Medium Voltage Drives in Industrial Applications

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Outline

• Introduction
• Medium Voltage Drive Topologies
  – A Brief Comparison
• Power Semiconductors
• Influence of the Semiconductor on Drives
• Influence of Topology on Power System
• A Hypothetical Drive for the Future
• Conclusion
Medium Voltage Drive Introduction

- **Voltage range**

  - Voltage range: 1 kV, 2.3 kV, 3.3 kV, 4.16 kV, 6.6 kV, 11 kV, 15 kV

- **Power Range**

  - Power Range: 0.2 MW, 0.5 MW, 1 MW, 2 MW, 4 MW, 8 MW, 12 MW
Target Industries / Applications

**Petrochemical**
- Pipeline pumps
- Gas compressors
- Brine pumps
- Mixers / extruders
- Electrical submersible pumps
- Induced Draft Fans
- Boiler feed water pumps

**Cement**
- Kiln induced draft fans
- Forced draft fans
- Cooler baghouse fans
- Preheat tower fans
- Raw mill induced draft fans
- Kiln gas fans
- Cooler exhaust fans
- Seperator fans
- Baghouse fans

**Forest Products**
- Fan pumps
- Induced draft fans
- Boiler feed water pumps
- Pulpers
- Refiners
- Kiln drives
- Line shafts

**Water / Waste Water**
- Raw sewage pumps
- Bio-roughing tower pumps
- Treatment pumps
- Freshwater pumps

**Mining & Metals**
- Slurry pumps
- Ventilation fans
- De-scaling pumps
- Conveyors
- Baghouse fans
- Cyclone feed pumps

**Electric Power**
- Feed water pumps
- Induced draft fans
- Forced draft fans
- Baghouse fans
- Effluent pumps
- Compressors

**Miscellaneous**
- Test stands
- Wind tunnels
- Agitators
- Rubber mixers
Medium Voltage Basic Topologies

Current Source Inverter

Voltage Source Inverter
Medium Voltage Topology Summary

MV Industrial Drives

- Series connection of LV Modules
  - Cascaded H-Bridge

- HV Devices
  - Current Source
    - PWM Rectifier - PWM CSI
    - 12/18P - PWM CSI
  - Voltage Source
    - 2 Level
    - 3 Level (NPC)
    - 5 Level
Current Source Inverter

- Inverter GCT based
- PWM Rectifier (AFE) GCT based
  - 6, 12, 18, or 24 pulse phase controlled thyristor
- Converter voltage capability increased by placing devices in series
2 Level Voltage Inverter

- Inverter IGBT based
- 6, 12, 18, or 24 pulse diode rectifier
  - PWM Rectifier (AFE)
- Converter voltage capability increased by placing devices in series
3 Level Voltage Inverter

- Inverter GCT or IGBT based
- 12, or 24 pulse diode rectifiers
  - PWM Rectifier (AFE) with GCTs or IGBTs
- Converter voltage capability is 4.16 kV. For greater voltage series devices are required doubling number of devices in the inverter
Cascaded H Bridge with LV IGBTs

- Inverter LV IGBT based
- Diode 6 pulse rectifiers fed from a minimum of 9 windings
- Converter voltage capability is increased by adding a set of 3 secondary windings and H-Bridge modules
Cascaded H Bridge with HV IGBTs

- Inverter HV IGBT based
- Diode 6 pulse rectifiers fed from a minimum of 12 windings
- Converter voltage capability is increased by greater secondary winding voltage and higher voltage Diodes & IGBTs
Medium Voltage Topology Summary

MV Industrial Drives

Series combination of LV Modules

- Cascaded H-Bridge

HV Devices

Current Source
- PWM Rectifier - PWM CSI
- 12/18P - PWM CSI

Voltage Source
- 2 Level
- 3 Level (NPC)
- 5 Level

Indicates the technology is still evolving!
## Performance Comparison

### Load Types

- **80% Variable Torque**
  - Medium Performance
  - < 10 rad/sec
- **18% Constant Torque**
  - Mean Performance
  - < 10 rad/sec
- **2% High Performance**
  - Low Performance
  - < 5 rad/sec
- **80% Variable Torque**
  - Low Performance
  - < 5 rad/sec

### Typical Performance Criteria Values

<table>
<thead>
<tr>
<th></th>
<th>Speed Regulation</th>
<th>Speed Regulator</th>
<th>Speed Range</th>
<th>VFD Efficiency</th>
<th>Regeneration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Open Loop</td>
<td>Close loop</td>
<td>Bandwidth</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CSIPWM-GTO</td>
<td>0.5%</td>
<td>0.1%</td>
<td>&lt; 10 rad/s</td>
<td>0-75 Hz</td>
<td>&gt;97</td>
</tr>
<tr>
<td>CSIPWM-SGCT</td>
<td>0.5%</td>
<td>&lt;0.1%</td>
<td>&lt; 20 rad/s</td>
<td>0-75 Hz</td>
<td>&gt;97</td>
</tr>
<tr>
<td>3Level-IGCT</td>
<td>0.5%</td>
<td>0.01%</td>
<td>Approx. 50 rad/s</td>
<td>0-66Hz</td>
<td>&gt;97</td>
</tr>
<tr>
<td>3Level-IGBT</td>
<td>0.5%</td>
<td>0.01%</td>
<td>Approx. 50 rad/s</td>
<td>150Hz at 4 kV 66 Hz at 6.6 kV</td>
<td>&gt;97</td>
</tr>
<tr>
<td>Series H-Bridge</td>
<td>0.5%</td>
<td>0.1%</td>
<td>Unknown</td>
<td>0-120 Hz</td>
<td>&gt;97</td>
</tr>
</tbody>
</table>
• Numerous reasons for reduction in complexity of system and component count
  – general increase in reliability
  – possibly reduce the number of spare parts required
  – possibly eliminate the need for costly entire cell replacement

• Ideally reduce complexity with the elimination of the multi winding transformer
  – presently only the PWMCSI is known to achieve this
## Component Count

### Rectifier Component Count for Transformerless

**4160 V, 750kW drive IEEE519-1992**

<table>
<thead>
<tr>
<th>Component</th>
<th>PWMCSI-GTO</th>
<th>PWMCSI-SGCT</th>
<th>2-Level IGBT Not Available</th>
<th>3-Level IGCT Not Available</th>
<th>3-Level IGBT Not Available</th>
<th>Series H Bridge Not Available</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectifier Semi-</td>
<td>-</td>
<td>12- 6.5 kV</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Conductors</td>
<td></td>
<td>SGCTs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rectifier Snubber</td>
<td>-</td>
<td>12 RC</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>


## Rectifier Component Count for 4160 V, 750kW drive with isolation transformer meeting IEEE519-1992 Isc/Il<20

<table>
<thead>
<tr>
<th>Component Type</th>
<th>PWMCSI-GTO 18p</th>
<th>PWMCSI-SGCT 18p</th>
<th>2-Level IGBT 18p</th>
<th>3-Level IGCT 24p</th>
<th>3-Level IGBT 24p</th>
<th>Series H Bridge 24p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer</td>
<td>1 primary 3 secondaries</td>
<td>1 primary 3 secondaries</td>
<td>1 primary 3 secondaries</td>
<td>1 primary 4 secondaries</td>
<td>1 primary 4 secondaries</td>
<td>1 primary 12 secondaries</td>
</tr>
<tr>
<td>Rectifier Semiconductors</td>
<td>18 thyristors</td>
<td>18 thyristors</td>
<td>18 diodes</td>
<td>24 diodes</td>
<td>24 diodes</td>
<td>72 diodes</td>
</tr>
<tr>
<td>Rectifier Snubber</td>
<td>18 RC</td>
<td>18 RC</td>
<td>Not required</td>
<td>Not required</td>
<td>Not required</td>
<td>Not required</td>
</tr>
</tbody>
</table>
## Component Count Cont’d

### DC Link & Inverter Component Count for 4160 V, 750kW

<table>
<thead>
<tr>
<th>Component</th>
<th>PWMCSI-GTO 18p</th>
<th>PWMCSI-SGCT 18p</th>
<th>2-Level IGBT 18p</th>
<th>3-Level IGCT 24p</th>
<th>3-Level IGBT 24p</th>
<th>Series H Bridge 24p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charging circuitry</td>
<td>Not required</td>
<td>Not required</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1 per cell</td>
</tr>
<tr>
<td>DC link</td>
<td>1, 0.6 per unit inductor</td>
<td>1, 0.4 per unit inductor</td>
<td>Oil Film, 4-0.5pu</td>
<td>Oil Film, 4-0.5pu</td>
<td>Oil Film, 4-0.5pu</td>
<td>180 electrolytic capacitors @ 6300uF</td>
</tr>
<tr>
<td>DC link Voltage sharing networks</td>
<td>Not Required</td>
<td>Not Required</td>
<td>Internal to capacitors</td>
<td>Internal to capacitors</td>
<td>Internal to capacitors</td>
<td>36 sharing resistors</td>
</tr>
<tr>
<td>DC Link Fusing</td>
<td>Not required</td>
<td>Not required</td>
<td>Normally not required</td>
<td>Yes or IGCTs</td>
<td>Normally not required</td>
<td>Normally not required</td>
</tr>
<tr>
<td>Inverter Semiconductors</td>
<td>12-6500 V GTOs</td>
<td>12 6500 V SGCTs</td>
<td>24-3300 V IGBTs</td>
<td>12-5500V IGBTs</td>
<td>24-3300 V IGBTs</td>
<td>48-1400V IGBTs</td>
</tr>
<tr>
<td>Neutral Point Clamping network</td>
<td>Not Required</td>
<td>Not Required</td>
<td>Not Required</td>
<td>6-diodes</td>
<td>6-diodes or 12-3300 V IGBTs</td>
<td>Not Required</td>
</tr>
<tr>
<td>Snubber for inverter</td>
<td>12-RCD</td>
<td>12-RC</td>
<td>Not Required</td>
<td>Clamp snubber</td>
<td>May not be required depends on layout</td>
<td>Not Required</td>
</tr>
<tr>
<td>Output filter</td>
<td>0.4-0.6 per unit capacitor</td>
<td>0.25-0.35 per unit capacitor</td>
<td>LC output filter (fres=5-6pu)</td>
<td>LC output filter (fres=7-8pu)</td>
<td>LC output filter (fres=7-8pu)</td>
<td>Not Implemented</td>
</tr>
<tr>
<td></td>
<td>L =0.1 pu</td>
<td>L=0.1 pu</td>
<td>L=0.1pu</td>
<td>L=0.1pu</td>
<td>L=0.2pu</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C = 0.3 pu</td>
<td>C=0.2 pu</td>
<td>C=0.2pu</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Loss & Efficiency Estimation

• System efficiency greatly affected by:
  – semiconductor, control algorithms, fsw, selection of passive components

• Literature has numerous comparisons between the IGBT and IGCT

• All manufactures indicate a drive efficiency of >97%
  – some do not include ancillary components
    • fans, power supplies, etc..
  – Which manufacturer is more correct?
    • difficult and challenging question for the end user to answer
Simulation Results for Input Power Factor vs Load Power for Different Rectifier Options
(Variable Torque Load)
Power System Impact
Input Harmonic Performance

line current harmonics and THD

- Topology: PWMR, 24P, 18P, 12P, 6P
- Harmonics order: 5th, 7th, 11th, 13th, 17th, 19th, 23rd, 25th, 29th
- THD:
  - 0.0%
  - 5.0%
  - 10.0%
  - 15.0%
  - 20.0%
  - 25.0%
  - 30.0%
Output Impact
Motor Voltage and Current Harmonics

THDI
THDV
Power Semiconductor Devices in MV Drives

- Wide variety of devices are used
  - Low voltage devices
    - IGBTs up to 1700 V
  - High voltage devices 3.3 kV to 6.5 kV
    - GCTs (symmetric, asymmetric, reverse conducting)
    - IGBTs
    - State of the art IGBTs 6500 V, 600 A
    - State of the art GCT 6500 V, 6000A
      - 10 kV devices have been demonstrated
- New device technology (e.g. SiC) would have a significant impact in consolidating the offerings or perhaps enabling a new MV topology

Device technology has yet to force a standard topology as in low voltage drives.
Symmetrical Gate Commutated Thyristor (SGCT)

- Modified GTO with integrated gate drive
- Gate drive close to the device creates low inductance path
  - more efficient and uniform gating
- Low conduction & switching losses
- Low failure rate
  - 100 failures per billion hours operation
- Double sided cooling
- Non rupture failure mode
Patented* Power Cage

- Houses main power components
- Compact, modular package
- Common design for rectifier & inverter modules
4160 Volt PWM Rectifier
Conclusions

• There is a diverse approach by industry
• Each of the topologies presented meet the performance requirements of a majority of the applications in industry
• Higher voltage semiconductors inherently reduce overall component count and system complexity
  – can eliminate the isolation transformer on CSI PWM rectifiers
• Higher voltage semiconductor costs have an advantage over low voltage devices. The (S)(I)GCT technology is presently very cost effective
• IEEE519 can be met with 18, 24, and PWM rectifiers
• The power factor for CSI PWM rectifiers can be held close to unity throughout the load range
A Medium Voltage Drive for the Future

• What should we expect from this future drive?
  – Competitive pricing
  – Greater ease of installation, operation and maintenance
  – Greater reliability

• We should expect to continue to see (for the next 3 to 5 years) MV drives with ‘standard’ stages of rectification, DC energy storage and inversion
  – It is unlikely that a different methodology will displace the ‘traditional’ approach used today

We must strive for greater simplicity and functionality!
Possible Alternative Device

- Bi-directional device
  - Using RB-IGBT technology can lead to the matrix converter

It remains to be seen if this is commercially viable at low voltage!
The Drive Layout

MV Drive System/Structure for the Future 3-5 years out 2007 - 2010

Input
- 3 cables in
- Standard cables
- Line current/voltage meet standards/guidelines

Rectifier
- Active rectifier
  - Control power factor to near unity
  - Provide active damping/clamping for oscillations/transients
  - Regenerative
- 6-device structure
- Line impedance, not necessarily transformer

DC Link
- Single to few components designed for the life of drive
- Optimize/minimize stage

Inverter
- Active Inverter
  - Provide low THD to motor
  - Provide damping/clamping for oscillations/transients
  - 6 device structure
  - Mitigate neutral to ground voltage

Output
- 3 cables out
- Standard cables
- Motor current/voltage facilitate standard motor design
- Cable length limited only due to voltage drop
• 3 cables in to drive
• Cables are to be standard
• Line current/voltage meet harmonic standard/guide lines
• Input impedance should be minimal with out the need to isolate the drive from the power system (no transformer)
• ‘Active’ line converter providing:
  – Harmonic mitigation
  – Power factor near unity through the load range
  – Capable of damping/clamping any system oscillation or transient
  – Regeneration
• 6 device line converter for voltages in the 4.16 kV to 6.6 kV
• Device would be self-powered identical to that used in the inverter
• Consist of a single to a few parts designed for life of the drive system
• No snubber or clamp assisting the operation of the converter devices
• 6 device machine converter for voltages in the 4.16 kV to 6.6 kV
• Device would be self-powered identical to that used in the rectifier
• Output voltage and current would be near sinusoidal eliminating issues with dv/dt, and wave reflection due to cable length
• Actively damp / clamp oscillations or transients
• Mitigate neutral to ground voltage concerns on the motor
• 3 cables from the output of the drive to the motor
• The output voltage/current waveforms allow for the use of standard motor designs
• Cable length from drive to the motor is ‘unlimited’
- The inverter waveform quality would result in **no** need for:
  - Inverter duty designs
  - Added insulation due to neutral to ground offset voltage
  - De-rating of existing standard machines while running on MV drives
Software based algorithms characterizing systems will decline in favor of adaptive controllers making knowledge of the system less critical.

More prognostic capability which will reduce the potential for unexpected down time.
Conclusion

- A summary of the MV topologies has been given
- A summary of the power semiconductors and their influence on topologies described
- A hypothetical drive for the near term described
- A significant advancement in power device technology will be the key to greater simplicity and functionality