Adjustable Frequency Drive Fundamentals

- By Rick Porembiski
- Of The Sandberg Div. of Bornquist.
Why do we want to do variable speed pumping?
Flow Control

HVAC systems are designed for “worst case” situations. Most of the time they have excess capacity. Controlling flow saves energy and improves occupant comfort.
Variable Speed Pumping Applications

Variable Speed Pumping - Affinity Laws

**Affinity Laws**

\[
\begin{align*}
\text{GPM2} &= \text{GPM1} \\
\text{RPM2} &= \text{RPM1} \\
\text{HEAD2} &= \text{HEAD1} \\
\text{HP2} &= \text{HP1} \\
\end{align*}
\]

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Why Adjustable Speed?

- Energy savings
  - Secondary pumping example
Energy Requirements

Important Curves

Pump Curve
Operating Point
Control Curve
System Curve

Minimum Control Head

Flow

Pressure

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Energy Requirements

Power $\propto$ Flow x Pressure

Design load Power
Energy Requirements

2-Way Valve (Throttling)

Less power required
Energy Requirements
3-Way Valve (Bypass)

Highest power draw

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Energy Requirements
Adjustable Speed

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Power

The most savings

[Graph showing flow and pressure relationships]
Why Adjustable Speed?

- Energy savings
- System control
- Reduced maintenance
- Sound control

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Good Retrofit Candidates

- Large energy saving possibility
  - Large motors
  - Poor present efficiency
    - Flows manually throttled back
    - Malfunctioning mechanical flow modulation
    - Inefficient control methods

- Easy retrofit
  - Sensors and related equipment installed or easy to install

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How does a VFD actually work?
Converts AC to DC, then DC to AC

Rectifier

Inverter

AC

DC

AC

460 V, 60 Hz

640 V, DC

307 V, 40 Hz

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Basic Drive

Diodes Change AC to DC

Capacitors Filter the DC

Transistors Switch DC to AC

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Ruggedness and Reliability

- Dual DC Link Reactors
- Protect the drive from power line current surges
- Provide a stable power source for the motor
- Reduce power line harmonic distortion
- Reduce radio frequency noise on the power line
- Maintain high drive efficiency

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Ruggedness and Reliability

- Generously-sized DC Bus Capacitors
- Provide ride-through for short power interruptions
- Reduce radio frequency noise on the power line
- Provide a stable power source for the motor to improve motor performance and efficiency
- Allow reliable motor deceleration

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Ruggedness and Reliability

- A fast Current Sensor on each motor lead
- Protects against motor line-to-line shorts and ground faults
- Detects motor phase loss and imbalance
- Motor disconnects won’t damage the drive
- Eliminates the need for output reactors
- Provides precise control of motor operation

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Ruggedness and Reliability

- Intelligently-controlled output power
- Output switching pattern can provide full motor voltage at full speed and load
- Nearly-perfect output sine wave current provides full motor torque and reduced motor heating
- Eliminates the need to over-size the motor

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Simplicity of the User Interface

- Hand / Off / Auto keys
- Indicator lights indicate the selected function
- Plain language display
- Meters display values in actual units
- Programmable free text displays available

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Simplicity of the User Interface

- Info key provides context-sensitive help
- Scroll bars and directional keys provide easy navigation through the displays
Simplicity of the User Interface

- Clear, plain-language alarm descriptions
- No codes to look up
- Icons and status lights communicate quickly
- Info key provides troubleshooting information

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Simplicity of the User Interface

- Quick Menus key provides easy access to most common parameters
- "My personal menu" provides a customizable user menu with its own password protection
- "Function Setups" provides access to advanced features
Simplicity of the User Interface

• “Function Setups” menu guides the user through common drive functions
  – General
  – Open Loop
  – Closed Loop

• “Application Settings” provides easy access to application-specific parameters
  – Fan Functions
  – Pump Functions
  – Compressor Functions
Application-Specific Capabilities

Pumps

Compressors

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Fans - Broken Belt Detection

- No external sensors
- Reliable
  - Based on motor power, not current
  - A proof timer eliminates false indications
- Flexible actions
  - Warning
  - Trip

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Flying Start

- Synchronizes the drive to the speed of a coasting fan
- Searches for the fan’s speed in both directions
- Applies DC braking if needed
- Provides a smooth start

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Vibration Avoidance

- Avoids speed that can cause mechanical resonant vibration
- Up to four frequency bands of individual sizes
- Simple, prompted automated setup
Intelligence for Fan Applications

- Automated Resonant Speed Testing
- Simplifies the discovery and bypassing of mechanical resonant speeds in the system
- Simply start the test and press OK as vibration is detected

Press OK

resonant speeds
resonant speeds

speed

time = 3 min.

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Multiple Feedbacks

- Feedback signals from multiple locations can be used
- A unique setpoint can be applied to each feedback signal
Application Intelligence

- Four Internal PID Controllers
- Allows the drive to coordinate and control other devices in the HVAC system

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Application Intelligence

- Coordinate with the rest of the System
- Run permissive operation

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Firefighter’s Override

Firefighter’s Override can run the drive at any speed in forward or reverse.

It can be activated either by a normally open or normally closed contact from the fire panel or through the building automation system.
Firefighter’s Override

The drive can be set to switch automatically to a constant speed bypass if operation through the drive becomes impossible due to failure of the drive’s power circuitry.

The bypass will then run the motor at full speed from the power line until firefighter’s override is deactivated.
Intelligence for Fan Applications

- Fire Mode

- For stairwell pressurization, fire zone control, and smoke exhaust

- Ignores:
  - Alarms (if desired)
  - Keypad commands
  - External commands and interlocks

- Flexible control choices:
  - Constant speed
  - Variable speed
  - Controlled by a feedback
  - Forward or reverse

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Intelligence for Fan Applications

- **Motor Pre-Heater**
- For outdoor applications like cooling tower fans and condenser water pumps
- Protects against motor damage due to condensation when stopped
- Provides a controlled DC current when the motor is stopped
- Eliminates the need for separate motor heaters

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Intelligence for Pump Applications

- Closed-Loop Controller
- P-I Auto-Tuning

- Tuning the closed-loop controller of a pump system can be time consuming
- Improper tuning can result in slow response or system oscillation
- The automated P-I tuning algorithm dynamically tests the system and calculates appropriate values for Proportional Gain and Integral Time

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Application Intelligence

- **Sleep Mode**

- Drive automatically starts and stops itself based on system demand

- Control can be based on
  - Operating speed
  - System feedback
  - Sensor Less no-flow detection
  - External contact

- Saves energy

- Reduces equipment wear
Sensor Less No-Flow Detection

- Protects a pump from dead-heading without the need for external sensors
- Conversational menu directs the set-up of the system
- Compares the power draw from a pump to the no flow power draw
Sensor Less No-Flow Detection

- If power draw is low, performs the selected action
  - Sleep
  - Stage off a pump in a multiple pump system
  - Warn
  - Alarm
Other Pump-Protection Functions

- Dry pump detection
- Over-flow ("end of curve") protection
Sensor Less Control Has A Second New Meaning
Sensor Less Control

Drive can be programmed to follow the control curve basing speed on the amount of power required.

Wrong system data at time of order could result in a transducer becoming necessary to best solve the differences.
Intelligent Timekeeping

- Time Based Actions
- Independent scheduling
  - Night setback
  - Customized week day and weekend operation
  - Hourly scheduling to meet unique building demands
- Maintenance reminders
- Date/time stamping of logged entries

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Intelligent Data Acquisition

- Trending
- Energy Log
- Payback Counter

- Captures load profile and similar operational data
- Tracks energy used by the motor
- Records energy used and estimates energy cost savings

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Intelligent Control Logic

- Smart Logic Controller
- Create control sequences using:
  - Boolean arithmetic
  - Timers
  - Comparators
  - 20-step state controller

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Communication Flexibility

- Supports a wide range of serial busses
- The Building Automation System determines the serial communication protocol used, not the drive
- The drive supports common serial busses
  - BACnet MS/TP
  - LonWorks FTP* (communication card must be added)
  - Modbus RTU
  - Johnson Controls Metasys N2
  - Siemens Apogee FLN (P1)

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Power Line Harmonics –

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What are Harmonics?

- A sinusoidal waveform is a pure frequency
- All waveforms have a fundamental frequency
- Harmonics are integer multiples of the fundamental frequency
- The first harmonic is the fundamental frequency
What is Harmonic Distortion?

- Harmonic distortion results when harmonics currents are combined with a fundamental frequency.
- The resulting waveform is no longer a pure sine wave.
- Harmonic currents operate at the same time as the fundamental, but at a faster rate.
- Harmonic currents are additive, producing a “distorted” sine wave.

Fundamental = 60Hz
5th Harmonic = 300Hz

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Why are Harmonics a concern?

- Overheating of power distribution transformers
- Overheating of conductors, especially neutral wiring
- Overheating of induction motors
- Torque reduction of induction motors
- Overheating of power factor correction capacitors
- Nuisance tripping of circuit breakers
- Blown fuses
Why are Harmonics a concern?

• Sensitive electronic equipment
  - Communication
  - Medical
  - Security
  ● Research
  ● Computer
  ● Airport electronics

• Stand-by generators
What Causes Harmonics?

- NON-LINEAR LOADS - Loads which do not draw sinusoidal current from the line
  - Non-incandescent lighting
  - Computers
  - Uninterruptible power supplies
  - Telecommunications equipment
  - Copy machines
  - Battery chargers
  - Electronic variable speed drives

- Any load with an AC to DC power converter
For a typical 6 pulse inverter, these multiples are:

- Fundamental = 60 Hz
- 5th Harmonic = 60 x 5 = 300 Hz
- 7th Harmonic = 60 x 7 = 420 Hz
- 11th Harmonic = 60 x 11 = 660 Hz
- 13th Harmonic = 60 x 13 = 780 Hz
- 17th Harmonic = 60 x 17 = 1,020 Hz
One Drive in Different Buildings

“Strong” Power Line
- Total harmonic voltage distortion 1.1%

“Weak” Power Line
- Total harmonic voltage distortion 5.1%

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 IEEE 519-1992

- Designed to protect the utility power grid
- Measured at the “Point of Common Coupling” (PCC)
  - “This recommendation ... focuses on the **Point of Common Coupling (PCC)** with the consumer-utility interface. ... some harmonic effects are unavoidable at some points in the system.” *(IEEE Std 519-1992, sec. 10.1)*
- The **PCC** is *not* at the wiring to an individual device
How Do Drive Manufactures Address Harmonics

- Some just ignore the problem
- Build in DC link reactors
- Built in line reactors
- Build special 12 and 18 pulse drives
- Optional separate filters

*Product Selection Goal: Select products that give you performance without excess cost*
Harmonic Reduction: DC Link Reactors

Generally a standard part of the drive; not an option.
DC-link Reactors

DC-link reactors limit harmonic distortion on the power line, reducing RMS input current by more than 40% compared to drives without input reactors.
Harmonic Reduction: AC Line Reactors

Often used when the drive has no built-in filtering

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AC Line Reactors

AC line reactors, usually external to the drive. Often, these are optional. AC line reactors are 50% larger than the DC-link reactors. This results in significant additional heat generation and reduced efficiency.

The harmonic performance of the DC-link reactors in the drive is equal to that of a 5% AC line reactor, but without the associated voltage drop and efficiency losses.
If DC link reactors are good, won’t adding AC line reactors be even better?
DC Link + AC Line Reactors?

Typical example (from drivesmag.com)

- no reactors: 62% current distortion
- 3% DC reactor: 31% current distortion
- 3% AC reactor: 37% current distortion
- 3% DC reactor + 3% AC reactor: 28% current distortion

*Remember,* the goals are:
- Keep harmonic distortion from causing a problem
- Avoid wasting money

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Input Protection

- Standard DC link reactors
- Add-on AC line reactors

but

- NOT BOTH
  - no reactors

Remember, the goals are:
Keep harmonic distortion from causing a problem
Avoid wasting money

62% current distortion

37% current distortion

31% current distortion

28% current distortion

3% AC reactor
Isolation Transformers

- Just as with DC link reactors and AC line reactors, the impedance of an isolation transformer reduces harmonics.
Output Reactor Waveforms

Drive did not have “soft switching”

1000 V

No Reactors

With Reactors

10 Ft Motor Lead
200 V/div – vertical; 2 µs/div – horizontal

90 Ft Motor Lead

With Reactors

210 Ft Motor Lead

With Reactors

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Output dV/dt Filter Waveforms

<table>
<thead>
<tr>
<th>1000 V</th>
<th>200 V/div – vertical; 2 µs/div – horizontal</th>
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<tbody>
<tr>
<td>No Filter</td>
<td>90 Ft Motor Lead</td>
</tr>
<tr>
<td>dV/dt Filter</td>
<td>10 Ft Motor Lead</td>
</tr>
<tr>
<td>dV/dt Filter</td>
<td>210 Ft Motor Lead</td>
</tr>
</tbody>
</table>

The rate of change in voltage versus a rate of change in time. When a motor is operated under VFD power a high value of dv/dt will indicate voltage spikes and/or line disturbances.

Drive did not have “soft switching”
Active Filter

• Connects in parallel with the power line to correct harmonic distortion
12-Pulse (and Higher) Rectifier

- Theoretically eliminates the 5th and 7th harmonics
- Uses two sets of input diodes
But ...

- 12 pulse is no different than 6 pulse except unless a phase-shifting transformer is used
  - Shifts the phase of voltage applied to each rectifier
  - Might not be supplied with the drive

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Comparing All Harmonic Solutions

Current Distortion

- Active Filter AHF 005
- 18 - Pulse Rectifier
- Active Filter AHF 010
- 12 - Pulse Rectifier
- 3% DC and 3% AC
- 3% DC Link Reactor
- 3% AC Line Reactor
- No Filtering

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Review of Harmonics

- Remember, the goals are:
  - Keep harmonic distortion from causing a problem
  - Avoid wasting money
HARMONIC ANALYSIS ~ INPUT DATA FORM

![Diagram of electrical system](image)

ENTER DATA BELOW

**Client Name:**

**Project Name:**

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<th>System Setup</th>
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<td>Transformer Data</td>
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<tr>
<td>Impedance (%)</td>
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<td>Secondary volts</td>
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<th>Other Loads</th>
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<td>Linear Load power factor</td>
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<tr>
<td>Power factor correct. Cap (kVAR)</td>
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<table>
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<td>Cable Size (AWG/kCMIL)</td>
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<td>Material (cu or al)</td>
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<tr>
<td>No. Conductors / phase</td>
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<table>
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<td>P(Hp)</td>
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<tr>
<td>Qty</td>
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<tr>
<td>AC line (%)</td>
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</tbody>
</table>
Adjustable Frequency Drives and Motor Interaction

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Drive and Motor Interaction

- Audible Motor Noise
- Motor Overheating
- Motor Insulation Stress
- Motor Bearing Damage
Audible Motor Noise

- Caused by the pulses of electrical energy that the drive uses to power the motor
- The loudness depends on
  - Motor design
  - Pulse frequency
  - Motor current

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Audible Motor Noise Solutions

• Automatic Switching Frequency Modulation (ASFM)
  - When motor load is light, the switching frequency is high
    - Reduces motor noise
    - No need to make any adjustments
    - Not very effective for constant torque loads
Audible Motor Noise Solutions

- Automatic Switching Frequency Modulation (ASFM)
  - When motor load is high, the switching frequency is reduced
  - Provides full output torque
  - Sound from the driven application generally masks motor sound
  - Reduces radio frequency noise when current is high
Audible Motor Noise Solutions

- Automatic Energy Optimization (AEO)
  - Automatically senses the motor’s load and adjusts motor voltage and current to provide the required torque without over-magnetizing the motor
  - Minimizes motor current and the noise it can generate
Drive and Motor Interaction

- Audible Motor Noise
- Motor Overheating
- Motor Insulation Stress
- Motor Bearing Damage
Motor Overheating – Variable Torque

• Not a concern for variable torque applications
  - Variable torque applications require little motor current at low speed
  - A *properly adjusted* variable torque drive will not cause a motor driving a variable torque load to overheat

Fans have a minimum speed of 6 Hz with air over the motor.

Pumps have a minimum speed of 18 Hz driven by motor cooling

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Drive and Motor Interaction

- Audible Motor Noise
- Motor Overheating
- Motor Insulation Stress
- Motor Bearing Damage
Motor Insulation Stress

- Shows up first as an over current trip, ground fault trip or fuse blowing in bypass
- Motor insulation looks and smells good
- “Megger” or “Hi Pot” test shows shorting between windings or from a winding to ground
Cause of Motor Insulation Stress

- When current is switched, a coil generates a “back voltage”
- The faster the change (dV/dt), the greater the “back voltage”
- This can arc through motor insulation
Minimizing Motor Insulation Stress

- Better motor insulation
  - Standard Motor
    NEMA MG 1, Part 30:
    1000 V peak voltage,
    2 µs rise time
  - Special-Purpose Motor
    NEMA MG 1, Part 31:
    1600 V peak voltage,
    0.1 µs rise time
Minimizing Motor Insulation Stress

- Better motor insulation
- Short wire length to the motor

The longer the motor leads, the less the effect of the diodes.

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Motors that are controlled by variable frequency drives are subjected to higher stresses and losses caused by PWM voltage and become especially vulnerable to premature failure when the cable lengths between VFD and motor are long.
Slow Switching Power Components

Soft Switching IGBT

Standard IGBT

90 ft motor leads

200 V/div – vertical; 0.5 µs/div – horizontal

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Drive and Motor Interaction

- Audible Motor Noise
- Motor Overheating
- Motor Insulation Stress
- Motor Bearing Damage
Motor Bearing Damage

- This can cause a “washboard” pattern to be etched into the bearings
- Capacitive coupling can couple voltage from the stator to the rotor
- If this gets too high, voltage can discharge through the motor bearings
Motor Bearing Damage Solutions

- Reduced motor peak voltage
  - Drives which reduce motor insulation stress also reduce the possibilities of bearing damage

Why would close coupled pumps need grounding brushes? The impeller is on the shaft and has a ground path to the system fluid and piping.

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Motor Bearing Damage Solutions

- Reduced motor peak voltage
- Fewer pulses from the drive
- Insulate the bearings
  - Sleeve
  - Ceramic bearings
  - SKF InsocoatTM bearings
Motor Bearing Damage Solutions

- Reduced motor peak voltage
- Fewer pulses from the drive
- Insulate the bearings
- Ground the motor’s shaft using a brush
  - Carbon
  - Copper
  - Mercury wetted rotary contact
  - Carbon fiber

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Motor Bearing Damage Solutions

- Reduced motor peak voltage
- Fewer pulses from the drive
- Insulate the bearings
- Brush to ground the motor’s shaft
- Tighter motor manufacturing tolerances
- Conductive bearing grease
- Faraday shield inside the motor
Faraday Shield Inside The Motor
CurrentShield Technology
Motors & Drives for Cleanroom Applications

White Paper:
http://www.reliance.com/pro

Expensive and hard to come by.
Long lead times.

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What Can I Do With A VFD

**Open Loop**

VFD Receives a **Reference** 4-20mA or 0-10V signal from an outside source. (Building Controls)

**Closed Loop**

VFD Receives a 4-20mA or 0-10V signal from a **Transducer** associated with the drive creating a **Feedback** of the system conditions.
Drive operating closed loop with a pan water temperature sensor, can reduce carry away (water & chemicals) along with wasted fan energy.

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Cooling Tower Fan

Notes

- Traditional Control Methods
  - None
    - Poor efficiency
  - Staging cells in multi-cell towers
    - Poor efficiency
    - High mechanical stress
  - Dual-speed motors
    - Moderate efficiency
    - High mechanical stress

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Cooling Tower Fan Notes, continued

• Traditional Control Methods, continued
  – Continuously variable pitch fan blades
    • Good efficiency, when functioning
    • High maintenance, often don’t function

• Other Concerns
  – Wasting highly treated water
  – Audible noise
Typical Large HVAC System
Heat Transfer Section

Chiller

Secondary Hot/Chilled Water Pumps

Boiler

Primary Hot/Chilled Water Pumps

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Heat Distribution Section

Secondary Pumps

Boilers or Chillers

Automatic valves at each coil control the flow of water to the coil.

Variable flow in the secondary loop.

Constant flow in the primary loop.

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Typical Large HVAC System
Air Supply Section

Supply Fan

Return Fan

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Or Keep It Simple

On-Off Switch

Remote speed control with a 5 K Pot.

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What to look for in an HVAC Drive

- Ruggedness and Reliability
- Simplicity
- Intelligence
- Flexibility
- Consistency

Questions?

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Thank You!

By Rick Porembski
Of The Sandberg Div. of Bornquist.