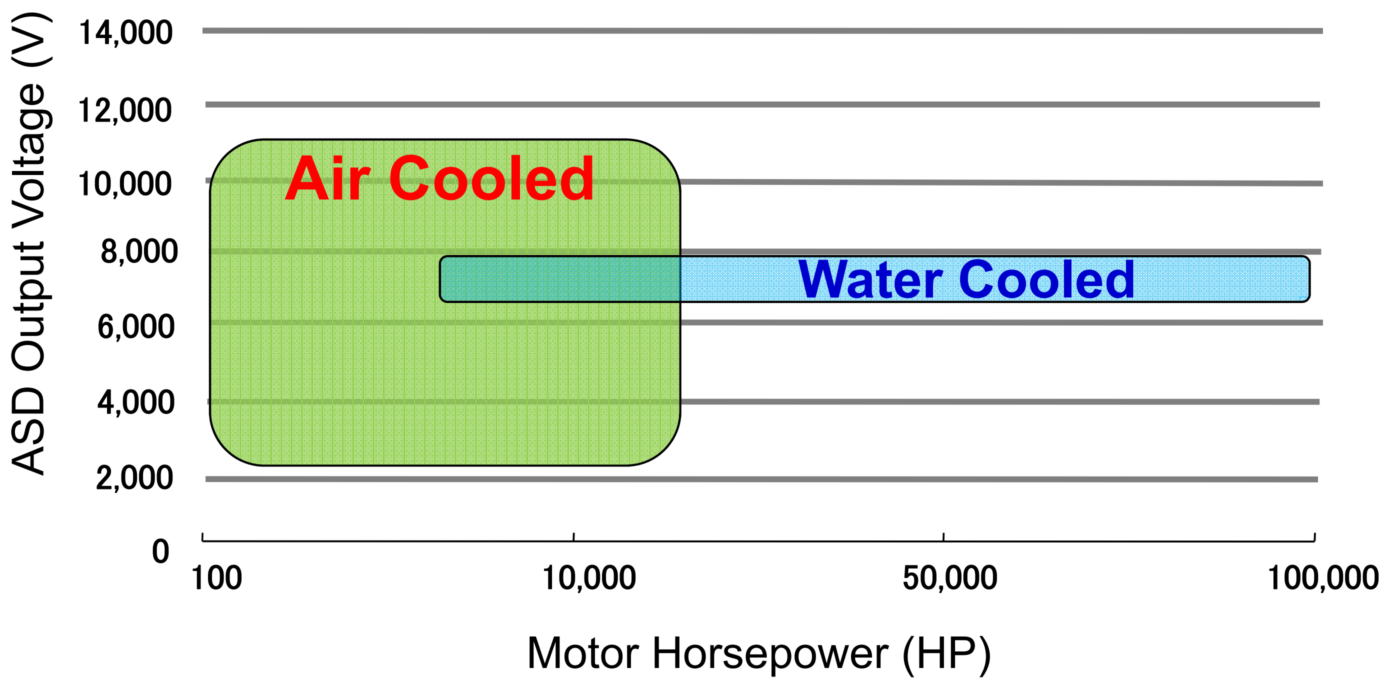


What is an ASD?

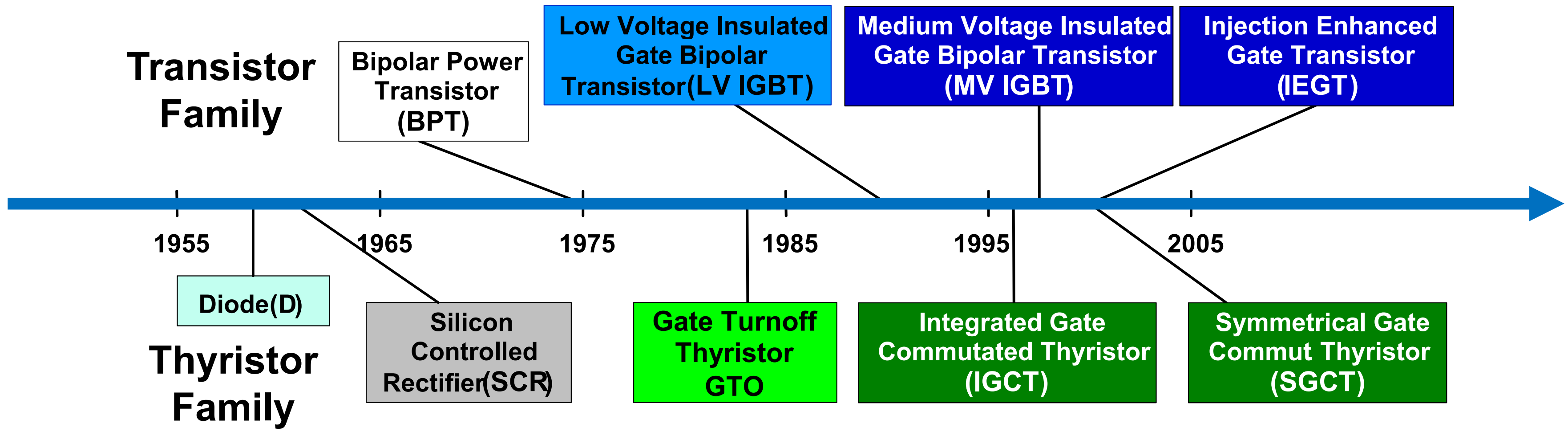
What is an ASD?

- Large Water cooled ASD
- 7.2kV Output
- ~38,000 HP
- Outdoor Transformer and cooling apparatus not shown

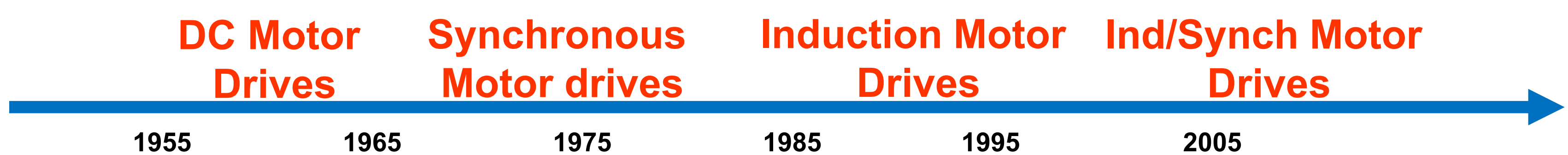
Typical Range of ASDs



Historical Overview of power semiconductor devices



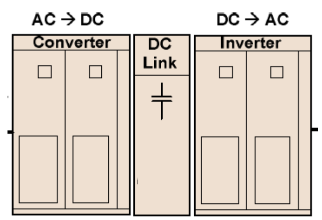
Time Line of Adjustable Speed Drives



Major ASD Topologies

Voltage Source Inverters (VSI)

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



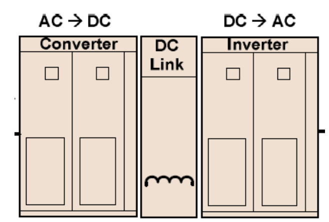
- Maintains constant Voltage at DC Link
- Converter (AC/DC) is either Passive (using diodes) or Active (using PWM)

Current Source Inverters (CSI)

Load Commutated Inverters (LCI)

Pulse Width Modulated (PWM)

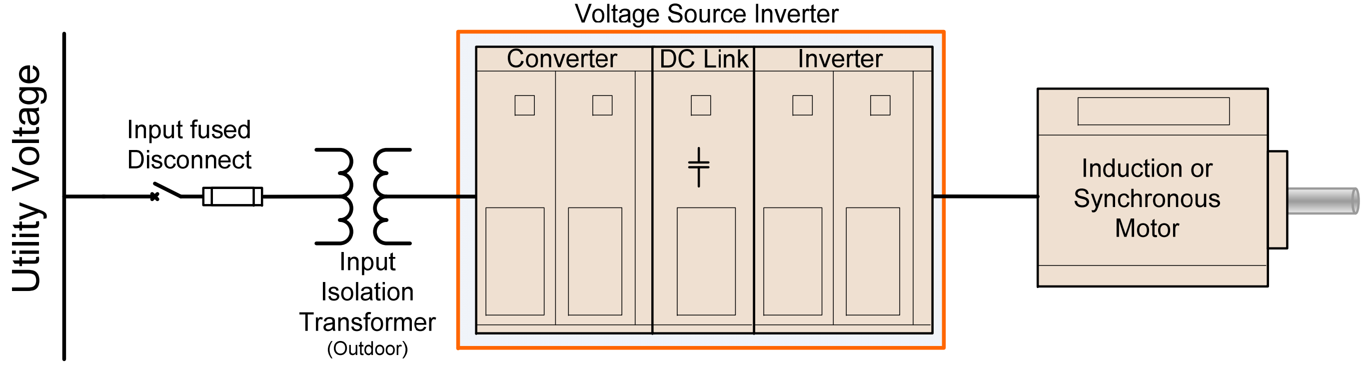
- Energy storage/DC Link is **Inductor**



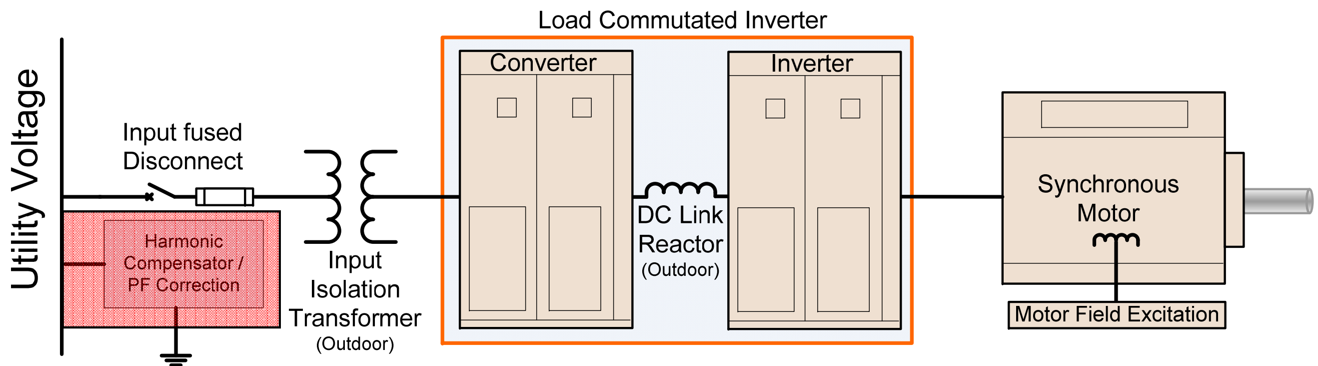
- Maintains constant current at DC Link
- Converter (AC/DC) is Active (using phase control or PWM)

Major VFD Topologies

Voltage Source Inverter



Load Commutated Inverter



Drive Topologies: How does it matter??

- They affect:-
  - Efficiency & reliability of the VFD
  - Line-side voltage & current performance
  - Motor-side insulation and thermal rating
  - Cable sizing
  - Auxiliary equipment needed to support the VFD
  - Safety
  - Total Cost of Ownership

- For drives with lots more parts, they must be very conservatively applied if reliability is to be achieved.

- In-service reliability is the best indicator of real reliability.

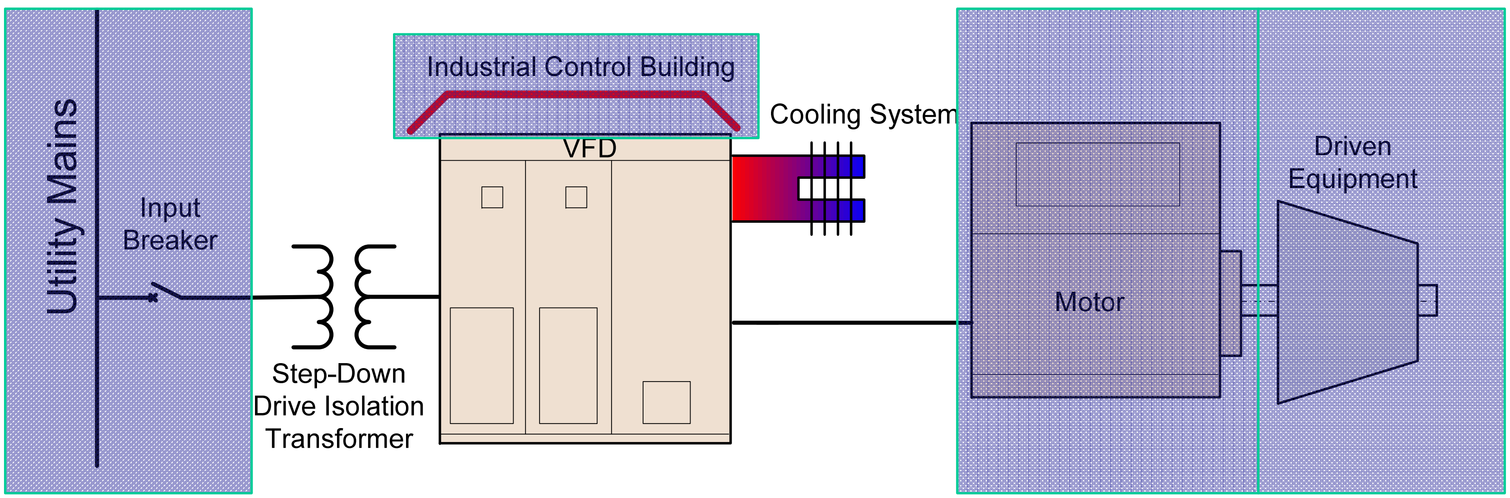
What does an ASD mean for the motor and the process?

- **Motor Starting**
  - Reduced inrush current
  - High Torque Loads
  - Close to unity power factor
- **Process Control**
  - Energy Savings
  - Speed Control
  - Torque Control
  - Optimized motor size (eg. large inertial applications)
- **Motor Running**
  - Power factor improvement
  - Unstable voltage supply
  - Quick stopping (Regeneration)
  - Reduced Mech. Wear / Tear

ASD System Considerations

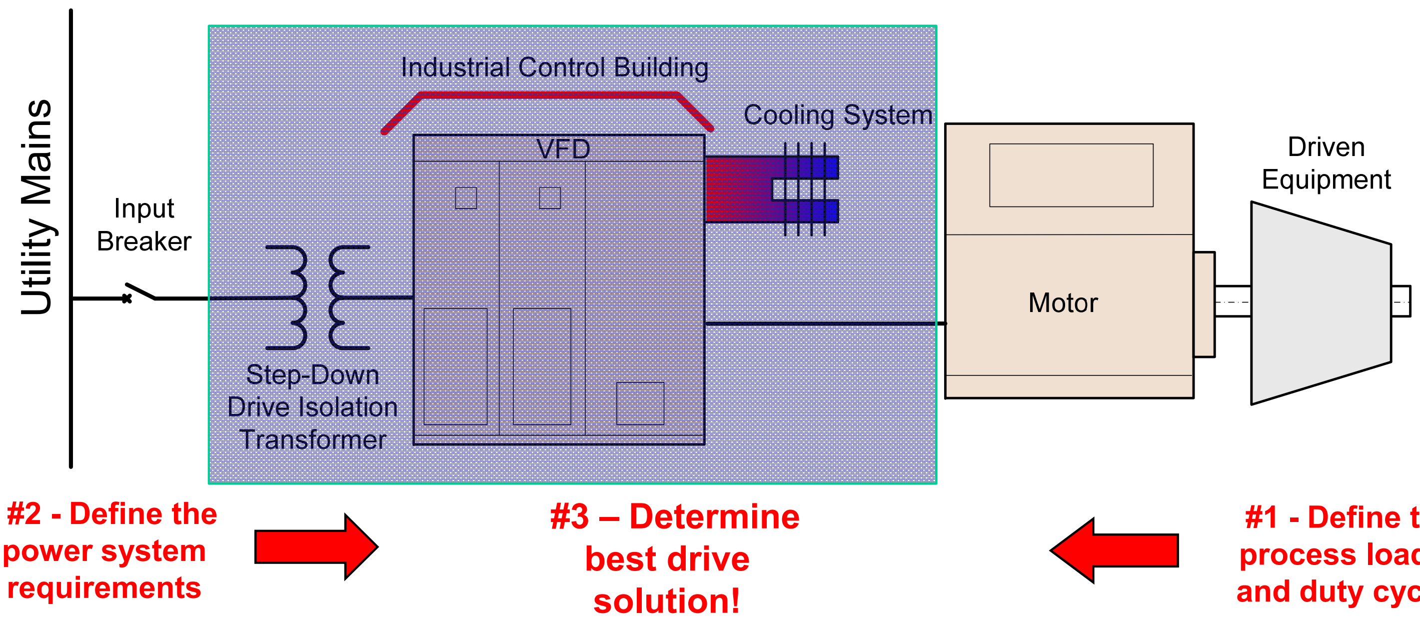
Must consider the whole system in which the ASD will work

- 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



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



Keep In Mind

Drives are sized & priced based on Motor Full Load Current, Operating Envelope & driven equipment Overload

Example:

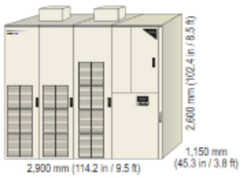
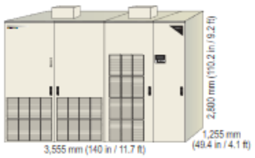
1. 7000 HP, 1800 rpm, 4000V, FLA 910A

   ASD Rating = 6300 kVA

2. 7000 HP, 450 rpm, 4000V, FLA 1240A

   ASD Rating = 8600 kVA

~37 % difference in rating

4-4.16 kV† UL/CSA				
VFD Outline		Approximate Motor Shaft HP (kW) at 4.16 kV	Rated Output Current (A) I phase AC*	Inverter kVA output at 4.16 kV
	Frame 100	536 (400)	69	500
	Frame 200	1,085 (810)	138	1,000
	Frame 300	1,500 (1,120)	191	1,380
	Frame 400	2,145 (1,600)	262	1,890

Power system compatibility - Keep In Mind

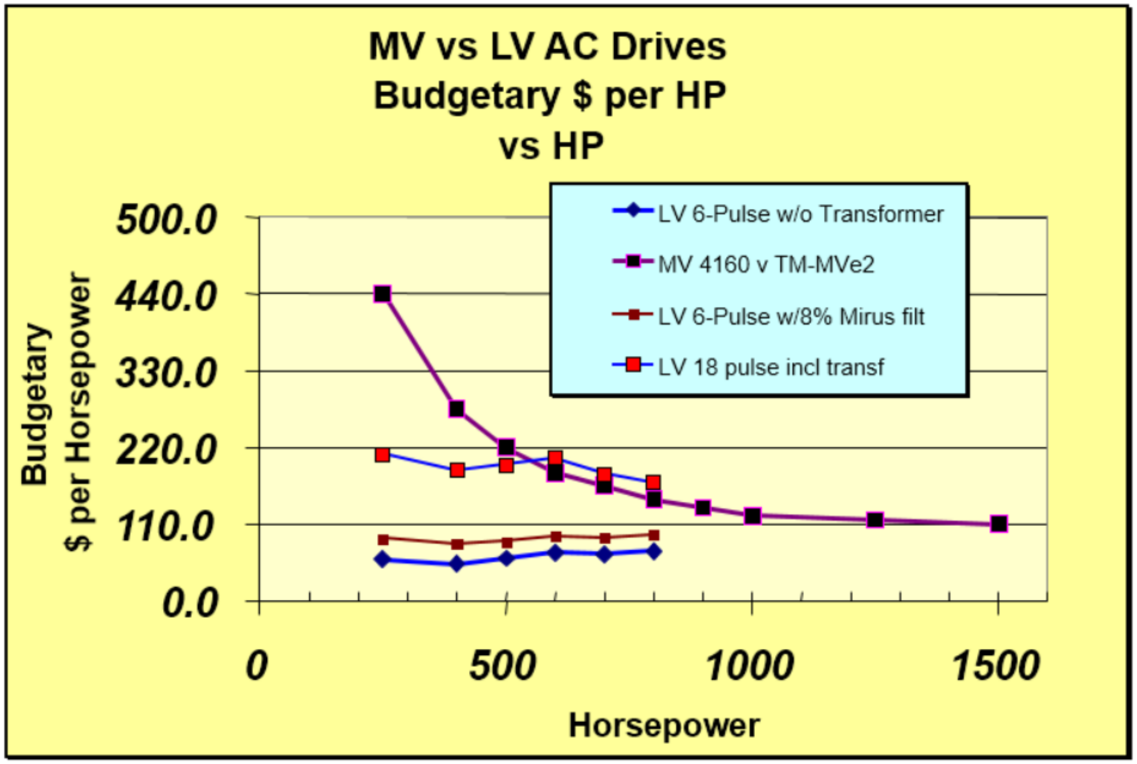
- Always provide and electrical one-line diagram
- Some tips for ASD voltage level selection

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 – Which to use?

- MV drive $ / HP decreases with HP
- Harmonic content can be important:
  - Installed cost must be considered
  - Reliability & cable cost
  - Cost of Special VFD rated cables
  - Additional cost for harmonic filters to meet IEEE 219 Requirements

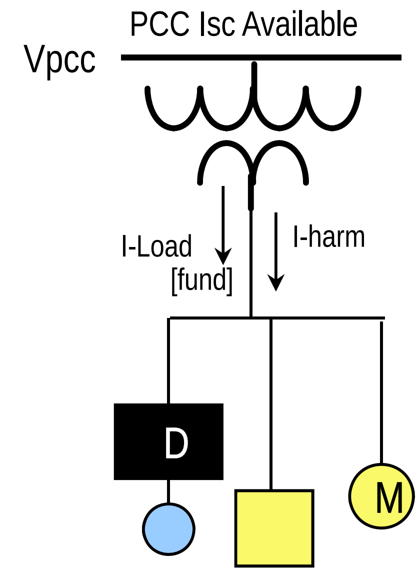


Recent Trend: Some users select MV >250 HP
Many users select MV > 500 HP.

Power Line Harmonics 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

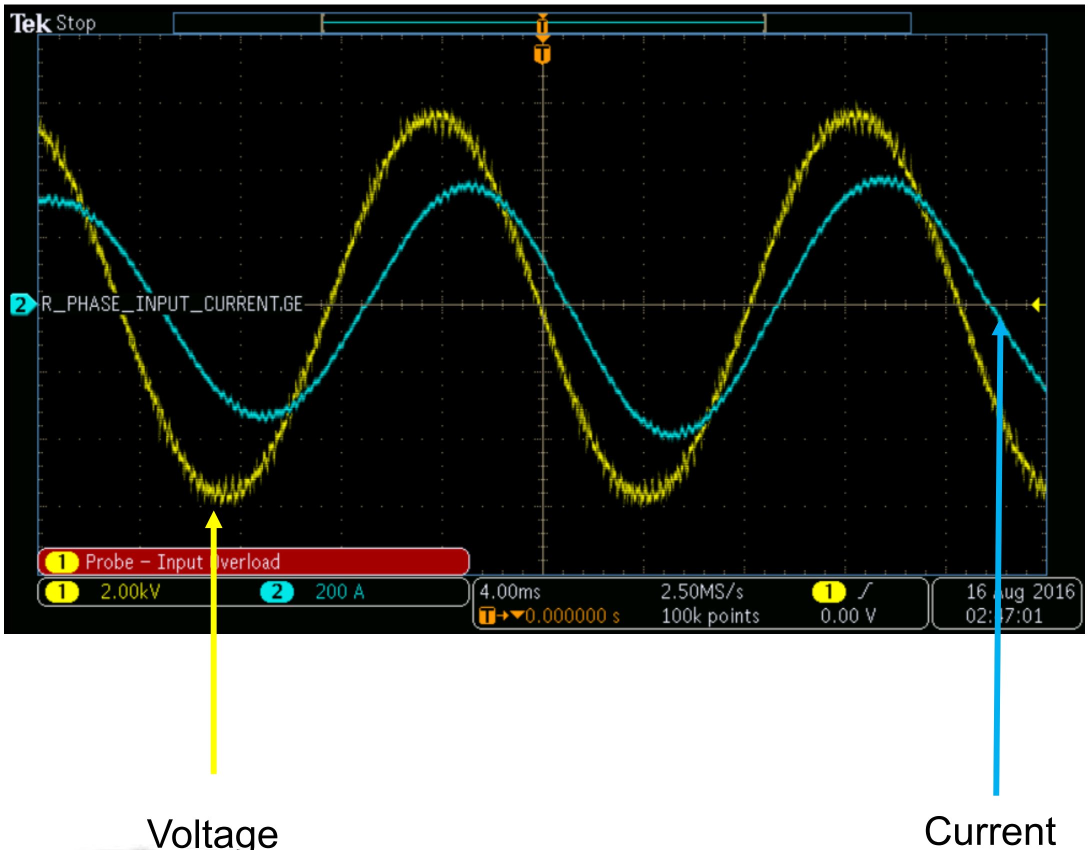
I-load = Fundamental freqency load current or kVA at the PCC

Specifying a min. 24-Pulse VSI VFDs or Active Front End VFD is safest option for harmonic mitigation. Best to ask for V & I harmonic spectrum

Specifying ASDs to avoid harmonics nightmare

- ASD shall be IEEE 519 – 2014 compliant and the I(TDD) shall NOT Exceed 5%
- A minimum of 24-pulse or higher input converter shall be supplied
- Harmonic mitigation shall be accomplished **without** the use of external filters (active/passive)
- Vendor shall provide the harmonic spectrum and line side voltage and current waveform of the ASD
- Active front end ASDs shall be provided with an input transformer

Line Side Performance – Voltage & Current

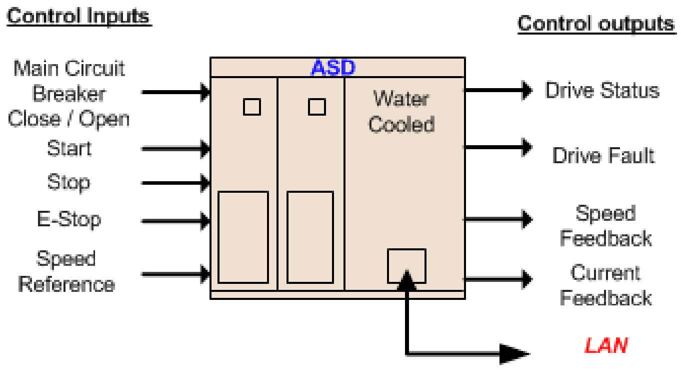


Harmonic Test Data

	100% Load / 100% Speed								
Harmonic Number n	Peak Input amps	RMS Input Amps	Peak Input Volts	RMS Input Volts	Peak Output amps	RMS Output Amps	Percent of Fund Amps	Peak Ouput Volts	RMS Output Volts
1	344.6	243.6	5655.4	3999.0	372.32	263.3	100.0%	5734.739	4055.1
2	1.69	1.197	15.18	10.732	2.33	1.646	0.6252%	16.320	11.540
3	2.62	1.852	16.50	11.664	2.80	1.978	0.7513%	22.136	15.653
4	0.59	0.417	2.44	1.727	0.30	0.210	0.0796%	2.693	1.904
5	2.07	1.467	18.97	13.416	3.29	2.325	0.8832%	28.597	20.221
6	0.23	0.164	1.06	0.748	0.21	0.148	0.0562%	1.773	1.253
7	1.38	0.978	16.66	11.783	1.15	0.812	0.3083%	8.481	5.997
8	0.30	0.212	1.38	0.973	0.20	0.141	0.0535%	2.523	1.784
9	0.42	0.300	6.44	4.552	0.82	0.580	0.2204%	2.508	1.774
10	0.24	0.172	2.37	1.673	0.20	0.143	0.0544%	2.050	1.449
87	0.09	0.066	1.21	0.855	0.19	0.131	0.0497%	8.973	6.345
88	0.13	0.092	3.43	2.425	0.27	0.188	0.0714%	32.180	22.755
89	0.12	0.082	0.88	0.623	0.13	0.091	0.0346%	5.303	3.750
90	0.08	0.057	1.00	0.705	0.09	0.062	0.0235%	8.792	6.217
91	0.10	0.069	1.39	0.980	0.14	0.096	0.0364%	7.551	5.340
92	0.11	0.075	3.40	2.407	0.67	0.471	0.1787%	81.731	57.792
93	0.14	0.102	0.79	0.558	0.13	0.094	0.0356%	13.492	9.540
94	0.11	0.080	3.83	2.706	0.88	0.623	0.2367%	109.613	77.508
95	0.12	0.083	3.22	2.275	0.08	0.057	0.0217%	6.714	4.748
96	0.17	0.122	3.71	2.623	0.13	0.089	0.0337%	6.122	4.329
97	0.09	0.065	4.01	2.837	0.10	0.070	0.0265%	10.564	7.470
98	0.10	0.073	2.58	1.826	0.76	0.536	0.2034%	110.552	78.172
99	0.10	0.069	1.07	0.756	0.10	0.072	0.0274%	4.104	2.902
100	0.14	0.099	2.28	1.615	0.70	0.493	0.1873%	84.358	59.650
Square Root, Sum of square Values		5.05		93.4		4.07			167.2
THD %, RMS / Fundamental RMS		2.07%		2.34%		1.55%			4.12%
		Amps		Volts		Amps			Volts
		INPUT				OUTPUT			

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

Power System & Drive Efficiency

- Drive itself is typically 98% or more efficient
  - With all fans, transformers, pumps, 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 vs. Water-cooled Overall system efficiency some tips:

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

Drive Installation

- Kept clean from dust, dirt & atmospheric contaminants
- Free from damaging moisture
- Operate within they rated ambient temperature & altitude ratings
- Properly connected & integrated into a reliable electrical system
- Integrated into the overall plant facility including proper site, equipment rooms, equipment handling
- **Properly stored BEFORE being installed**

Enclosures for VFDs

NEMA 1 (IP 20/21)

- Indoor Use
- Protect from contact & falling dust
- Force ventilated
- Gasketed

NEMA 3R (IP 23/33)

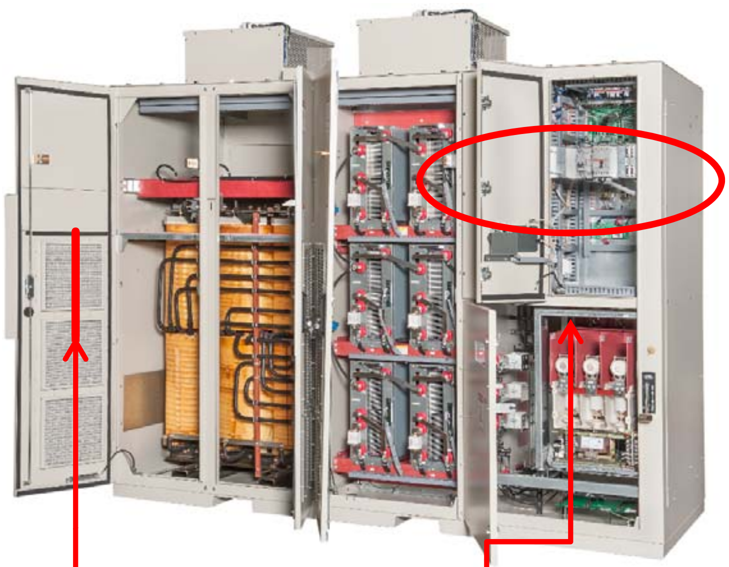
- Outdoor use
- Protect from the elements
- Convection or passive cooling

NEMA 12 (IP 51/52)

- Indoor use
- Protect against dust & dripping liquids
- Non ventilated
- VFD control section typically hosted

Enclosures for VFDs

NEMA 1 Gasketed enclosure



NEMA 1

Gasketed

NEMA 12

NEMA 3R Enclosure

Convection

cooling

Passive

cooling

Enclosure

- NEMA 1 air-cooled VFD's MUST be placed in climate controlled E-houses

- Special attention MUST be paid:
  - Air-cooled VFD's in dusty environments like rubber & cement plants.
  - Water cooled might be better option >4000HP
  - Corrosive environments where H2S might be present like water / chemical plants

- Cost basis of NEMA 1: NEMA 3R = 1 : 2.5.

- Follow manufacturer guidelines for air quality control requirements

Air Quality UL Pollution Degree 2. And Meet or Exceed: EN50178:1994 Section A.6.1.4 Table A.2 (m) IEC 529:1989-11 (IP20) (e) UL 508C	**Gas**: Maximum concentration of corrosive gases at 50% relative humidity and 40°C Sulfur Dioxide (SO_2) 30 ppb Hydrogen Sulfide (H_2S) 10 ppb Nitrous fumes (NO_x) 30 ppb Chlorine (Cl_2) 10 ppb Hydrogen Fluoride (HF) 10 ppb Ammonia (NH_3) 500 ppb Ozone (O_3) 5 ppb **Dust:** Particle sizes from 10 - 100 microns for the following materials Aluminum Oxide, Cement Ink, Sand/Dirt Lint, Steel Mill Oxides Coal/Carbon dust, Paper Soot

Enclosure

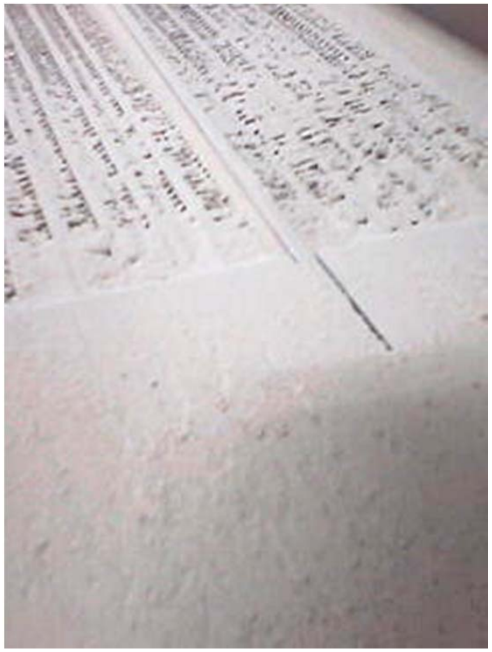
Filtered, pressurized room, caulking, extra filters…

Extra filters with Velcro…

Enclosure

Dust!

Some time later!



There are lots of ways to run from dust, but you can't hide!

Storage & running

Drip Shield – just in case!

Space heaters for storage

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

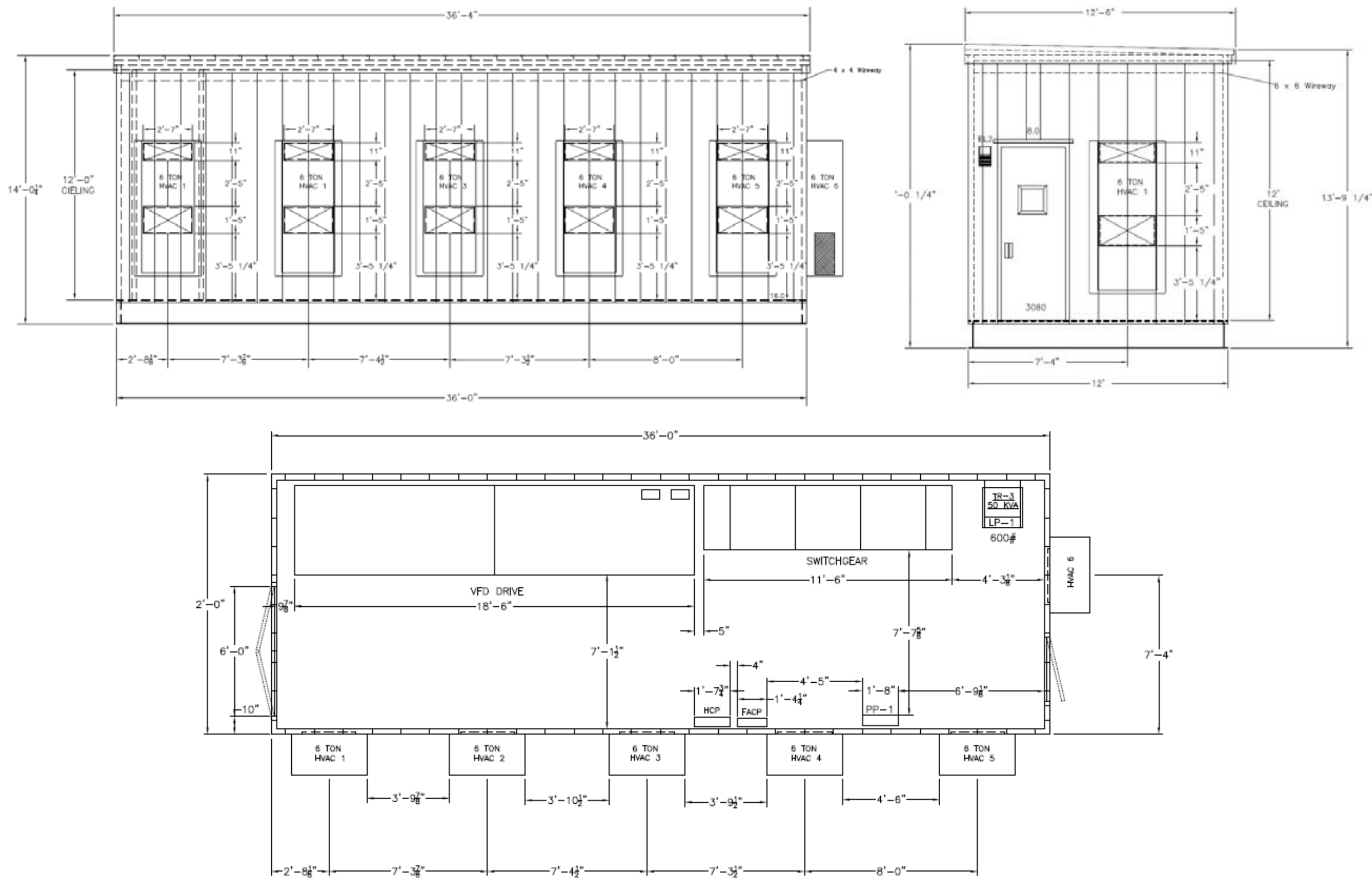
ASD Vendor ↔ Building Vendor

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

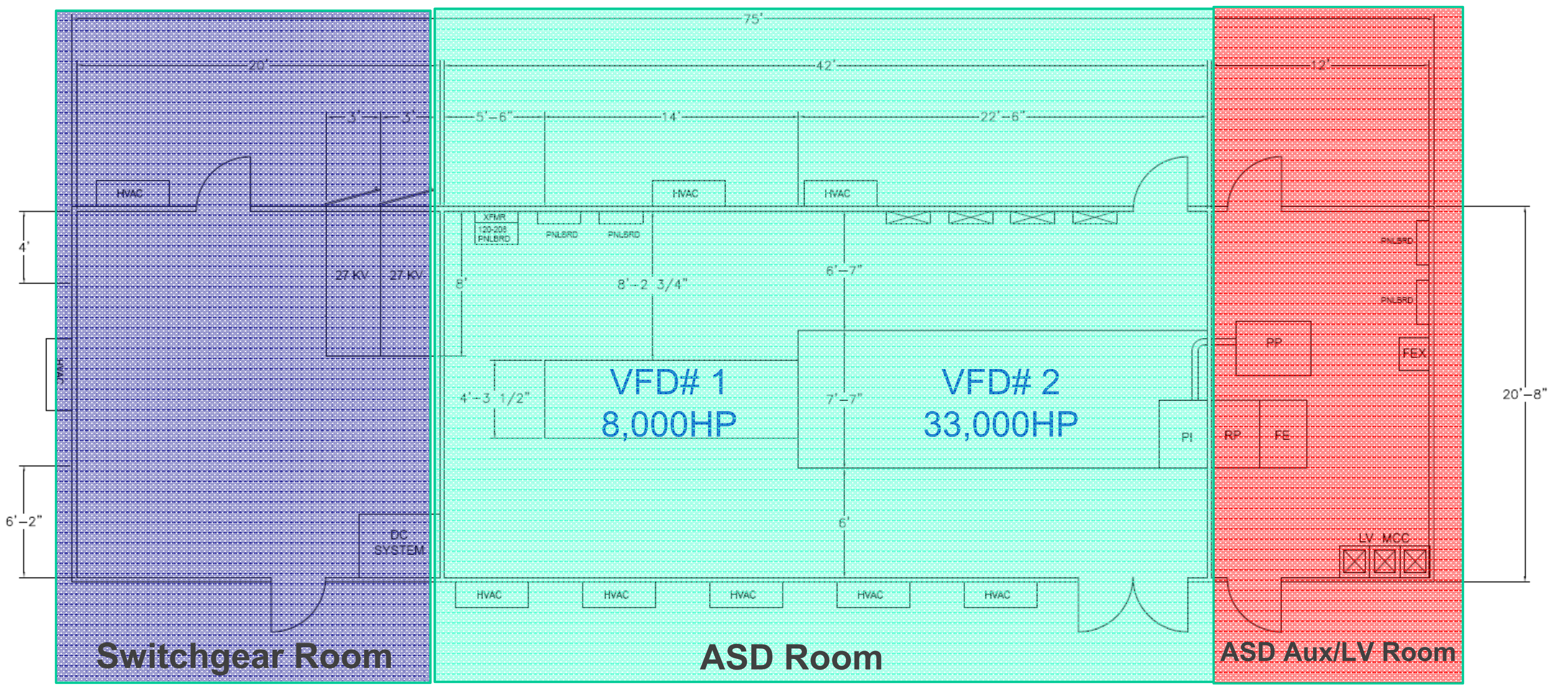
E-house requirements

- 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

ASD Solutions

ICB / PCR for Starting Duty VFD

Low Capacity ACU

ICB / PCR for 5000 HP VFD

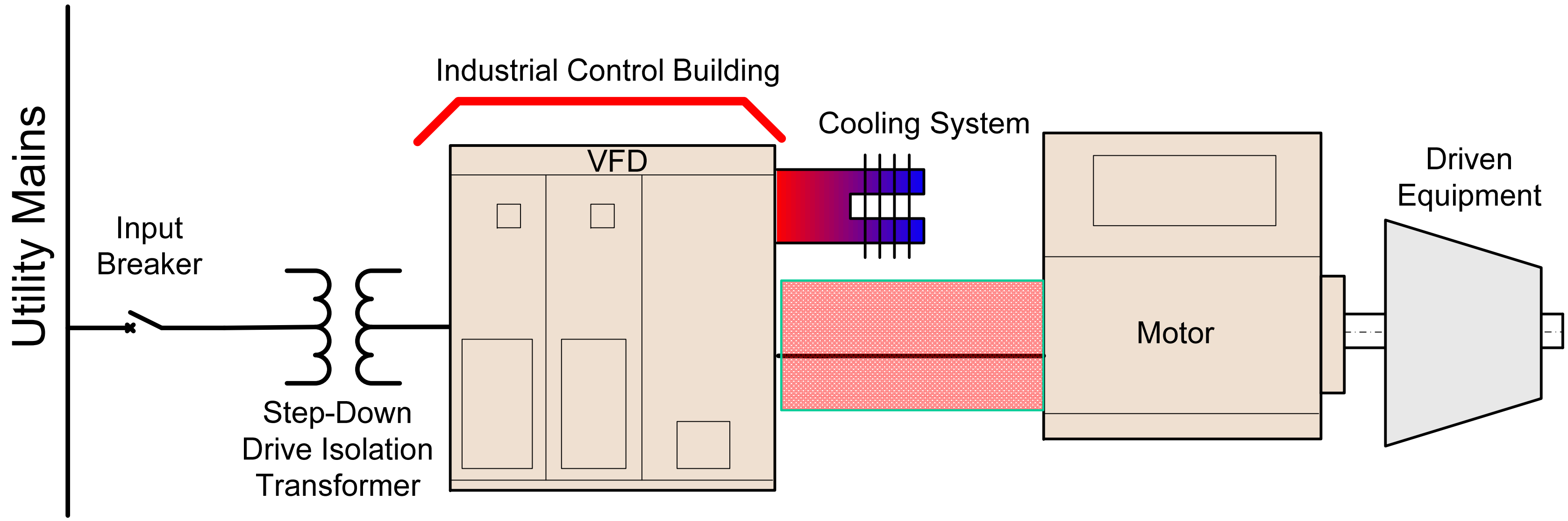
Redundant ACU

Temp. Controlled E-house versus ducting air out

- Many clients ask if they can duct-out hot air from the ASD to save on HVAC building
- YES, **but:-**
  - Make-up air must be provided: ~4500CFM to 17,000CFM
  - Air must be scrubbed off moisture content, fine dust, hazardous gases and other contaminants
  - Air must be heated if temperature gets to sub-zero. Big air heaters required
  - ASD might need to be de-rated for hot ambient conditions
  - Warranty might not be honored.
  - Installer / End user assumes all risk
  - Usually not suitable for very low/high ambient, high humidity, dusty or areas where gas might be present.

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]



Cable Sample Recommendations

CABLE RECOMMENDATIONS FOR POWER CABLING RATED 2000VAC OR ABOVE.

SELECTION AND TERMINATION OF POWER CABLING IS CRITICAL TO THE SAFE AND RELIABLE OPERATION OF THIS SYSTEM. ISSUES WITH RADIATED ELECTRICAL NOISE, DISRUPTIVE GROUND CURRENTS AND SAFETY ALL HAVE ROOTS IN POWER CABLING SELECTION AND TERMINATION. THESE RECOMMENDATIONS COMPLY WITH THE REQUIREMENTS OF THE NATIONAL ELECTRIC CODE OF THE USA. IT IS THE RESPONSIBILITY OF THE INSTALLER TO INSURE THAT LOCAL CODES ARE FOLLOWED WHERE THEY CONFLICT WITH THESE RECOMMENDATIONS.

SELECTION:

RECOMMENDED FOR INVERTER OUTPUT IS OKONITE OKOGUARD OKOSEAL TYPE MV-105 P/N 115-23-3816.

CONVERTER INPUT DOES NOT REQUIRE MC TYPE CABLE OR SYMMETRICAL GROUNDS. HOWEVER, SHIELDED POWER CABLE SHOULD BE USED PER NEC GUIDELINES. SEE FIGURE 2. CONVERTER CABLE INSULATION LEVEL SPECIFIED SHOULD BE EQUAL TO OR HIGHER THAN 8.2KV.

TERMINATION AT THE MOTOR OR TRANSFORMER:

WHERE MC CABLES ARE USED, FITTINGS SHOULD BE USED TO INSURE THAT THERE IS A 360 DEGREE ELECTRICAL CONNECTION BETWEEN THE ALUMINUM SHIELD AND THE JUNCTION BOX. ANY GROUND CONDUCTORS SHOULD BE TERMINATED TO THE EQUIPMENT GROUNDING LUG PROVIDED FOR THAT PURPOSE. INDIVIDUAL CONDUCTORS SHOULD BE CONNECTED USING COMPRESSION LUGS.

TERMINATION AT THE INVERTER OR CONVERTER:

IT IS NECESSARY TO REMOVE ENOUGH CABLE SHIELD AND PHASE CONDUCTOR SHIELD SO THAT INDIVIDUAL PHASE CONDUCTORS CAN REACH FROM THE POINT THE CABLE ENTERS THE EQUIPMENT CABINET, TO THE AC CONNECTION POINTS OF THE INVERTER OR CONVERTER. ONCE THE SHIELD HAS BEEN REMOVED, FITTINGS SHOULD BE USED, TO INSURE THAT THERE IS A 360 DEGREE ELECTRICAL CONNECTION BETWEEN THE ALUMINUM SHIELD AND THE CABINET GROUND (MC TYPE CABLE). GROUND CONDUCTORS SHOULD BE CONNECTED TO THE E1 GROUND BUS PROVIDED FOR THAT PURPOSE. PHASE CONDUCTORS SHOULD BE CONNECTED ACCORDING TO THE EQUIPMENT DRAWINGS. ALL CONDUCTORS SHOULD BE TERMINATED WITH COMPRESSION LUGS.

SHIELDED CABLES MAY BE RUN IN CLOSE PROXIMITY TO OTHER SHIELDED POWER CABLES, SO FAR AS ELECTRICAL COUPLING IS CONCERNED. RULES REGARDING SPACING FOR THERMAL REASONS MUST BE RESPECTED.

NOTE: CUSTOMER REQUIREMENT

ALL CABLES RATED AT OR ABOVE 2000V SHALL USE STRESS RELIEF CONES.

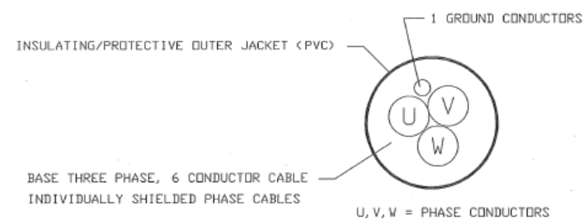


FIGURE 1: OKONITE OKOGUARD OKOSEAL TYPE MV-105 RECOMMENDED FOR INVERTER OUTPUT

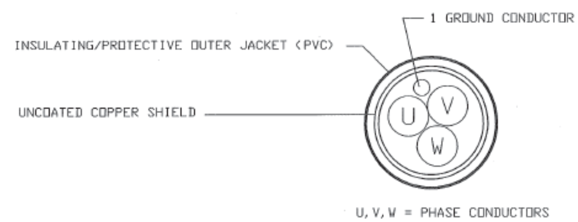


FIGURE 2: THREE PHASE SHIELDED CABLE WITH GROUND. RECOMMENDED FOR CONVERTER INPUT

Cable Sample Recommendations

Power Cable with armor and fittings

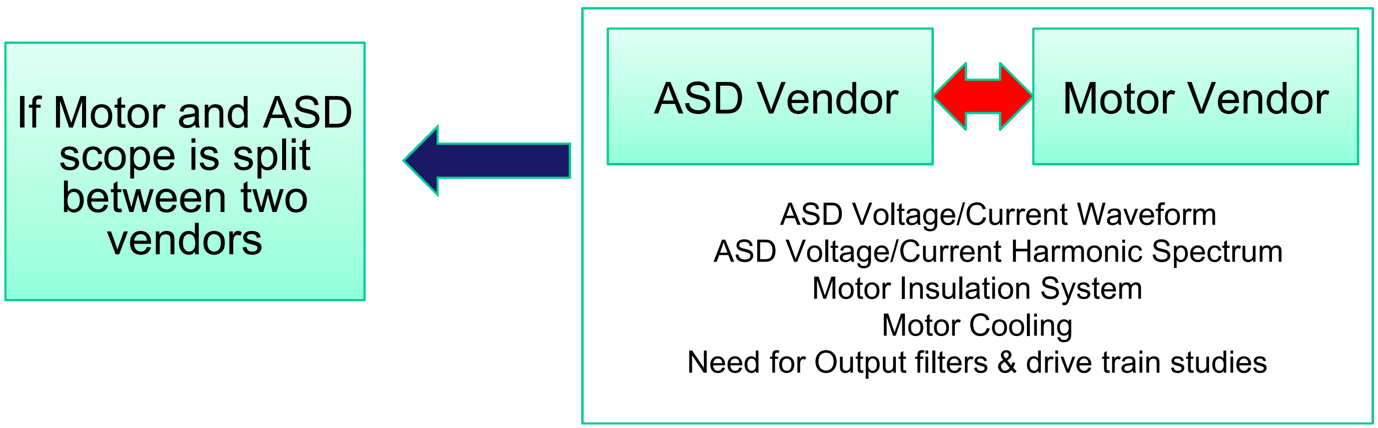
Control Connections [bottom picture]

Segregated by voltage level

Segregated by signal type

Motors application consideration – New Installs

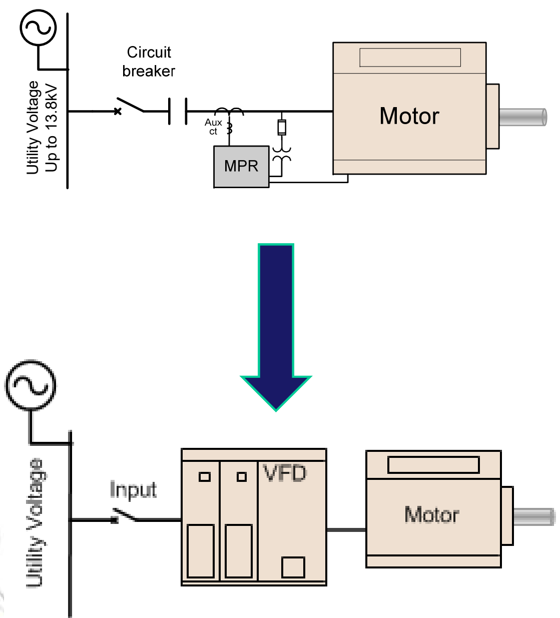
- All ASDs inject harmonic currents on the Motor
- Harmonic Currents vary over speed range
  - Verify motor cooling can handle harmonic currents
- ASDs also produce common mode voltage,
  - Verify motor insulation is suitably designed
  - Output filters might be needed with standard motor



For large applications, preferable to procure from the same Motor & ASD Vendor to avoid future issues

Motors application consideration – Retrofit Installs

If Fixed speed motor converted for variable speed operation



ASD Vendor ⟷ Existing Motor

- ASD Voltage/Current Waveform
- ASD Voltage/Current Harmonic Spectrum
- Need for Output filters & drive train studies

- Motor Insulation System
- Motor Cooling for speed range
- Motor Bearing
- Motor lubrication system
- Motor critical speed range avoidance
- Elimination of surge arrestors, & capacitors

- ASD to Motor Cabling / Distance

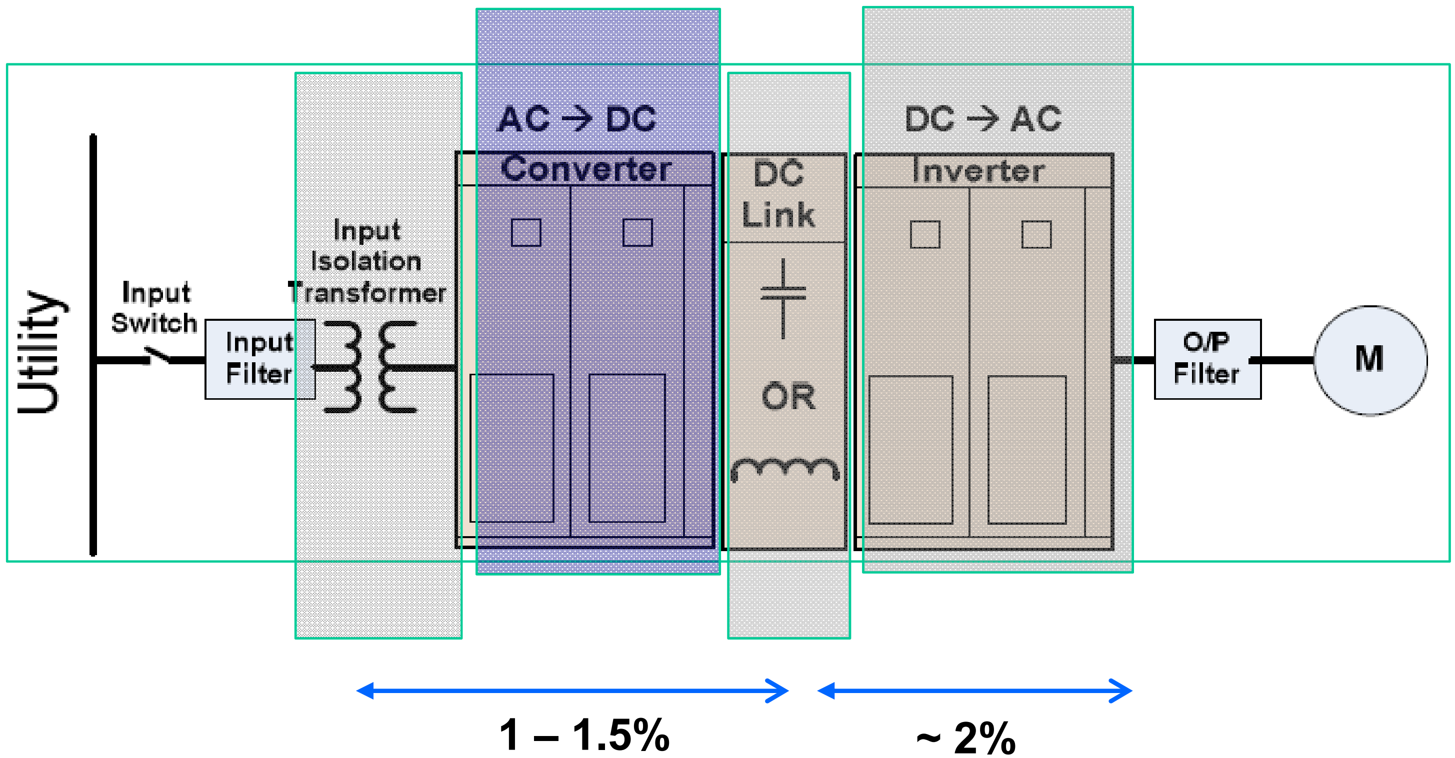
ASD Cooling Systems

- Cools the power cells & auxiliary components
- Enhances the life of the ASD
- Allows the ASD to deliver rated power in smallest footprint

<u>However,</u>

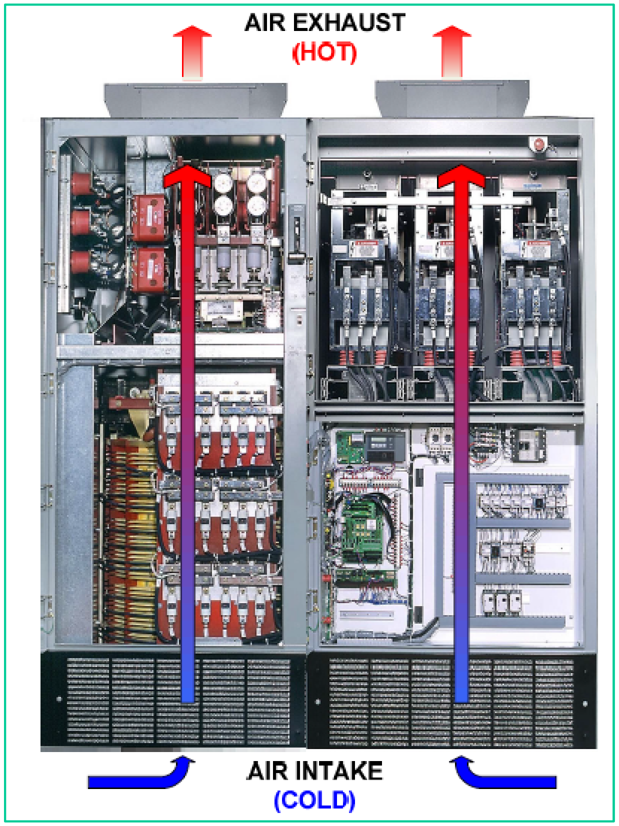
- Poor design can lead to pre-mature failure
- Operation beyond thermal limits → Safety hazard
- Poor choice of cooling type (Air vs. Water) can prove expensive
- Poor cooling materials (pipes, hoses, etc) can cause leaks and reduced reliability

Major Sources of Heat in an ASD System



How Air Cooling Works?

- The most basic form of cooling
- Uses industrial fans
- Cool air suction from front or bottom and exhaust hot air to top or back



Advantages of Air-cooling

- Air cooled drive is simpler –
  - No pumps, filters, deionizers
  - Only need to keep the air filters clean

- HVAC knowledgeable people are easy to find

- Redundancy can be designed into both the VFD fans and HVAC.

- HVAC is required for any Medium Voltage VFD

- Typical VFD (s) rated for 40 deg C

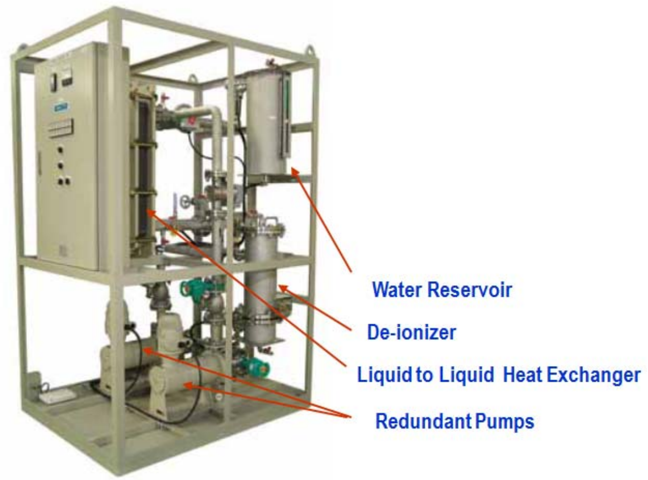
- Can be used for starting duty ONLY for large motors

Disadvantages of Air-cooling

- Air cooled drive has a much larger footprint –
  - Will require much larger control room or E-house
- Higher noise level in control room (> 79 dB @ 1m)
- Must control level of dust in room to avoid frequent filter changes
- For higher reliability, redundancy will be required for both fans and air conditioning – driving HVAC & life cycle costs up
- HVAC power levels can be 8-9 times higher than water cooled

How liquid cooling system works?

- Major components of ASD liquid cooling
  - Pumps
  - Coolant reservoir
  - Heat Exchanger
  - De-ionizer
  - Control system

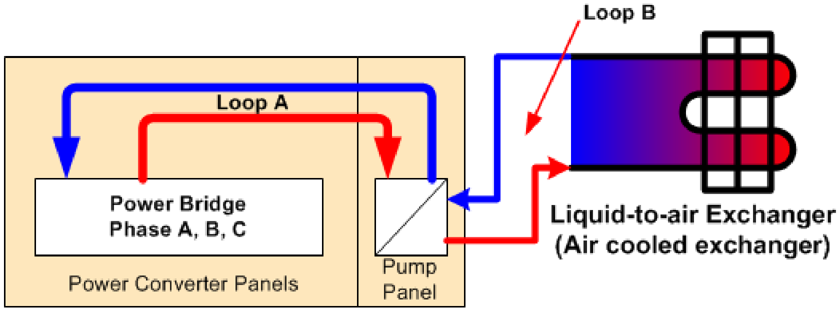


- Coolant is pumped through the ASD power cells and heat is extracted
- Hot coolant is pumped through a heat exchanger to cool the liquid
- Continuous process

Types of liquid cooled system

Closed Loop

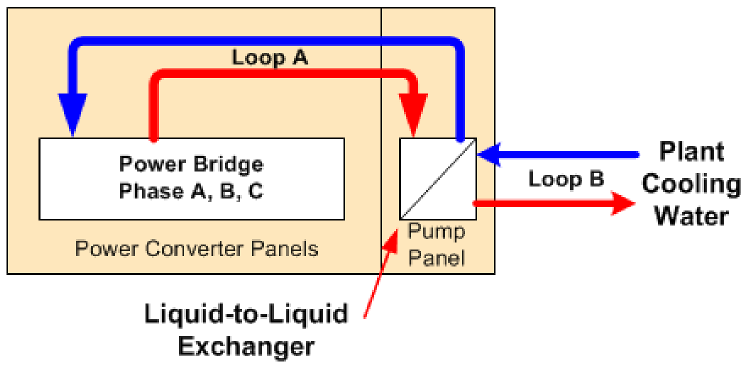
- Liquid-to-Air Exchanger
- No plant liquid needed
- Redundancy on pumps and exchanger fans



- Expensive, need extra space, design dependent on ambient temperature

Open Loop

- Liquid-to-Liquid exchanger
- Specific plant water temp. needed
- Redundant pumps
- Less expensive and space saving



• Note: VFD loop is always closed unless a stainless steel air cooled HEX is used

Typical Pump Panel for water cooled VFDs

Redundant Di Filter

Redundant Pumps rated for 100% capacity

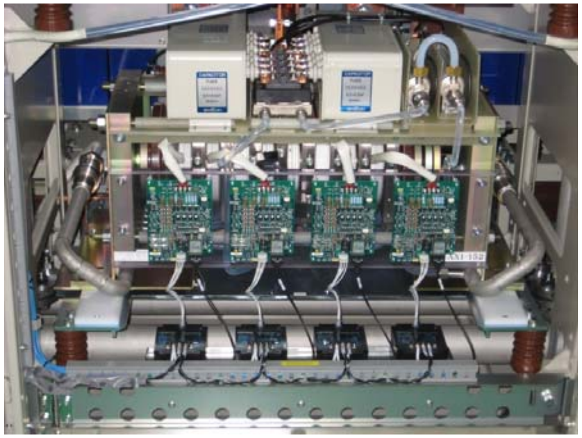
Evaluating liquid cooling systems

- Main liquid supply systems
  - All stainless steel construction
  - Tight regulation on liquid conductivity, pressure, flow & temperature
  - Factory tested at full rating

Straub Coupling between the inverter panels

Water-cooled inverter unit

- Main Inverter/Converter Circuit

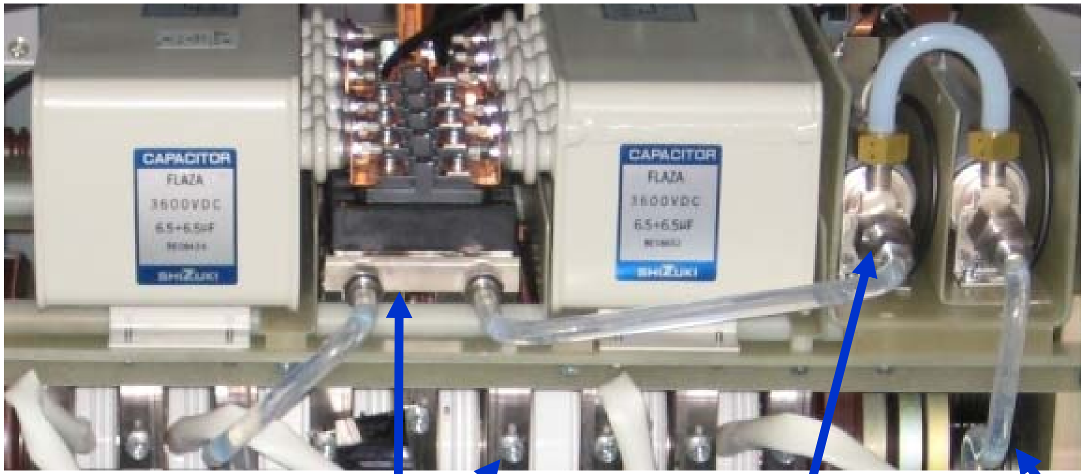


Quick Disconnect

Robust Piping

Water Cooled inverter unit

- Main Inverter/Converter Circuit

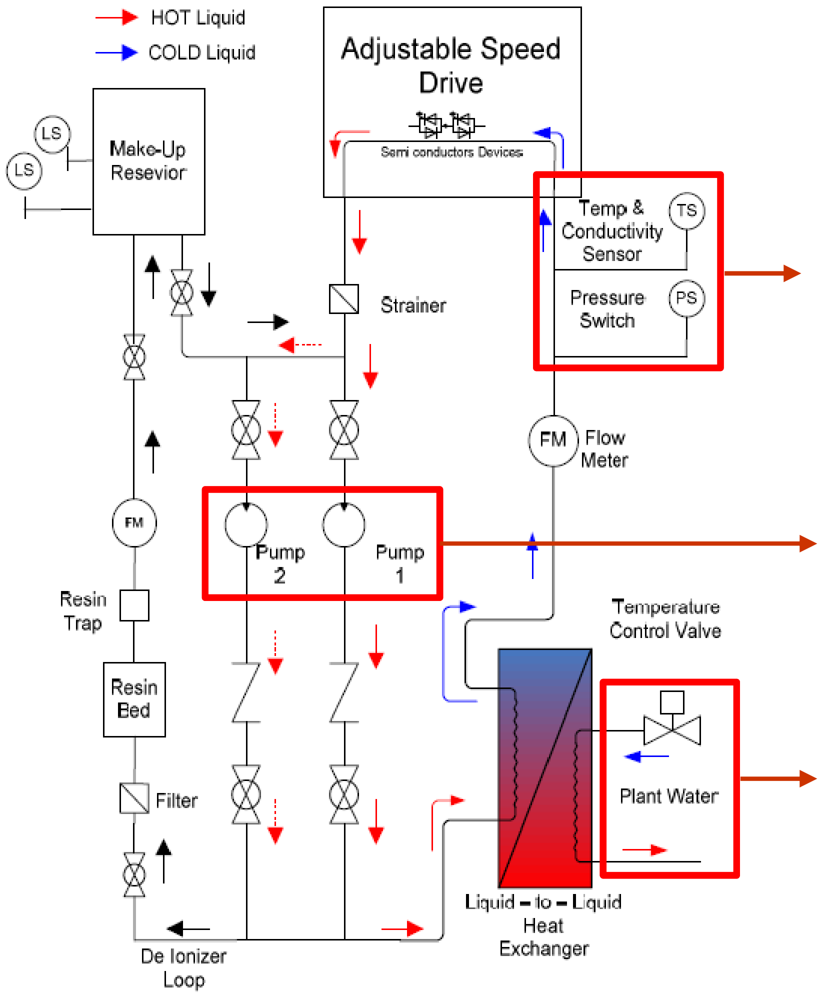


Heat Sink

Quick
Connect
Couplings

Teflon Piping

Water-cooled related specifications – Keep in mind



Avoidance of dissimilar metals in the liquid cooling systems.

Redundant temp/pressure/conductivity sensors for critical services

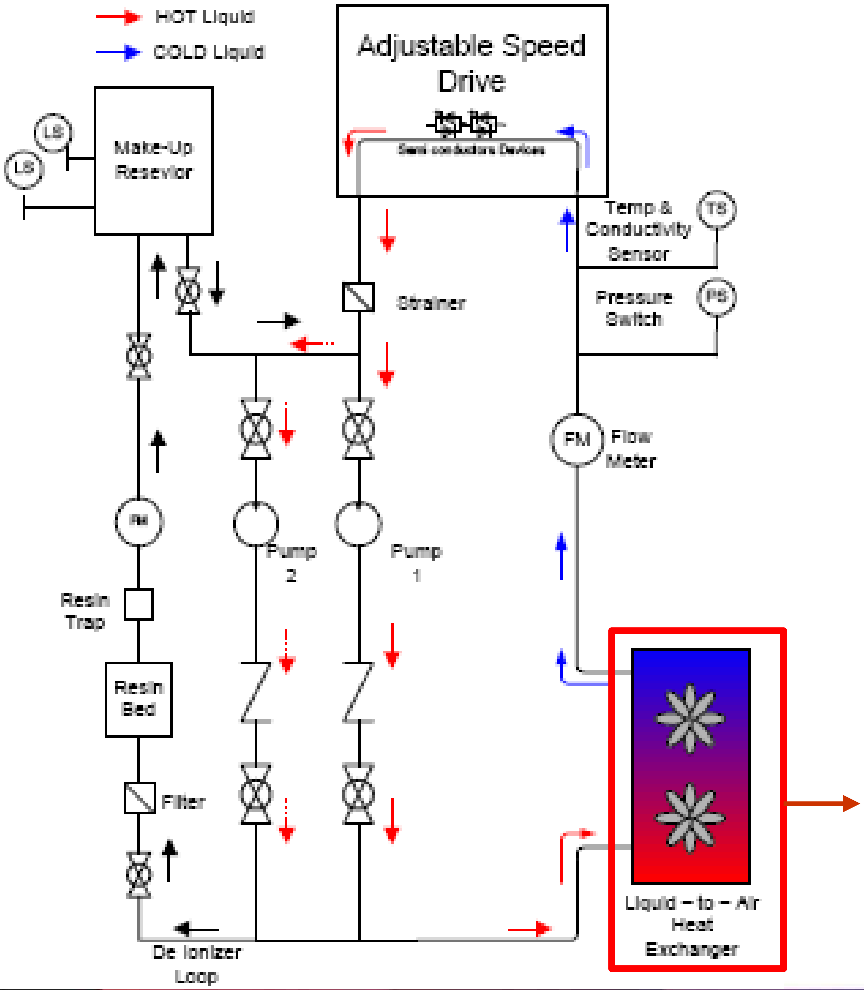
Avoidance of condensation

100% Redundant Pumps w/Auto Switchover

Stainless Steel piping with Di-Water

Specify liquid quality, pressure, temperature (Liquid/Liquid ONLY)

Water-cooled related specifications – Keep in mind



Clearly define the responsibilities between EU / EPC / ASD Vendor for plumbing, mounting and initial liquid fill-up

Life Cycle Cost Comparison -- 6000 HP ASD

	Comparision Parameter	Liquid-Cooled Drive (4.4MW)	Air-Cooled Drive (4.4MW)
1	Base Cost of the ASD	$750,000	$600,000
2	HVAC Unit Costs	$4,000	$60,000
3	HVAC Annual Operatin costs ($0.04/kWh)	$400	$7,000
4	HVAC Life Cycle Cost (20 yr)	$18,000	$290,000
5	Spare Parts Cost	$100,000	$80,000
6	Annual Maintainence Cost	$1,300	$4,000
7	Training/Learning Cost	$5,000	$4,000
8	Downtime Costs (over 20 life) per year	$1,000	$5,000
9	Xfmr + Xchgr Installation cost	$15,000	$0
10	Commissioning Cost	$20,000	$10,000
11	Building cost (Per ASD sqft ONLY)	$8,000	$13,000
	GRAND TOTAL (Per VFD)	**$922,700**	**$1,073,000**

Good Reference: Verma, M.; Phares, D.; Grinbaum, Il; Nanney, J., "Cooling systems of large capacity adjustable speed drive systems," *Petroleum and Chemical Industry Technical Conference (PCIC), 2013 Record of Conference Papers Industry Applications Society 60th Annual IEEE* , vol., no., pp.1,11, 23-25 Sept. 2013

Optimizing E-houses

- Proper selection of VFD cooling type: Air / Water
- Moving the transformer outdoors. Possible under limited cases. Eliminating transformer opens up other issues.
- Maintain temperatures up to 40 deg C. Less HVAC required.
- When using the VFDs for starting ONLY, HVAC can be sized for up to 25% of continuous duty application.
- No rear space requirement for TMEIC air-cooled VFDs
- Roof/Floor mounted HVACs instead of wall mounted.

ASD Cooling - Summary

- Specify cooling systems based on:-
  - Motor Power
  - Environment

- Evaluate cooling systems based on:-
  - Design for Safety
  - Cooling system design and redundancy
  - Data Sheets
  - Servicing intervals
  - Availability
  - Total Installed + Life cycle Cost

What are the VFD standards?

- There are North American and International ASD standards
- The two applicable standards are IEC 61800-4 and UL-347A
- These are design standards

Comparison of Standards

- UL 347A addresses only the medium voltage ASD
- IEC 61800-4 more broadly written to encompass the total medium voltage Power Drive System (PDS)

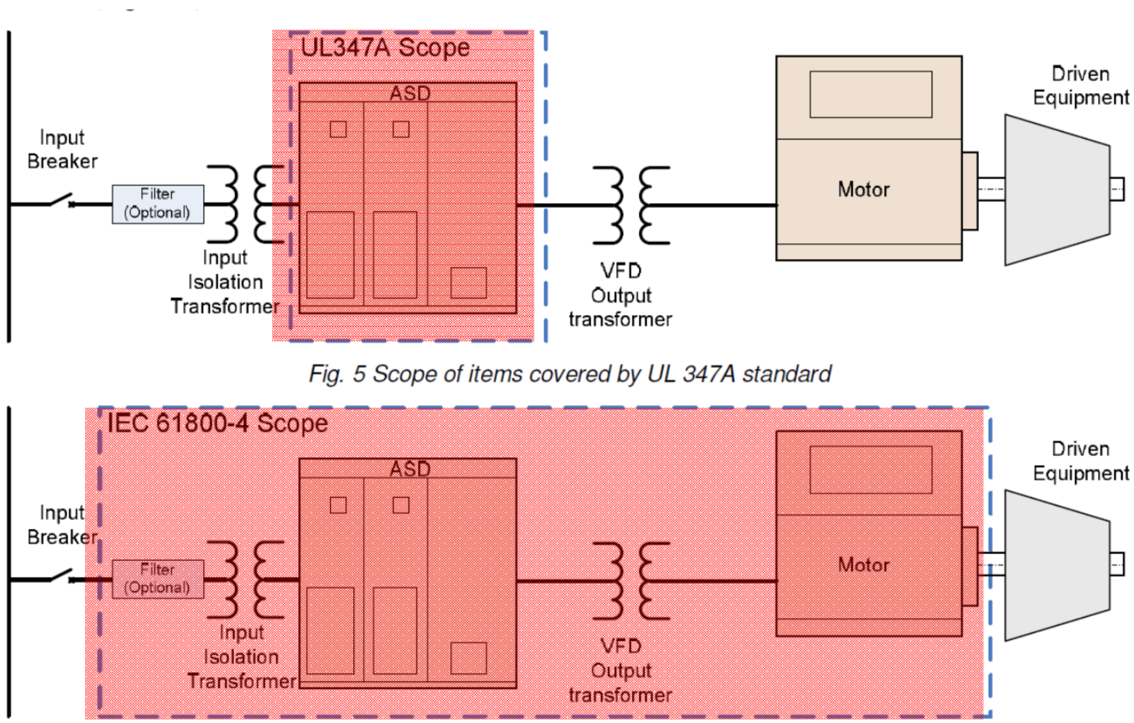


Table of Comparison

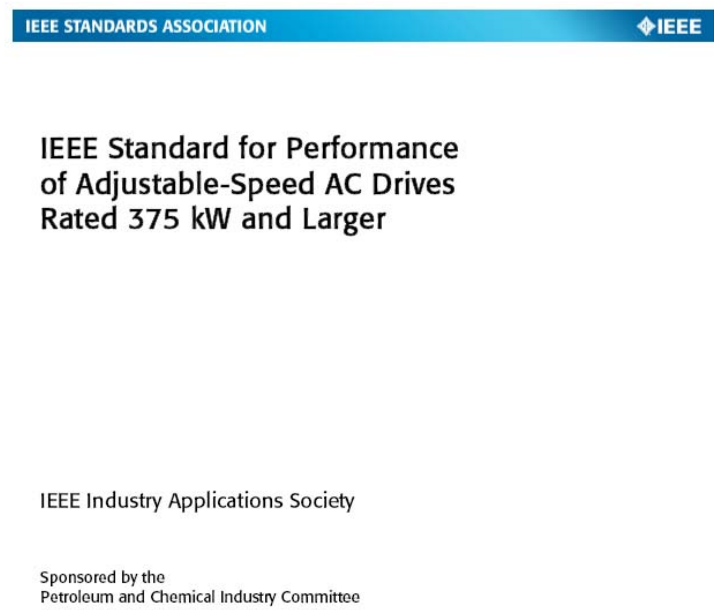
Standard Category	**IEC 61800-4** **Section reference**	**UL347-A** **Section reference**
Scope	MV Adj speed AC drive systems including power conversion, control **and motor**	MV Adj speed AC drive systems including power conversion and control but **excluding motors**
Definitions/Glossary/Units	3	2, 3 ,4
Drive system Topology	4	Not addressed
Electrical Input/Service Conditions	5.1.1 Details given with level and acceptable range	5 Defines necessary parameters but no levels or ranges
Source Impedance	5.1.1.2	Not addressed
Climate Conditions	5.1.2.1 Defines accepable environment for drive	Not addressed
Mounting/Vibration	5.1.2.2 defines normal vibration requirements for stationary equipment	Not addressed
Transportation & Storage	5.2 and 5.3 Defines environmental, temperature and humidity ranges	Not addressed

Good Reference: Phares, D.; Verma, M.; Horvath, B.; Rodgers, N., "Comparing International standards to North American standards for large adjustable speed drives," *Cement Industry Technical Conference, 2012 IEEE-IAS/PCA 53rd* , vol., no., pp.1,10, 14-17 May 2012

IEEE 1566 – 2015 Standard

- **Standard for Performance of Adjustable Speed AC Drives rated 375KW and Larger**

- **Created in about 2006**
- **Released in March 2015**
- **Includes a set of data sheets**

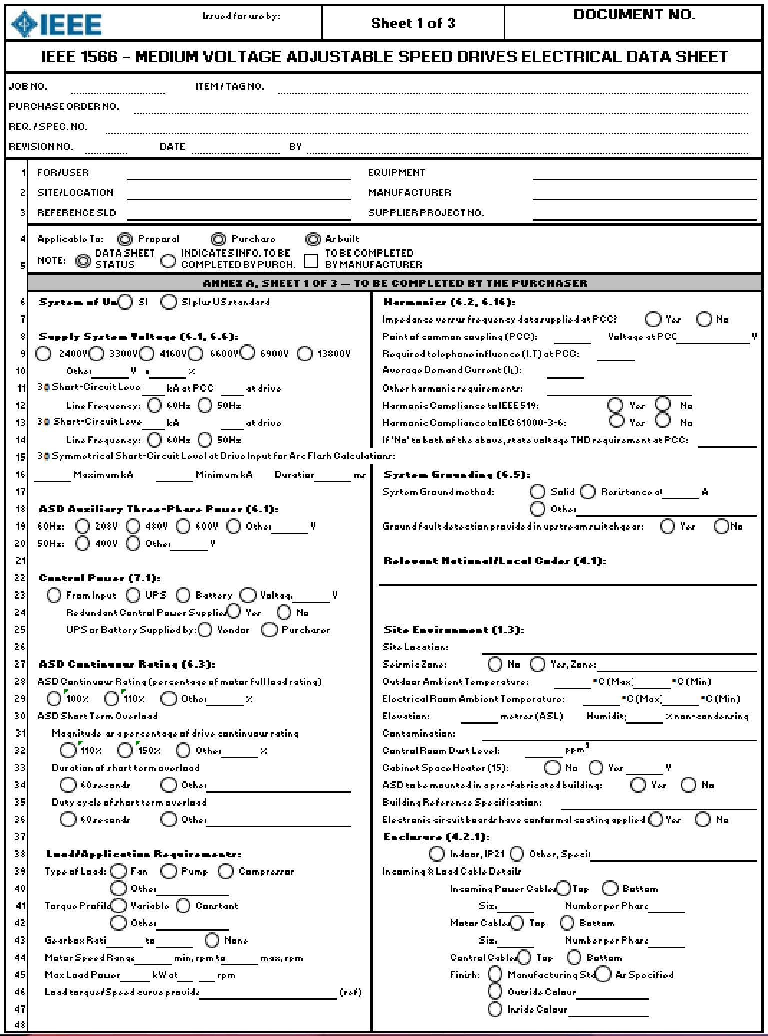

IEEE STANDARDS ASSOCIATION IEEE

IEEE Standard for Performance of Adjustable-Speed AC Drives Rated 375 kW and Larger

IEEE Industry Applications Society

Sponsored by the
Petroleum and Chemical Industry Committee

IEEE 1566 – 2015 Standard



IEEE | Issued for use by: | Sheet 1 of 3 | DOCUMENT NO.

IEEE 1566 – MEDIUM VOLTAGE ADJUSTABLE SPEED DRIVES ELECTRICAL DATA SHEET

JOB NO. .... ITEM / TAG NO. ....
PURCHASE ORDER NO. ....
REQ. / SPEC. NO. ....
REVISION NO. .... DATE .... BY ....

1 FOR/USER ______ EQUIPMENT ______
2 SITE/LOCATION ______ MANUFACTURER ______
3 REFERENCE SLD ______ SUPPLIER PROJECT NO. ______

4 Applicable To: Proposal Purchase As built
5 NOTE: DATA SHEET STATUS; INDICATES INFO. TO BE COMPLETED BY PURCH.; TO BE COMPLETED BY MANUFACTURER

ANNEX A, SHEET 1 OF 3 — TO BE COMPLETED BY THE PURCHASER

6 System of Units: SI; SI plus US standard
8 Supply System Voltage (6.1, 6.6):
9 2400V 3300V 4160V 6600V 6900V 13800V
10 Other ___ V ± ___ %
11 3Ø Short-Circuit Level ___ kA at PCC ___ at drive
12 Line Frequency: 60Hz 50Hz
13 3Ø Short-Circuit Level ___ kA ___ at drive
14 Line Frequency: 60Hz 50Hz
15 3Ø Symmetrical Short-Circuit Level at Drive Input for Arc Flash Calculations:
16 ___ Maximum kA ___ Minimum kA Duration ___ ms
18 ASD Auxiliary Three-Phase Power (6.1):
19 60Hz: 208V 480V 600V Other ___ V
20 50Hz: 400V Other ___ V
22 Control Power (7.1):
23 From Input UPS Battery Voltage ___ V
24 Redundant Control Power Supplied: Yes No
25 UPS or Battery Supplied by: Vendor Purchaser
27 ASD Continuous Rating (6.3):
28 ASD Continuous Rating (percentage of motor full load rating)
29 100% 110% Other ___ %
30 ASD Short Term Overload
31 Magnitude as a percentage of drive continuous rating
32 110% 150% Other ___ %
33 Duration of short term overload
34 60 seconds Other ___
35 Duty cycle of short term overload
36 60 seconds Other ___
38 Load/Application Requirements:
39 Type of Load: Fan Pump Compressor
40 Other ___
41 Torque Profile: Variable Constant
42 Other ___
43 Gearbox Ratio ___ to ___ None
44 Motor Speed Range ___ min, rpm to ___ max, rpm
45 Max Load Power ___ kW at ___ rpm
46 Load torque/Speed curve provided ___ (ref)

Harmonics (6.2, 6.16):
Impedance versus frequency data supplied at PCC? Yes No
Point of common coupling (PCC): ___ Voltage at PCC ___ V
Required telephone influence (I.T) at PCC: ___
Average Demand Current (I_L): ___
Other harmonic requirements: ___
Harmonic Compliance to IEEE 519: Yes No
Harmonic Compliance to IEC 61000-3-6: Yes No
If 'No' to both of the above, state voltage THD requirement at PCC: ___

System Grounding (6.5):
System Ground method: Solid Resistance at ___ A
Other ___
Ground fault detection provided in upstream switchgear: Yes No

Relevant National/Local Codes (4.1):

Site Environment (1.3):
Site Location: ___
Seismic Zone: No Yes, Zone: ___
Outdoor Ambient Temperature: ___ °C (Max) ___ °C (Min)
Electrical Room Ambient Temperature: ___ °C (Max) ___ °C (Min)
Elevation: ___ meters (ASL) Humidity ___ % non-condensing
Contamination: ___
Control Room Dust Level: ___ ppm³
Cabinet Space Heater (15): No Yes ___ V
ASD to be mounted in a pre-fabricated building: Yes No
Building Reference Specification: ___
Electronic circuit boards have conformal coating applied: Yes No

Enclosures (4.2.1):
Indoor, IP21 Other, Specify ___
Incoming & Load Cable Details
Incoming Power Cables: Top Bottom
Size ___ Number per Phase ___
Motor Cables: Top Bottom
Size ___ Number per Phase ___
Control Cables: Top Bottom
Finish: Manufacturing Std. As Specified
Outside Colour ___
Inside Colour ___

Datasheets are available in Excel format and PDF –

- Three for Purchaser
- Three for Manufacturer

Additional reading material, Peer reviewed publications

- M. Verma, D. Parker, I. I. Grinbaum and J. Nanney, "Making the Leap to Electric Motors and Adjustable-Speed Drives: A Case Study of a 20,000-hp Gas Turbine-Driven Compressor," in IEEE Industry Applications Magazine, vol. 23, no. 6, pp. 29-38, Nov.-Dec. 2017.
- M. Verma, I. l. Grinbaum, J. Arnold and J. Nanney, "Preparing to Witness a Multi-Megawatt Motor and Adjustable Speed Drive Acceptance Test - The Basics," in *IEEE Transactions on Industry Applications*, vol. PP, no. 99, pp. 1-1
- Verma, M.; Phares, D.; Grinbaum, I.; Nanney, J., "Cooling Systems of Large-Capacity Adjustable-Speed Drive Systems," in *Industry Applications, IEEE Transactions on* , vol.51, no.1, pp.148-158, Jan.-Feb. 2015
- Phares, D.; Verma, M.; Horvath, B.; Rodgers, N., "Comparing International Standards to North American Standards for Large Adjustable-Speed Drives," in *Industry Applications, IEEE Transactions on* , vol.49, no.5, pp.1939-1945, Sept.-Oct. 2013
- Verma, M.; Dick, B.; Phares, D.; Bondy, S., "Bringing New Life to High-Capacity Systems: Modernization of Legacy Adjustable-Speed Drives," in *Industry Applications Magazine, IEEE* , vol.19, no.6, pp.66-74, Nov.-Dec. 2013
- Verma, Manish, "Powering gas compressors: Electric prime mover technologies." LNG Industry Editorial, May 2018.

Additional reading material, Peer reviewed publications

- M. Verma, N. Bhatia, S. Holdridge and T. O'Neal, "Isolation techniques for various topologies of medium voltage adjustable speed drives," *2017 Petroleum and Chemical Industry Technical Conference (PCIC)*, Calgary, AB, Canada, 2017, pp. 327-334.
  doi: 10.1109/PCICON.2017.8188752
- Bondy, S.; Phares, D.; Verma, M.; Horvath, B.; , "New advances in pulse width modulated slip power recovery drives for pumps," *Proceedings of the Forty-First Turbomachinery Symposium*, 24-27 Sept.2012
- Verma, Manish, and James T. Nanney. "Select the Right Starting Strategy for Large Motors." Pumps & Systems Magazine, 14 Nov. 2014.
- Verma, Manish, and James T. Nanney. "Adjustable Speed Drives, Motors for Electric Compression - Cool Facts about Cooling Large Units." COMPRESSORtech2 - May 2014.
- Phares, Douglas, Joshua Karpen and Jason Shores "Applying VFDs to existing Motors," Processing Magazine – Feb 2017

Questions?

The Curse of Knowledge