AC IGBT DRIVE SYSTEM
for
Conventional Draglines
(New Machine and/or Electrical Upgrade)

Mark Johnston
Contel™  

Walter Koellner
Siemens
History of Innovation

A Tradition of Proven Performance
Industry Trends Towards AC Drives

**Mining**
- AC Drive Trucks
- Ball Mills
- Electric Rope Shovels (*not just Bucyrus*)
- Large Draglines
- Winders

**Other Industries**
- Paper, steel, transportation, machine tools, etc. (*Basically all industry.*)

*Note:*
1. No new M-G sets are being installed in any other industry.
2. Australia - moving at a fast pace with
   a) The first full AC Conventional 8750 Dragline and
   b) The first AC Conventional 8200 Hoist and Drag Helper Drives
DC to AC Evolution in Mining
(20th Century)

1920’s Ward-Leonard Generator DC drives introduced on Shovels & Draglines.

1970’s General Industry starts migration to AC drives.

1976 Bucyrus forms alliance with Siemens for AC drive development.

1980 Bucyrus introduces analog SCR AC drives - shovels and small draglines.


1999 Bucyrus & Siemens design next generation of AC Drives utilizing AC IGBT/AFE technology - shovels and large dragline swing

Mines typically liked the move to AC for production, but, complexity and reliability of the AC analog and GTO drives were of real concern.
DC to AC Evolution in Mining (21st Century)

1999-2006 Bucyrus sells AC IGBT/AFE drives for 495BII, HD, HR & HF shovels and large dragline swing - 2570WS.

2003 Bucyrus & Siemens develop first all AC IGBT/AFE gearless drive system using Synchronous Motors for Hoist and Drag - large draglines.

2004 Bucyrus sells first AC IGBT/AFE gearless 8750 dragline (start up due late 2006).

2006 Bucyrus & Siemens develop new AC drive motor (same motor for all motions - BI 348) in conjunction with existing AC IGBT/AFE technology for use with conventional gearing - small and large draglines.

2006 Bucyrus sells first AC IGBT/AFE Conventional 8750 Dragline to Lake Lindsay in Australia

AC IGBT/AFE technology has given mining excavators simplicity, reliability, performance and production benefits required to move into the 21st century.
Dragline Electrical Systems
Available through Bucyrus Today

1. DC Ward-Leonard.
   - new machine.
   - upgrade for all motions.
   - upgrade for individual motions.
   - helper drive upgrade - Static DC.

2. AC IGBT/AFE Gearless.
   - new machine.
   - upgrade for hoist and drag.

3. AC IGBT/AFE with Conventional Gearing.
   - new machine.
   - upgrade for all motions.
   - helper drive upgrades for DC Ward-Leonard.
Dragline Electrical Systems

Efficiency

74% overall system efficiency for DC Ward-Leonard.

89% overall system efficiency for AC IGBT/AFE Gearless.

85% overall system efficiency for AC IGBT/AFE Conventional.

Save $2.25M (US) to $3.75M (US) in power / 10 years.

Higher losses in DC = more heat production.

The energy saved could power a 495HR for free!
1. DC Ward-Leonard

Typically consists of:

Motor-Generator sets containing:
- Synchronous motors.
- Generators of various sizes.

DC motors of various sizes.

Rotating and/or static exciters (SCR).

Carbon brushes.

Multiple, large, mostly non-interchangeable parts inventory.
DC Ward-Leonard

Big Muskie
2. AC IGBT/AFE Gearless

Typically consists of:

Multiple skids.
AFE technology.
IGBT devices as used with shovel systems (*unprecedented reliability*).
Water-cooled heatsinks (*reliable technology from transportation systems*).
Synchronous motors for hoist and drag.
Swing and propel motors as used with shovels.
Full System Remote diagnostics.

1. Multiple common and interchangeable IGBT and AFE parts.
AC IGBT/AFE Gearless

8750 AC Layout (Zhungeer machine)

- Horizontal and/or Vertical AC Motors for Swing and Walk
- Synch Motors for Hoist and Drag
- IGBT Skids

 заболевания
AC IGBT/AFE Gearless

Synchronous Motor - Hoist or Drag

Motor blowers
AC IGBT/AFE Gearless
Zhungeer Update

8750 scheduled for late 2006 operation.

360 ft. (110 m) boom

Full AC IGBT/AFE
- Hoist  1 x 13,000 HP
- Drag   1 x 13,000 HP
- Swing  6 x 1,250 HP
- Walk   4 x 1,150 HP
AC IGBT/AFE Gearless
Zhungeer Update

Lowering top half of hoist motor.
AC IGBT/AFE Gearless
Zhungeer Erection Site
AC IGBT/AFE Gearless
Zhungeer Erection Site
AC IGBT/AFE Gearless
Zhungeer Erection Site
3. AC IGBT/AFE Conventional

Typically consists of:

- Multiple skids.
- AFE technology.
- IGBT devices as used with shovel systems (*unprecedented reliability*).
- Water-cooled heatsinks (*reliable technology from transportation systems*).
- BL 348 drive motor - same motor for hoist, drag, swing and walk. Can be mounted vertically or horizontally. (*Reliable technology from off-highway systems*).
- Full System Remote diagnostics.

1. Multiple common and interchangeable IGBT and AFE parts.
2. Interchangeable motors for horizontal and vertical operation.
AC IGBT/AFE Conventional
New Dragline

Each new dragline is designed to effectively maximize productivity, to meet customer specifications.

The recently sold Lake Lindsay 8750 (Anglo) new deck layout compliments the AC Conventional package which includes the Water Cooled IGBT Skids along with the new BI348 AC Motors.

Mechanical engineers are presently designing new gearcases to effectively take advantage of the full system capability of the AC IGBT/AFE conventional package.
AC IGBT/AFE Conventional
New Lake Lindsay 8750

MEDIA RELEASE

20 October 2006

Dragline ordered for Lake Lindsay Project

Anglo Coal Australia (ACA) has placed an order for a Bucyrus 8750 electric walking dragline for the Lake Lindsay project in Central Queensland. Lake Lindsay is a significant project increasing ACA’s coal production and product range.

Bruce Patrick, Lake Lindsay Project Manager said the Bucyrus 8750 AC was selected following a detailed evaluation of more than twenty different combinations of dragline types and configurations.

“This dragline will be Australia’s first Alternating Current (AC) dragline and the world’s first AC gearbox driven dragline and has significant structural, operating, maintenance and safety improvement innovations.

“The advantage of using AC drives is improved power efficiency, as AC drives use less power to do the same job.”

“The AC option with fewer components and modular design will require less maintenance, leading to reduced maintenance downtime,” said Bruce.

The dragline will be erected on site at Lake Lindsay near Middlemount, with the site crew commencing work in March 2007 and with commissioning in September 2008.

The Bucyrus 8750 dragline will:
- Include more than 28,000 kW of installed motor power
- Weigh in at over 5600 tons
- Walk itself around the pit using two shoes each more than 21m long and 4m wide
- Dig to a depth of more than 50m and dump spoil more than 50m high into the air
- Features a boom of over 109m in length
AC IGBT/AFE Conventional
New Lake Lindsay 8750

26 Identical Motors
(B1 348)
AC IGBT/AFE Conventional
Upgraded Dragline

Each dragline that is considered for an AC Electrical Upgrade, will be fully analyzed to determine the machines maximum potential productivity increase.

The assessment will include review of current dragline productivity, installed electric capability and additional mechanical enhancements that could be included, such as increased suspended load, which will allow us to take full advantage of the AC IGBT/AFE system and BI 348 motor with it’s increased capability and still operate the machine within Bucyrus recommended criteria.
8750 AC Upgrade Layout

- Motion Transformer
- IGBT Skids
- 24 Common Drive Motors
- IGBT Skids
- Motion Transformer
AC IGBT/AFE Conventional
8200 AC Upgrade Layout

- Motion Transformer
- IGBT Skids
- Motion Transformer
- 15 Common Drive Motors
AC IGBT/AFE Conventional
1370W AC Upgrade Layout

16 Common Drive Motors

IGBT Skids

Motion Transformer
**AC IGBT/AFE Conventional**

Example of 1370W Repowering Options

<table>
<thead>
<tr>
<th></th>
<th>1370W (Existing)</th>
<th>1370W (DC Upgrade)</th>
<th>1370W (AC Upgrade)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hoist</td>
<td>4x1045HP</td>
<td>4x1430HP</td>
<td>4x1650HP*</td>
</tr>
<tr>
<td>Drag</td>
<td>4x1045HP</td>
<td>4x1045HP</td>
<td>4x1650HP*</td>
</tr>
<tr>
<td>Swing</td>
<td>4x640HP</td>
<td>4x800HP</td>
<td>4x1650HP*</td>
</tr>
<tr>
<td>Walk</td>
<td>4x375HP</td>
<td>4x375HP</td>
<td>4x1650HP*</td>
</tr>
</tbody>
</table>

* Derated to suit mechanical requirements

**Note:** 1. All AC BI 348 motors are identical.
2. Machine capable of additional motors.
AC IGBT/AFE Conventional
Why Conventional?

Active Front End (AFE) using AC IGBT devices. *(Proven capability - Power factor capable of 0.8 leading).*

AC motors plug directly into existing style gearcases. *(One-style motor required, common to all motions).*

Performance / Productivity increases.

Rugged Skid design for excavator use. *(Proven reliability).*

Siemens SiBAS drive control. *(Proven reliability).*

AC IGBT devices. *(Proven reliability).*

Water-cooled technology. *(Proven technology in transportation).*

No carbon brushes. *(Reduced maintenance costs).*

Complete remote diagnostic system *(Full system capability).*
AC IGBT/AFE Conventional
Active Front End (AFE)
History and Barriers for Static Draglines

- Reliable operation but limited with respect to efficiency, productivity, maintenance and operating costs.

- Compliance with utility requirements on voltage fluctuation at the PCC and harmonics was major barrier for static DC or AC systems on large draglines.

- This can be overcome for the first time in history with AFEs (Active Front End rectifiers).
AC IGBT/AFE Conventional

Active Front End (AFE)

Active Front End Rectifiers (AFEs) provide leading Power Factor just like M-G sets before. This makes Static Dragline Drives feasible for the first time in history.
AC IGBT/AFE Conventional
Active Front End (features)

- Regenerative feedback into the line supply (four quadrant operation).
- Sinusoidal line currents; low harmonics are fed back into the line supply.
- No commutation faults when the power fails in regenerative operation.
- Line supply voltage fluctuations are compensated.
- Extremely high dynamic performance.
- Selectable power factor up to 0.8 leading.
AC IGBT/AFE Conventional
Active Front End (operation)

Three Phase Power
AC Circuit

AFE 3 Phase Diagram

Power Circuit
AC IGBT/AFE Conventional
Active Front End (operation)

Positive Half-Cycle:
Initial State: All Switches Open

AFE Single Phase Diagram #1
AC IGBT/AFE Conventional
Active Front End (operation)

Positive Half-Cycle:
Initial State: All Switches Open

S1 & S2 Close—Causing a large current flow through L1 & L2.

Line = 900 vac
= 1272 peak

AFE Single Phase Diagram #2
Positive Half-Cycle: Initial State: All Switches Open

S1 & S2 Close—Causing a large current flow through L1 & L2.

S1 & S2 Open—L1 & L2 try and maintain the current flow in the Same Direction. As the Voltage rises above 1800 volts, there is a current flow through D3 & D2.
Negative Half-Cycle:
Initial State: All Switches Open
S3 & S4 Close--Causing a large current flow through L1 & L2. The Current is in the opposite direction compared to the positive half-cycle.
S3 & S4 Open--L1 & L2 try and maintain the current flow in the same Direction. As the Voltage rises above 1800 volts, there is a current flow through D4 & D1
AC IGBT/AFE Conventional
Active Front End (operation)

Control Circuit
Motoring: The AFE supplies VARs to the line depending on the input voltage.

VAR are controlled by voltage amplitude = modulation = excitation.
AC IGBT/AFE Conventional
Active Front End (operation)

- **Staggered Operation**

In staggered mode the 24 AFE’s are synchronized with the firing pulses shifted by 1 degree (PP15, 24AFE’s=360/15/24) Result: 24x900 Hz=21.6KHz effective switching frequency and lowest THD

Control system for staggered AFES
AC IGBT/AFE Conventional
Voltage Fluctuation and Harmonic Analysis

1. Create single line diagram of distribution system with loads and convert to p.u. values for analysis.

2. Convert to Per Unit values

3. Create condensed single line diagram for analysis

4. Set voltage level at PCC to 1 (100%) with new dragline off and all other loads present

5. Study voltage fluctuation at PCC and other network points with new dragline peak motoring and generating loads
AC IGBT/AFE Conventional

Voltage Fluctuation and Harmonic Analysis

6 Define leading PF for motoring and generating loads which reduces the voltage fluctuation at PCC to 0.1% (1.001, 0.999)

7 Define THD (total harmonic distortion) created by the dragline drive system

8 Expand model with line and other capacitance's and check for resonant frequencies
AC IGBT/AFE Conventional
Voltage Fluctuation and Harmonic Analysis

To 1: Create single line diagram of distribution system and loads
AC IGBT/AFE Conventional
Voltage Fluctuation and Harmonic Analysis

To 2: Convert to Per Unit Values

kVA base = 100,000 kVA
kV base = 110 kV

To 3: Create condensed single line diagram for analysis
AC IGBT/AFE Conventional
Voltage Fluctuation and Harmonic Analysis

To 4: Set voltage level at PCC to 1 (100%) with new dragline off and all other loads present
AC IGBT/APE Conventional

Voltage Fluctuation and Harmonic Analysis

To 5. & 6: Define leading PF for motoring and generating loads which reduces the voltage fluctuation at PCC to < 1% (1.01, 0.99)

@ 22MW Motoring
pf = 0.965

V1pu = 0.9947

V5pu = 0.9961
AC IGBT/AFE Conventional

Voltage Fluctuation and Harmonic Analysis

To 5. & 6: Define leading PF for motoring and generating loads which reduces the voltage fluctuation at PCC to < 1% (1.01, 0.99)

@ 13MW Regeneration
pf = 0.985

V1pu = 0.9990
V5pu = 0.9885
AC IGBT/AFE Conventional
Voltage Fluctuation and Harmonic Analysis

To 5. & 6: Evaluate Voltage Swing at PCC over complete duty cycle

![Graph showing duty cycle and voltage fluctuation](image-url)
AC IGBT/AFE Conventional

Voltage Fluctuation and Harmonic Analysis

To 5. & 6: Evaluate Voltage Swing at PCC over complete duty cycle w/o auxiliaries

<table>
<thead>
<tr>
<th>DUTY CYCLE</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Delta</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1pu</td>
<td>1.0002</td>
<td>0.9970</td>
<td>0.0032</td>
</tr>
<tr>
<td>V5pu</td>
<td>1.0056</td>
<td>0.9940</td>
<td>0.0116</td>
</tr>
</tbody>
</table>
AC IGBT/APE Conventional Voltage Fluctuation and Harmonic Analysis

To7: THD and harmonic spectrum at primary of MPT on dragline →

Harmonic Current Spectrum and IEEE519 standard @ 22kV

THD = 1.17%
To 8: Expand model with line and other capacitances and check for resonance frequencies.
AC IGBT/AFE Conventional
Voltage Fluctuation and Harmonic Analysis

To 8: Example: 23\textsuperscript{rd} harmonic produces resonance
AC IGBT/AFE Conventional
Typical System Layout (One Skid)
AC IGBT/AFE Conventional

AFE Industry Perception

AC Draglines **cannot** regenerate excess braking energy to the supply!

**False**

AFE (active front end) technology on Bucyrus AC Draglines will allow full regenerative braking on all motions with excess power returned to the grid. Bucyrus AC Draglines will regenerate more efficiently than Ward-Leonard systems due to the inherent efficiencies of the technology. *(Less losses 85% vs 74% efficiency).*

**More Power is Returned to the Grid**
AC IGBT/AFE Conventional

AFE Industry Perception

VAR (*power factor*) control capability of synch motors far surpasses that of AC drives.

**False**

AFE (*active front end*) with its advanced control system will allow Bucyrus AC Draglines to actively control VAR flow in order to minimize flicker at the utilities Point of Common Connection (*PCC*). The Bucyrus AC Dragline AFE VAR control also significantly exceeds that of typical DC Synch Motor capability along with exceptionally faster responses to changes in load.

**Less Flicker Than DC Synch. Motor Systems**
AC IGBT/AFE Conventional

AFE Industry Perception

AC Draglines are highly susceptible to instability with incoming power voltage swings.

**False**

AFE (*active front end*) and the advanced control system allow Bucyrus AC draglines to compensate for dips and spikes with incoming power supplies from +10% to -30% of nominal supply voltage.
AC IGBT/AFE Conventional

AFE Industry Perception

AC systems create unacceptable harmonics on the power supply & additional passive supply filters are required!

False

The high switching frequency capability of the current generation of IGBTs in the AFE (active front end) allows for exceptional harmonic distortion control (THD) particularly in the critical low frequency spectrum exceeding the capability of all other static drives.
AC IGBT/AFE Conventional
Motor BI 348

AC Blower Motor

Common to all motions

Disc Brake

Hoist and Drag Motor Support Mount
AC IGBT/AFE Conventional
Motor BI 348

1,650 HP
1,400 V

Same motion motor for any size large dragline.

Dragline fleet interchange ability.
AC IGBT/AFE Conventional
Motor BI 348 Drive End

Mounting Flange

Cooling Vents
AC IGBT/AFE Conventional
Motor BI 348 Non Drive End

Cooling Vents
AC IGBT/AFE Conventional
Motor Bl 348 Rotor

Internal Tach Location
AC IGBT/AFE Conventional
Motor Internal Tach

Internal Disk

Speed Sensor
AC IGBT/AFE Conventional
Hoist / Drag Performance Increase

Increased Hoist and Drag Speeds

Higher Torque at Higher Speed
AC IGBT/AFE Conventional Swing Performance Increase

Swing Motion Comparing AC Conventional with Zhungeer (Standard AC Motors) and DC 822's

Higher Swing Speeds
Zhungeer 8750
BNI 8200
Ensham 8750
BI 348 Motor Capability
higher Torque at Higher Speed
822 max setting
AC IGBT/AFE Conventional

Typical Skid Layouts

- 3 SKIDS
- Shown Controlling:
  - AFE
  - 7 Hoist
  - 7 Drag
  - 6 Swing
AC IGBT/AFE Conventional Skid with Water-Cooled Devices

SiBAS Control

IGBT Water-Cooled Modules

PLC Customer Preference
AC IGBT/AFE Conventional Skid with Maint. Station & Test Panel

Maintenance Station

Test Panel for Field Use

NOTE: Both can be relocated to a dedicated clean room (customer’s choice).
AC IGBT/AFE Conventional
SiBAS Drive Control Rack

SiBAS “Transportation Grade” digital control with military spec. components for low-temperature applications.

Same control cards for AFE and inverter.

Digital communication bus.

Parameter selectable machine adjustments.

Proven reliability with mining shovels.
AC IGBT/AFE Conventional

IGBT Device Reliability

IGBT's (Insulated Gate Bipolar Transistor) used as power switches.

Transistor needs only low power gating signal to turn on and off.

IGBT: 3300 V, 1200 amp
motor voltage: 1400 V

Same IGBT power modules for Active Front End (AFE) and inverter with "plug-in" design.

Proven reliability with mining shovels.
AC IGBT/AFE Conventional

IGBT Device Reliability

IGBT's utilize simple, reliable, gate drivers without snubbers and di/dt reactors

IGBT's can safely turn-off overload currents without damage (GTO's fail if overloaded even momentarily)

High switching frequency means smoother currents

Water cooled or air cooled and NO Fuses
AC IGBT/AFE Conventional

IGBT Module

- Water cooling allows module to be rated at 1.5 x air cooled module
- Water-cooled IGBT Phase Module same for AFE and Inverter
AC IGBT/AFE Conventional Water-Cooled Technology

NOTE:
Water used is demineralized with special antifreeze additive (Antifrogen N).
AC IGBT/AFE Conventional Water-Cooled Technology

IGBT modules shown mounted and connected in skid.

Water-Cooled Connections
AC IGBT/AFE Conventional Water-Cooled Technology

Cabinet Housing Tank, Pump and Control
AC IGBT/AFE Conventional Water-Cooled Technology

Internal Cabinet Layout
AC IGBT/AFE Conventional Water-Cooled Technology

External Cabinet Connections
AC IGBT/AFE Conventional Water-Cooled Technology

Cooling Radiators

One fan module per skid.
AC IGBT/AFE Conventional Water-Cooled Technology

Radiators connected in circuit
AC IGBT/AFE Conventional Maintenance Savings

DC brush maintenance materials & labor
Approx. 1.5M (US$) / 10 years in brush purchases.
Approx. 10,000 utilized man hours / 10 years.
Approx. 10 tonnes of carbon brush dust / 10 years.

DC generator and motor overhauls & other maintenance
Approx. 3.75M (US$) / 10 years.

AC motors total maintenance costs
Approx. < 550K (US$) / 10 years.

Potential Savings (AC Conventional vs DC dragline)
> 4.7M (US$) over 10 years.
+ Man hours
+ Machine downtime hours.
AC IGBT/AFE Conventional Maintenance Savings

Availability / Reliability (*compared to DC Ward-Leonard*)

- Almost nil maintenance hours required on motors.
- No carbon brush replacement required.
- Less moving components (*by half*).
- No commutator wear.
- Less potential for unplanned failures (*i.e. motor flashovers*).
- No motor rebuild requirement (*50,000 hrs*).
- Less human interference & reliance on maintenance.

High Availability + Longer MTBF = Better Reliability
AC IGBT/AFE Conventional

**Complete** Remote Diagnostics

What does **Complete** mean?

Most remote packages connect to an onboard PLC that allows access to PLC software with limited drive interface. You cannot fully access and/or change drive system software and/or troubleshoot drive related issues effectively.

The AC IGBT/AFE System has a *fully integrated* onboard computer package that allows complete access to the drive application software and PLC software.

It is called: **AccessDirect™**
AC IGBT/AFE Conventional Complete Remote Diagnostics

- Access remotely from maint. office and/or from Bucyrus.
  
  Factory experts can log on to drive system from around the world for monitoring, troubleshooting and maintenance. Live video available.

- Interact with local maintenance people.
  
  During normal maintenance or troubleshooting – the system supports messaging and voice over communication.
AC IGBT/AFE Conventional
*Complete* Remote Diagnostics

- Download, upload and monitor the Drive motion software and PLC software remotely.
- Monitor and record motion data at high speed.
- XY or YT plots to determine machine performance.
- Store complete, real time, onboard data via **MIDAS** for maintenance and/or production requirements.
- Supply software updates if required and modify PLC software and Drive software, as required, for customer specific options.
AC IGBT/AFE Conventional Complete Remote Diagnostics

Software allows AccessDirect to run all functions of the Dragline maintenance PC remotely by remapping the I/O vectors (similar to “PC Anywhere”).
AC IGBT/AFE Conventional
Complete Remote Diagnostics

Availability - Reliability - Simplicity

Maintenance Office

Bucyrus Assistance
we make the earth move.