VSDs and Their Effect on System Components

Lee Cline, PE | senior principal systems engineer | Trane

Lee is an engineer in the Systems Engineering Department with over 29 years experience at Trane. His career at Trane started as a factory service engineer for heavy refrigeration, helping to introduce the CVHE centrifugal chiller with electronic controls to the industry. Following that Lee was a member of the team that kicked off the microelectronic building automation and Integrated Comfort Systems controls – ICS - offering at Trane. He continues to push new unit and system control and optimization concepts into the industry. As a Systems Engineer Lee also has the opportunity to discuss HVAC system application and control with owners, engineers and contractors on a daily basis.

Lee has a Bachelors degree in Mechanical Engineering from Michigan Technological University. He is a member of ASHRAE and a Registered Professional Engineer in the State of Wisconsin.

Donald Eppelheimer, PE | senior principal applications engineer | Trane

Don has over 38 years of experience with Trane HVAC systems and their application since earning an engineering degree from Michigan State University. His expertise encompasses variable-air-volume systems and comfort cooling, with particular emphasis on direct-expansion refrigerant piping, chiller selection, chiller-plant design and control, thermal storage, and cold-air distribution. Don has served on the ASHRAE Journal review committee. He has also been a member of various ASHRAE committees, including TG/TB–Task Group for Tall Buildings, TC 9.1–Large Building Systems, and TC9.8–Large Building Applications.

W. Ryan Geister | global portfolio leader, centrifugal chillers | Trane

Ryan is Global Portfolio Leader for Centrifugal Chillers. During his 20 years with Trane, he helped develop and support Trane’s design and analysis tools, managed the systems training portion of the Trane Graduate Training Program, served as a regional sales manager and lead the product field sales support team.

Ryan has been a featured speaker for the International District Energy Association (IDEA), the American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE), the American Society of Hospital Engineers (ASHE), and the Massachusetts Energy Efficiency Partnership (formerly MAIOF). He earned a bachelor’s degree in engineering from the University of Illinois in 1995 and a master's degree in business from the University of Wisconsin in 2000.

Mick Schwedler, PE | manager, applications engineering | Trane

Mick has been involved in the development, training, and support of mechanical systems for Trane since 1982. With expertise in system optimization and control (in which he holds patents), and in chilled-water system design, Mick’s primary responsibility is to help designers properly apply Trane products and systems. To do so, he provides one-on-one support, writes technical publications, and presents seminars.

A recipient of ASHRAE’s Distinguished Service Award, Mick is the immediate past Chair of SSPC 90.1, which was responsible for writing ANSI/ASHRAE/IESNA 90.1-2007, a prerequisite for LEED. He also contributed to the ASHRAE GreenGuide and is a former member of the LEED Energy and Atmospheric Technical Advisory Group (TAG). Mick earned his mechanical engineering degree from Northwestern University and holds a master’s degree from the University of Wisconsin Solar Energy Laboratory.
VSDs and Their Effect on System Components

Variable-speed drives (VSDs) can save energy, but the savings may not equal “the cube of the speed” in every case. This ENL looks at how VSDs affect the performance of pumps, cooling-tower fans, air-handler fans, and chillers, and discusses the differences in VSD control in each of these applications.

Presenters: Lee Cline, Don Eppelheimer, Ryan Geister, Mick Schwedler

Learning Objectives:
1. Identify how adding a VSD to one component affects other components in the system and understand that it’s important to make building owners aware of these interactions
2. Summarize why energy savings from VSDs vary by application and may not correspond to the “cube of the speed”
3. Summarize how other equipment in the system is affected when a VSD is added (to a condenser water pump, for example)
4. Apply control methods that can enhance the benefits of a VSD.

Outline:
1. Welcome, Introduction
2. Fan Laws
   a) Velocity-pressure relationships
   b) Darcy-Weisbach equation
   c) System relationships
   d) Fan laws
3. Free Discharge Fans
   a) System performance
   b) Fan performance
   c) Fan speed/efficiency curves
   d) Cooling tower fans
4. Air-Handling Fans
   a) System resistance curves
   b) Fan modulation
   c) Control
5. Chilled-Water Pumps
   a) ASHRAE 90.1 requirements
   b) Chilled water system pressure drops
   c) Pump curves
   d) System design options and comparisons
   e) System control options
   f) Energy savings
6. Condenser Water Pumps
   a) Minimum allowable flow rate
   b) Pump energy consumption
   c) System interactions
   d) Effect of variable condenser water flow on components
   e) Additional effect of variable tower speed control
   f) System energy comparisons and guidance
5. Chillers
   a) A commonly misused analogy
   b) Compressor
   c) The effect of load and lift
   d) Comparative discussion
   e) Rating methods
   f) System analysis
6. Close
VSDs and Their Effect on System Components

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AIA continuing education
Learning Objectives

Participants will learn the following about varying the speed of rotating equipment:

- Varying speed theoretically affects energy consumption
- Theoretical performance doesn’t occur in most HVAC situations
- Specific applications of different fans, pumps, and chillers yield varying levels of energy efficiency

variable-speed drives (VSDs)
Today’s Topics

- Fundamentals
  - Speed and performance
  - Fan laws
- Practical application
  - Control signal options
  - Effect on energy use
Today’s Presenters

- **Don Eppelheimer**  
  applications engineer

- **Lee Cline**  
  systems marketing engineer

- **Ryan Geister**  
  manager, absorption and centrifugal chillers

---

VSDs in HVAC systems  
**Effect on Components**

- **Airside**
  - Cooling tower fans
  - Supply fans

- **Waterside**
  - Chilled water pumps (effect on chiller performance, system control)
  - Condenser water pumps (system interactions)
  - Chillers
Fundamentals: Speed, Performance, Fan Laws

VSDs and their effect on system components

e = mc²

speed of light 299,792,458 m/s
water 2 m/s
air 10–20 m/s
work = mass × resistance
Darcy-Weisbach Equation

\[ \Delta p = f \frac{L \rho V^2}{D^2 g_c} \]

Darcy-Weisbach Equation

resistance \( \alpha \) velocity\(^2\)
System Resistance

dampers

return duct

supply duct

diffusers and grilles

coil

Fan Laws

cfm $\alpha$ rpm

$\Delta p$ $\alpha$ rpm$^2$

$\alpha$ cfm$^2$

hp $\alpha$ rpm$^3$
**Chiller Laws?**

resistance ∝ velocity²

resistance ∝ “lift”

**Practical Application:** Free Discharge Fans

VSDs and their effect on system components
Free Discharge System

- Draw-through cooling tower
- Propeller fan

General Fan Performance

\[ \text{cfm} \propto \text{rpm} \]
\[ \Delta p \propto \text{rpm}^2 \]
\[ \text{hp} \propto \text{rpm}^3 \]
As fan speed varies so does airflow volume.
fan performance curves

Cooling Tower

- 1-speed motor
- 2-speed motor
- Potential energy savings

fan and motor power, %

0 20 40 60 80 100

airflow, %

0 20 40 60 80 100

fan and motor power, %

0 20 40 60 80 100

airflow, %
fan performance curves
Cooling Tower

fan and motor power, %

0 20 40 60 80 100

0 20 40 60 80 100

cooling tower application
Fan Energy Comparison

<table>
<thead>
<tr>
<th>Control strategy</th>
<th>Energy use factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-speed fan cycling (base)</td>
<td>100% kWh</td>
</tr>
<tr>
<td>2-speed fan cycling</td>
<td>39% kWh</td>
</tr>
<tr>
<td>variable-speed control</td>
<td>19% kWh</td>
</tr>
</tbody>
</table>

source: Marley Technical Report H-001A
fan/tower performance curves
Free Cooling at Low Load

Free discharge fans
Summary

- Performance approximates the “cube of the speed”
- Variable-speed drives (VSDs) are a great option for modulating capacity
- When considering VSDs for chilled water plants, start at the cooling tower
Practical Application: Ducted Indoor Fans

VSDs and their effect on system components

System Resistance

- 3,500 cfm
- 2.0 in. wg
System Resistance

\[ \Delta p = f \frac{L \rho V^2}{D^2 g_c} \]

System Resistance

- 3,500 cfm, 2.0 in. wg
- 2,000 cfm, 0.65 in. wg

Airflow vs. Static Pressure Curve
Some devices don’t obey the rules for System Resistance.

System Resistance

- Valves closed
- Valves open

Static pressure

Airflow

System resistance curve
VAV System

- Surge region
- System resistance
- Actual vs. design
- Modulation range

Fan Performance

- Blocked-tight static pressure
- 1100 rpm
- Wide-open airflow
VAV System

System resistance changes as valves modulate...

Fan Modulation

<table>
<thead>
<tr>
<th>Method</th>
<th>Design Airflow, %</th>
<th>Design Power, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>BI fan with discharge dampers</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>AF fan with inlet vanes</td>
<td>100</td>
<td>90</td>
</tr>
<tr>
<td>FC fan with discharge dampers</td>
<td>100</td>
<td>80</td>
</tr>
<tr>
<td>FC fan with inlet vanes</td>
<td>100</td>
<td>70</td>
</tr>
<tr>
<td>Fan-speed control</td>
<td>100</td>
<td>60</td>
</tr>
<tr>
<td>Vaneaxial fan with variable-pitch blades</td>
<td>100</td>
<td>50</td>
</tr>
</tbody>
</table>
fan modulation

Objectives

- Produce adequate static pressure
- Eliminate excess static pressure
- Exploit diversity
- Maximize energy savings at fan
- Provide stable control
- Keep everyone comfortable

Static Pressure Control

Insufficient static pressure?

VAV box delivers too little airflow
Static Pressure Control

Excessive static pressure?

- Wasted energy
- Poor comfort control
- Poor acoustics

Fan Control Loop

supply fan

static pressure sensor

controller
VAV System Modulation

static pressure control
Sensor at Fan Outlet
static pressure control
Sensor Down 3/4 of Duct

optimized static pressure control
Sensor at Fan Outlet

supply fan
controller
VAV boxes

static pressure setpoint
communicating BAS
VAV damper positions
static pressure
supply fan speed or inlet vane position

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static pressure control methods
Performance Comparison

<table>
<thead>
<tr>
<th>Control method</th>
<th>Airflow</th>
<th>Fan static pressure</th>
<th>Fan input power</th>
<th>Full-load power</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>24,000 cfm</td>
<td>2.7 in. wg</td>
<td>22 hp</td>
<td>100%</td>
</tr>
<tr>
<td>Fan outlet</td>
<td>18,000 cfm</td>
<td>2.1 in. wg</td>
<td>13 hp</td>
<td>60%</td>
</tr>
<tr>
<td>Supply duct</td>
<td>18,000 cfm</td>
<td>1.9 in. wg</td>
<td>12 hp</td>
<td>55%</td>
</tr>
<tr>
<td>Optimized</td>
<td>18,000 cfm</td>
<td>1.5 in. wg</td>
<td>9.5 hp</td>
<td>43%</td>
</tr>
</tbody>
</table>

Practical Application: Pumping Water

VSDs and Their Effect on System Components
why care about Pumpkin Energy

According to the DOE ...

- Pumps represent 5% of industrial energy consumption
- Total cost of owning a pump is 90% energy consumption
- Pump energy consumption generally can be reduced by as much as 20%

pumping chilled water

ASHRAE 90.1-2001

Requires variable chilled water flow if:

- Total pump power exceeds 75 hp
  AND
- System includes > 3 control valves
pumping chilled water
ASHRAE 90.1-2001

Requires 30% design wattage at 50% flow if:

- Any variable-flow pump motor ≥ 50 hp
  AND
- Design head pressure ≥ 100 ft

Typical solution: Variable-speed drive

chilled water system
Variable Primary Flow

1 750 gpm
2 750 gpm
chilled water system
Full-Load Pressure Drop

1
750 gpm

2
750 gpm

tP

ΔP

close valve

VSDs and Their Effect on System Components
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**Pumping System**

Pump & System Curves

- Pump head, %
- Water flow, %
- Design point

**Pump Characteristics**

Power

- Pump head, %
- Water flow, %
- Design point

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variable-flow water system
How Does It Unload?

Depends on:

- Chilled-water system curve
- Pump curve
- Pump control method
  - Ride the curve
  - Different pump sizes
  - Vary the speed

Ride the Curve

pump characteristics

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Part Load: Ride the Curve

Variable-flow water system

How Does It Unload?

Depends on:
- Chilled water system curve
- Pump curve
- Pump control method
  - Ride the curve
  - Different pump sizes
  - Vary the speed
**pump characteristics**

**Different Pump Sizes**

- **pump head, %**
- **water flow, %**
- **system**
- **pump power**

**VFD = Different Pumps**

- **pump head, %**
- **water flow, %**
- **system**
- **power**
- **1750 rpm**
- **1488 rpm**
- **1225 rpm**
variable-speed pump

Control Methods

- Pressure control ($\Delta P$) at pump
- Pressure control ($\Delta P$) at end of system
- Critical-valve pressure reset

chilled water system

Part Load: $\Delta P$ at Pump

1 750 gpm
2 750 gpm
variable-speed pump
Control Methods

- Pressure control (ΔP) at pump
- Pressure control (ΔP) at end of system
- Critical-valve pressure reset

chilled water system
Part Load: ΔP at End of System
variable-speed pump
Control Methods

- Pressure control at pump
- Pressure control at end of system
- Critical valve pressure reset

chilled water system
Part Load: Critical Valve Reset

1 750 gpm

valve position
Part Load: Ride the Pump Curve

What the pump needs to produce the required system pressure determines minimum pump pressure, motor speed

Part Load: ΔP Control at Pump

What the pump needs to produce the required system pressure determines minimum pump pressure, motor speed
Part Load: \( \Delta P \) Control at End of System

Pump \( \Delta P \) “slides” down the system curve...

Part Load: Critical Valve Reset

Pump \( \Delta P \) constantly reset to lowest possible value... almost all pressure drop is dynamic.
variable-flow pumping

Summary

- Energy savings depends on:
  - Pump selections
  - Fixed vs. frictional pressure components
  - Control strategy
- Energy savings can approach “cube of speed”
- Great application for variable-speed drives

variable-flow condenser water

Pump Speed

- Determining minimum speed
- How variable flow affects:
  - Pump
  - Cooling tower
  - Chiller
- Controlling flow to improve system performance
condenser water pump
Minimum Speed

Determinants:

- Minimum condenser flow
- Tower static lift
- Minimum tower flow
  - Nozzle selection
  - Performance
- Compare curve with cubic
Example

1500 gpm system, 1770 rpm

- Minimum flows:
  - Chiller: 658 gpm
  - Tower: 750 gpm
- Tower static lift: 12.2 ft
- Pump:
  - Speed: 974 rpm
  - Pump flow: 875 gpm
variable condenser-water flow

Effect on Pump

- Pump head, ft
- Capacity, gpm
- RPM

operating dependencies

Full Flow

- Tower design
- Condenser water temperature & flow
- Heat rejection
- Wet bulb
- Chiller design
- Condenser water temperature & flow
- Load
variable condenser water flow
Effect on Tower

variable condenser water flow
Effect on Chiller

Conditions:
- 70% load
- 70°F WB
- Full-speed tower fan
variable condenser water flow
Effect on System

reducing flow & fan speed
Effect on Tower
reducing flow & fan speed
Effect on System

conditions:
- 70% load
- 70°F WB
reducing flow & fan speed
Effect on System

conditions:
- 30% load
- 50°F WB

variable condenser water flow
Summary

Determine what savings, if any, are possible
- Are pumps already low power?
- Can reducing tower-fan speed achieve most of the savings?
**Summary**

If you decide to reduce flow:

- Find minimum condenser-water flow rate
- Examine system at various loads and wet-bulbs... keep chiller out of surge
- Document the sequence of operation
- Help commission the system

---

**Guidance**

- Can provide savings ...
  - Finding proper operating points requires more time, more fine-tuning
- Two-step process:
  1. Reduce design pump power
  2. Is variable condenser-water flow still warranted?
Practical Application: How VSDs Affect Chillers

VSDs and their effect on system components

VSDs and Chiller Laws

Variable-speed drives benefit centrifugal compressors in water chillers

- Review “chiller laws”
- Explore scientific cause-and-effect relationships
- Maximize benefits

\[
\text{resistance } \propto \text{velocity}^2
\]

\[
\text{resistance } \propto \text{“lift”}
\]
**VSD and centrifugal chillers**

**A Simple Analogy**

- **brake**
  - (inlet guide vanes for unloading)

- **accelerator**
  - (speed control of chiller motor)

---

**a simple analogy**

**Constant-Speed Chiller**

- **Motor runs at constant speed, regardless of load**

- **Inlet guide vanes restrict refrigerant at off-design conditions**
**a simple analogy**

**Variable-Speed Chiller**

Based on load, motor speeds up or slows down

---

**VSDs and centrifugal chillers**

**An Analogy**

In each case:

- Energy is wasted
- Mechanical wear-and-tear is increased
Lift versus Load

\[ \text{lift} \propto P_{\text{cond}} - P_{\text{evp}} \]

\[ \text{lift} \propto T_{\text{lvg cond}} - T_{\text{lvg evp}} \]

\[ \text{load} \propto \text{gpm} \times (T_{\text{lvg cond}} - T_{\text{lvg evp}}) \]

Compressor Work and Chiller Efficiency

\[ \text{compressor work} \]

\[ \text{cooling capacity/“load”} \]

500 tons

\[ \text{lvg cond water} \]

\[ \text{lvg evap water} \]

58°F
**Impeller Dynamics**

\[ V_r \propto \text{refrig flow rate} \]

\[ V_t \propto \text{rpm} \times \text{diameter} \]

- \( V_t \): Tangential velocity
- \( V_r \): Radial velocity
- \( R \): Resultant velocity
- \( \text{LOAD} \): Compressor work
- \( \text{refrigerant flow rate} \)
- \( \text{rotational speed} \)

**Compressor Response to \text{Load}**

- Full load
- Part load

VSDs and Their Effect on System Components

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Compressor Response to Lift

**Lessons Learned**

- **To reduce lift:**
  - Decrease condenser pressure by reducing leaving-tower water temperature
  - Increase evaporator pressure by raising chilled water setpoint
- **VSDs optimize chiller lift efficiency**
various system components

Energy Use

VSDs and centrifugal chillers
A Simple Analogy

But misleading and technically incorrect

brake
(inlet guide vanes for unloading)

accelerator
(speed control of chiller motor)
**VSDs and centrifugal chillers**

*A Closer Look at IPLV*

<table>
<thead>
<tr>
<th>Load</th>
<th>Weighting</th>
<th>ECWT</th>
<th>kW/Ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>0.01</td>
<td>85°F</td>
<td>0.572</td>
</tr>
<tr>
<td>75%</td>
<td>0.42</td>
<td>75°F</td>
<td>0.429</td>
</tr>
<tr>
<td>50%</td>
<td>0.45</td>
<td>65°F</td>
<td>0.324</td>
</tr>
<tr>
<td>25%</td>
<td>0.12</td>
<td>65°F</td>
<td>0.393</td>
</tr>
</tbody>
</table>

VSDs improve part-lift performance, so running two chillers with VSDs at part load *seems* more efficient than one chiller at double the same load, but ...
### VSDs and Centrifugal Chillers

#### Performance at 90% Load

<table>
<thead>
<tr>
<th>ECWT</th>
<th>2 Chillers*</th>
<th>1 Chiller</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>85°F</td>
<td>306.4</td>
<td>268.0</td>
<td>-38.4</td>
</tr>
<tr>
<td>80°F</td>
<td>268.0</td>
<td>238.0</td>
<td>-30.0</td>
</tr>
<tr>
<td>75°F</td>
<td>230.8</td>
<td>210.6</td>
<td>-20.2</td>
</tr>
<tr>
<td>70°F</td>
<td>195.2</td>
<td>185.7</td>
<td>-9.5</td>
</tr>
<tr>
<td>65°F</td>
<td>160.3</td>
<td>164.3</td>
<td>+4.3</td>
</tr>
</tbody>
</table>

Note: Data shows only chiller power. *Load equally divided

---

### VSDs and Centrifugal Chillers

#### Performance at 90% Load

**Graph:**

- **2 Chillers:** 45% load each
- **1 Chiller:** 90% load

**Conclusion:** 1 chiller uses less power than 2 chillers
Analyze the System

- **Model:**
  - Building use
  - Local weather
  - Economizers
  - Utility rates
  - System design

- Use programs like TRACE™, DOE 2.x, Chiller Plant Analyzer, HAP

VSDs and centrifugal chillers Summary

- **VFDs improve chiller part-lift performance**
  - Lots of operational hours
  - Reduced condenser water temperatures
  - Higher costs of electricity

- **IPLV is not an economic tool**
Answers to Your Questions

This concludes the American Institute of Architects Continuing Education System Program

VSDs and their effect on system components

wrap-up

VSD Effect Differs

- Cubic relationship to speed only occurs in “free discharge” systems
- Control parameters affect savings
- In chillers, external parameters define lift (pressure difference)
## VSD Effect Differs

### Cooling towers: Nearly cubic

- Depends on control strategy
- Fan pressure optimization is best

### HVAC fans: Not cubic

- Affected by valves and control method
- Consider pump pressure optimization based on critical valve

### Chilled water pumps: Not cubic

- Must meet minimum flow or pressure
  - Tower static lift
  - Minimum condenser water flow
  - Minimum tower flow
- Reduced flow affects chiller and tower performance
- Before applying a VFD, reduce pump design power (CW flow rate)
wrap-up
VSD Effect Differs

- Power for any chiller is reduced at part load and lift
- Chiller savings? Not even close to cubic
  - VFD helps more at part-lift conditions
  - MUST reduce lift for VSD to slow down and give benefit
  - Use same condenser water temperature to compare constant- and variable-speed chillers

VFDs and Gensets

Trane Engineers Newsletter volume 35-1
“How VFDs Affect Genset Sizing” by Court Nebuda

references for this broadcast

Where to Learn More

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  http://www.trane.com/enl

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