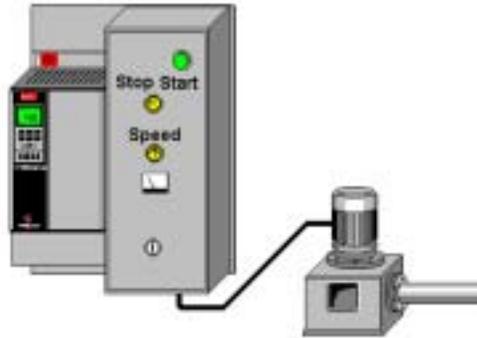**VFD 101**
Lesson 2
Control Arrangements for a VFD
Pumping Applications

This training covers the major control arrangements for a VFD, starting with the simplest arrangement then moving to the more complex.

Many of the control arrangements shown in the previous lesson (Lesson 1: Functions of an VFD) were Closed Loop Control. There can be other arrangements which are covered in detail in this lesson.

1) Local or Hand Control
2) Remote or Auto Control
3) Multi-motor
4) Master/Slave
5) Closed Loop
6) Cascade Control – Fixed Stages
7) Cascade Control – Variable Stages
8) SCADA System - Enable
9) SCADA System – Enable and Reference
10) SCADA System – Serial Communications

Note: There are other names for a VFD such as Adjustable Frequency Drive (AFD); Variable Speed Drive; Adjustable Speed Drive; Inverter and Frequency Converter. The name VFD is consistently used through out this lesson.

1) Local (Hand) Control
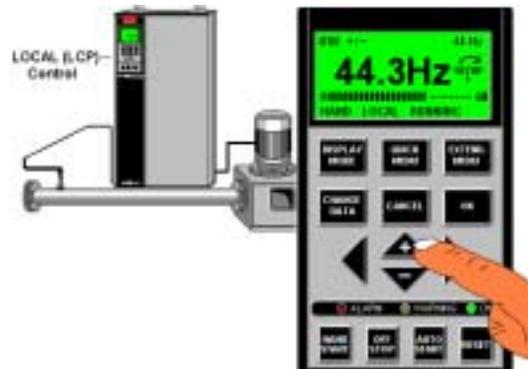
Local or Hand control means controlling the system through the keypad on the VFD.

1.   Local (Hand) Control

In the picture above, a VFD, motor and pump are operated from the keypad on the front of the drive. Local (Hand) control of the VFD means that operation of the VFD is completed strictly through the keypad on the front of the drive, or Local Control Panel (LCP). An operator monitors the readings and controls the VFD by using this keypad. Even if the keypad, LCP is remotely mounted away from the drive, maximum of 3m (10'), the control arrangement inside the program of the VFD is still considered as LOCAL. If any line is labeled as LOCAL in the program, think KEYPAD.

1) Local (Hand) Control

HAND START key starts the drive in Hand (local control) – speed set by + and - keys

OFF STOP key stops the drive locally

AUTO START key ends manual control

RESET – clears the drives from an alarm condition.

In the picture above there are 2 VFDs, each being controlled by its own LCP or keypad. The one on the right uses a remote keypad kit to place the keypad in a convenient location. The operational site on both VFDs is considered as LOCAL or HAND.

The "Hand Start" key starts the VFD, assuming safeties have been enabled. The display on the keypad changes as seen on the last page. This allows the operator to increase (+ key) or decrease (- key) the speed of the motor. Other start commands are ignored.

The "OFF Stop" key stops the drive. The display starts to flash to indicate that this key has been pressed. Other start commands are ignored. To remove this stop command, the Hand Start or Auto Start must be pressed.

The "Auto Start" key ends Local or Hand control. This means that remote controls, which are described in the pages that follow are in control.

The "Reset" key clears an alarm from the VFD, assuming that the alarm has been corrected and is set for manual reset. Some alarms require that power be removed (Disc.Mains) before they can be reset.

2) Remote Control

Remote Control

Start_Stop

Speed
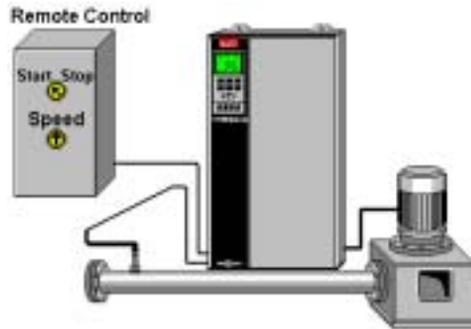
Remote signals are wired into the control section of the
VFD. They come in 4 types:
Digital Inputs (DI), Analog Inputs (AI),
Analog Outputs (AO), Digital/Relay Outputs (DO).

2.   Remote (Auto) Control

Other arrangements are possible including remote signals. If there is a problem with the pump and it must be stopped immediately, it might be time consuming to run back to the VFD to stop it. Stop switches can be placed at key positions to stop the VFD, AC motor and pump. It is important that the VFD accept these stop signals as well as other remote signals. These remote control signals come in four types:

1) Digital Inputs (DI) are 2-position (ON/OFF) signals sent into the VFD. These commands check safeties, then tell the VFD to Start, to Stop, etc. A DI requires 24Vdc which is supplied by a terminal on the drive.

2) Analog Inputs (AI) are proportional or modulating signals sent into the VFD. These commands tell the VFD what the reference speed should be or tell the VFD what a feedback signal is doing such as pressure. These signals are usually from 0-10Vdc or 4-20mA.

3) Analog Outputs (AO) are modulating signals sent by the VFD to a device such as a meter which could display feedback, speed or current.

4) Digital/Relay Outputs (DO/RO) are 2-position (ON/OFF) signals sent by the VFD to a device such as a light to indicate an Alarm, or when the feedback signal has reached a certain limit. Digital Outputs have power 24Vdc attached and Relay Outputs do not have power, which are known as "dry" contacts.

2) Remote Control
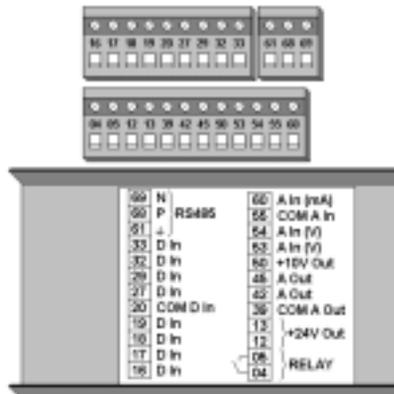
Above, connectors are shown for remote signals. These signals are divided into 4 types – Digital Inputs, Analog Inputs, Analog Outputs and Digital/Relay Outputs. The terminal numbers are listed on the cover plate shown above.

Besides stop switches, other signals can be sent into the VFD. These could be a reference pot to change the speed, increase and decrease buttons which would also change the speed, remote Start and Stop switches, or other signals. All the different options for remote signals are considered as control wiring. In the program of the drive, if the Hand keys are used, remote signal except for safeties are ignored. On the VFD shown above, all the control wiring terminals are shown on the black plastic cover just under the LCP keypad.

The amount of connections for the control wiring is a means of comparison between manufacturers of VFDs. As an example, the Danfoss drive shown above has the ability to accept the following signals:

8 – Digital Inputs

3 – Analog Inputs (2 are setup for 0-10Vdc; 1 for 0-20mA)

2 – Analog/Digital Outputs (0-20mA or 4-20mA signals or these can be programmed as Digital Outputs with 24Vdc attached)

2 – Relay Outputs (dry contacts)

3) Multi-Motor Operation
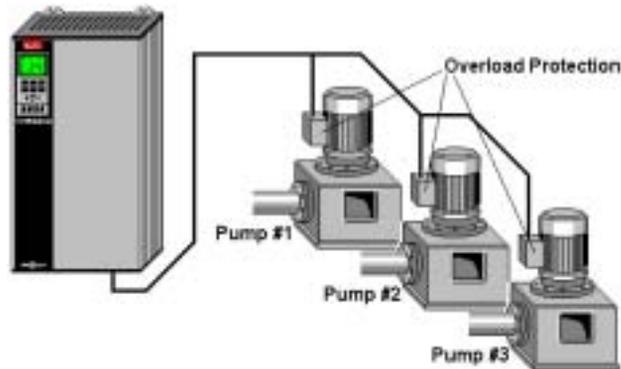
One VFD is used to operate 3 separate pumps. The VFD must be able to handle the maximum current for the 3 motors. Some features of the VFD in this arrangement are restricted.

3.   Multi-Motor Operation

The multi-motor arrangement is usually done because of strict cost considerations. Not only must the VFD have the current capacity for all the motors, but each individual motor must have overload protection. In the picture above, one VFD operates 3 AC motors, which in turn operates the 3 pumps together. They operate at the same speed or close to the same speed.

When this arrangement is used some VFD features are restricted. First the motors and pumps must all run at the same speed. Another restriction is that the VFD can not be tuned to a individual motor. Motor Tuning is where the VFD is tuned or matched to an individual motor for better performance and energy savings. The last restriction given here is that the slip compensation (calculating the difference between the field speed and rotor speed) should be set to OFF.

3) Multi-Motor Operation

Overload Protection

Motor 1   Motor 2   Motor 3
15 amps   15 amps   15 amps
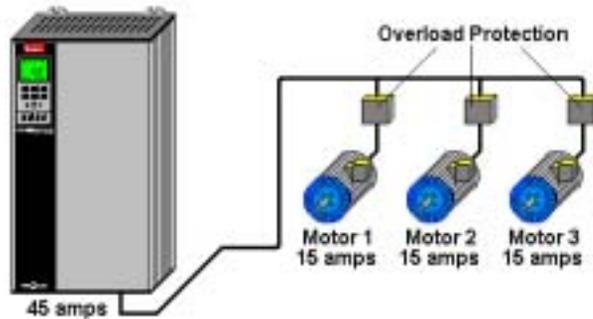
45 amps

In the example above each of the 3 AC motors is the same size and has a maximum current rating, Full Load Amps (FLA) of 15 amps. The VFD must be sized for 45 amps. Note individual overload protection on each motor.

If the pumps were operating with a very light load but motor 3 got jammed. The amp draw on motors 1 and 2, might be low, say 5 amps each, but the amp draw on motor 3 would need to surpass 35 amps before the drive saw any problem. This would cause damage to motor 3. As shown in this example, individual overload protection, such as thermal overloads are needed to protect each motor. Motors in this arrangement operate close to the same speed.

4) Master/Slave (Leader/Follower)

In the Master/Slave arrangement a Master or Lead VFD monitors the pressure sensor and operates a single pump. It sends a corresponding signal to another following pump. Features of the VFD which were restricted in the multi-motor can be used in this arrangement.

4.   Master/Slave (Leader/Follower)

This arrangement allows motors to operate closer together than in the multi-motor application. Each VFD also provides safeties for its own motor.

One VFD is selected as a Master or Leader drive. It is setup to send a reference signal and ON/OFF commands to the Slave or Follower drive. In the example above, 2 pumps are used to maintain the water pressure. The VFD operating the top pump is considered the Master or Leader. It varies its speed to match the pressure needs in water line. The bottom pump and VFD, follows the top supply pump and is known as the slave or follower. The slave can match the speed to within 0.3Hz of the master, over the operating range from about 18Hz to 60Hz.

## 4) Master/Slave (Leader/Follower) *Danfoss*
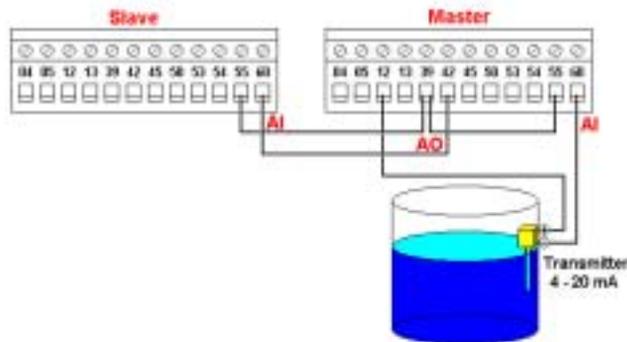
A Level sensor sends a signal to the AI (term 60) of
   the master/ leader.   Using a 4-20mA signal from
   its AO (term 42) the Master sends a signal to the AI
   of the Slave (term 60).

In the picture above, the VFD on the first pump is the Master/Leader
and it generates a reference signal for one of its analog outputs (AO). The
VFD on the second pump is the Slave/Follower, and it monitors this 4-20mA
reference signal from the master using the slave's analog input (AI).

It is possible with Danfoss drives to use a Digital Output (DO) as a
pulsed reference. The follower uses a Digital Input (DI) to follow this pulsed
reference signal. These 2 pumps must run closely together, the greatest
variance between drives using the pulsed signal is around 0.2Hz along the
entire range of frequencies (18 to 60Hz). There is a time delay in this
arrangement. The master drive starts going to its reference before it sends
the signal to the slave drive. Usually this delay is very small, in milliseconds,
and of no consequence in this application.

5) Closed Loop/PID Control
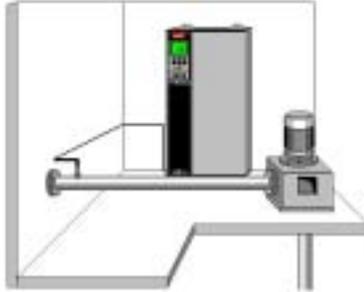
This arrangement has been seen already, but needs additional explanation. A 4-20mA pressure transmitter is wired directly into the VFD. This is a Feedback signal and is always referred to as Closed Loop. The VFD monitors its own signal and result.

5. Closed Loop/PID Control

Up to this point most of the previous control arrangements have been closed loop, which means that there is feedback signal monitoring the controlled variable, going directly to the VFD. Closed Loop is used for stand alone control. In the example above, the VFD monitors the signal coming from the 4-20mA pressure sensor in the water line.

In all closed loop applications, additional parameters must be programmed. These include a setpoint, and PID settings. In this application, the VFD is constantly comparing the pressure setpoint, 80psi, (550kPa) with the actual feedback value coming from the pressure transmitter. The VFD modulates the speed of the supply pump to maintain that pressure.

Controller action is one of the parameters that must be checked in the VFD. There are 2 selections which are as follows:

Normal Control (Reverse Acting) which increases the speed of the pump when the signal decreases from the pressure sensor, as in the example above.

Inverse Control (Direct Acting) increases the speed of the pump when the signal increases from the sensor.

5) Closed Loop/PID Control
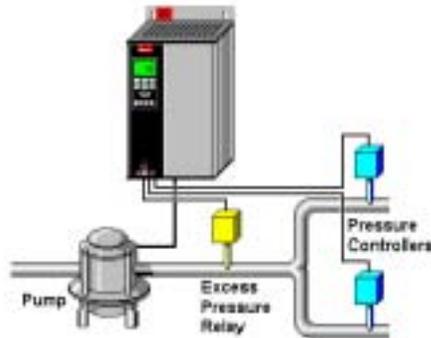
In the picture above, Pressure in the water supply is maintained by modulating the speed of the pump. Proportional gain, and integral settings must be setup in the VFD, along with a setpoint, feedback signal choice and proper controller action.

There is always a difference between the setpoint and the actual feedback pressure. This is referred to as Offset,"off the setpoint" or error. PID settings attempt to reduce this error. "P" stands for Proportional Gain which can be considered as a multiplier of the error. The higher the gain the more accurate, but if it is set too high, the control can become unstable and jittery. With too high of a gain setting, the VFD oscillates between maximum speed and minimum speed, "hunting" for the correct speed. The gain must be high enough to be sensitive but not too high to cause hunting. Each application is different, but a proper starting setting for pumps is 4.0 and 2.0 for fans.

"I" stands for Integral which looks at the error over a certain amount of time. The lower the number the more frequently it checks the error. If the I setting is too low, the motor again appears to be hunting. SCADAed on most applications, a pump has its I setting for 20 seconds and 30 seconds for fans.

"D" stands for derivative which, if used, compensates for momentary changes in the load. In most water applications, this parameter is not used, keeping it OFF.

6) Cascade Control Card – Fixed Stages
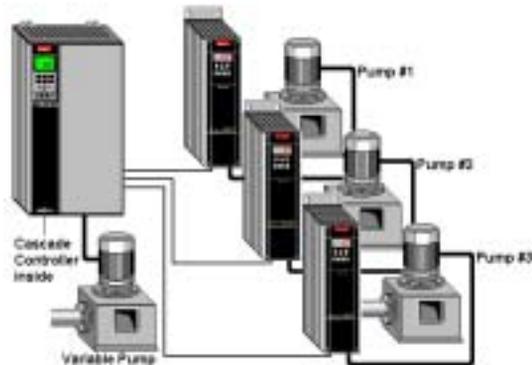
There are occasions where a group of pumps or fans must work together. There is an optional Cascade Card that may be placed inside the VFD. This card operates up to a maximum of 5 motors together.

6.   Cascade Control Card – Fixed Stages

There are some applications where multiple pumps or fans must operate together. It is desired to only operate the number of pumps necessary to achieve the load requirements, keeping other pumps off to save energy. A separate Cascade Controller card which can be mounted inside the VFD, can be used to coordinate the operation of up to a maximum of 5 pumps. One way to operate these pumps is to have the first pump be varied by the VFD and the fixed stages using soft starts. When it reaches 100% output, a fixed stage is started. Each time the 1st pump reaches 100%, another stage is enabled.

In the example above, the variable pump is the first pump to start. When this variable pump goes to 100% or 60Hz, a relay on the Cascade Card is enabled which starts a soft-starter on Pump #1. Since soft-starters do not modulate, pump #1 goes to 60Hz. The variable pump then drops its output. When the load requires more output, and the variable pump again reaches 100% then the soft-starter on Pump #2 is enabled.
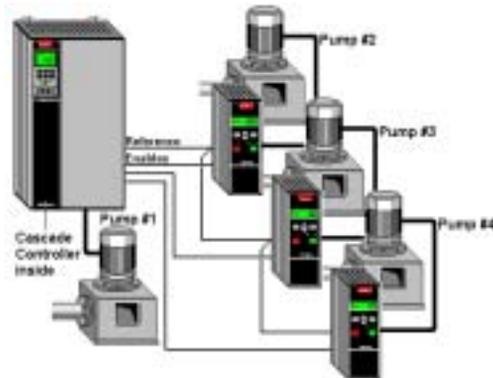
6) Cascade Control Card – Fixed Stages
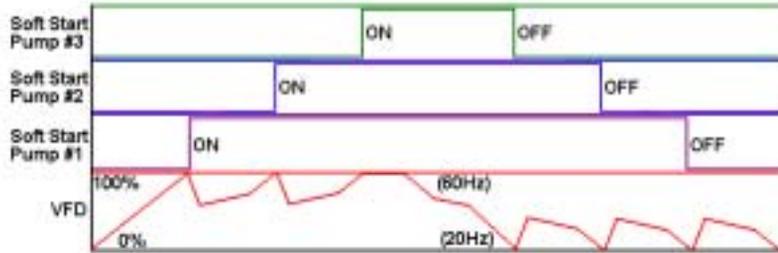
The diagram above shows the operation of the fixed
stages. Notice that every time the VFD signal
reaches 100%, a fixed stage comes ON and every
time the VFD drops to minimum, a fixed stage goes
OFF.

The diagram above shows the operation of the variable pump, VFD at
the bottom of the chart and how it relates to the fixed stages, which are
shown at the top. Notice that every time the VFD reaches 100% or 60Hz, a
fixed stage on the Cascade Controller card is enabled. When the fixed pump
is running, this causes the VFD to drop its signal. With an increase in
demand the VFD goes to 100% again causing the second fixed stage to
come ON.

When the demand drops and the VFD goes to 0% or minimum speed,
20Hz, the fixed stages go OFF. With a loss of a fixed pump, the VFD then
increases its signal. Every time the VFD drops to minimum speed, a fixed
stage is turned OFF. It is possible to use 4 stages, but only 3 stages are
shown here.

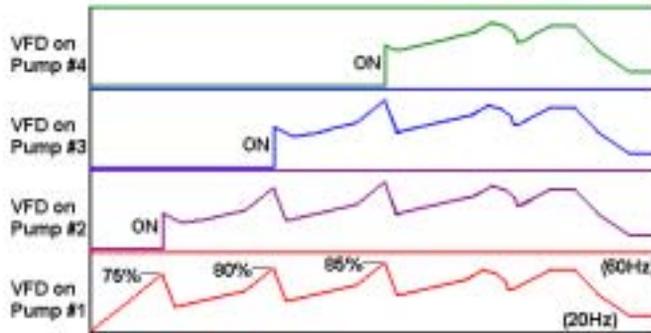# 7) Cascade Control Card – Variable Stages

Rather than having pumps come ON as fixed stages, it is desired to modulate all the pumps. In the example shown, pump #1 has the VFD with the Cascade Controller and pumps 2-4 each have a VFD.

6.   Cascade Control Card – Fixed Stages

There are some applications where multiple pumps or fans must operate together, but the operator wants each pump or fan to have a VFD. The same Cascade Controller card discussed in the last arrangement can be used to coordinate the proportional operation of up to a maximum of 5 pumps. When the lead pump reaches a certain output, say 75%, the second VFD is enabled and now they both modulate using the same reference. As the first VFD has its output go progressively higher say to 80%, an additional VFD is enabled. A further explanation of this operation is shown on the chart on the next page.

7) Cascade Control Card – Variable Stages

The diagram above shows the operation of the variable stages. The lead VFD which has the Cascade Controller, on pump #1, enables the other stages as the demand is increased from 75% up to 85%.

The diagram above shows the operation of the variable pump, VFD at the bottom of the chart and how it relates to pumps 2-4. When the 1st pump reaches 75%, pump 2 is enabled and quickly follows the same signal that goes to pump 1. If the demand for both pumps continues to increase to 80%, pump 3 is enabled. Pump 4 is enabled when the demand goes to 85%.

When the demand drops all the pumps start to slow down. Although this is NOT shown above, when the demand drops to 30%, pump 4 is disabled. When the demand drops to 20%, pump 3 is disabled; and pump 2 is disabled at 10%. Pump 1 then continues to monitor the demand. Remember that 0% is still a minimum speed of 20Hz.

8) SCADA Enable
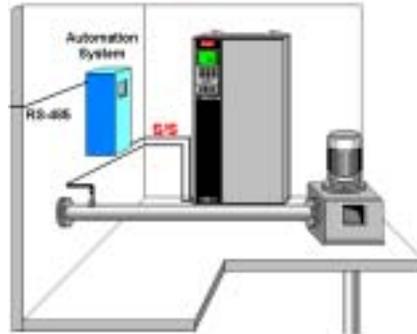
An SCADA System coordinate the use of the VFD with numerous other schedules and commands. In the picture above, a local SCADA Controller starts/stops (S/S) the VFD by use of a Digital Output.

8)   SCADA - Enable

On numerous occasions a VFD works with a SCADA (Supervisory Control and Data Acquisition) System. This system coordinates the VFD with more information such as schedules, holidays, water usage, electric demand limiting to name a few. There are a few ways to wire the VFD with this SCADA system; three arrangements are covered in this lesson.

In the example above, a controller monitors and issues commands concerning the water supply. It enables and disables the VFD. This is done with a DO coming from the controller wired to the DI of the VFD which issues the Start and Stop (S/S) commands. Any wire attachment to the SCADA controller, other than communications, is known as a "point". On some controllers, "points" or certain types of points, can be restricted. Here only one point is used on the controller which saves on wiring costs.

In this arrangement, the pressure sensor is wired directly to the VFD. The closed loop inside the VFD modulates the pump speed to maintain a setpoint keeping the proper pressure in the water line. The SCADA system only enables or disables the VFD. The SCADA controller does not monitor or control the setpoint for the pressure, which makes this arrangement the least desirable for this system.
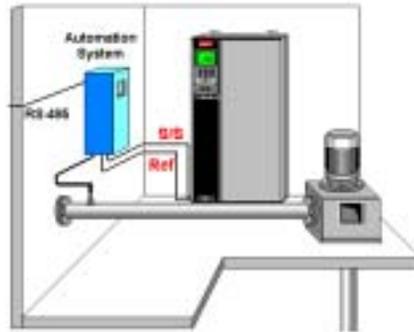
8) SCADA Enable
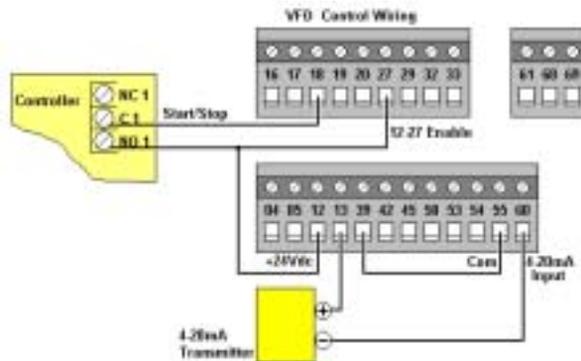
A Start/Stop command from a DO of the SCADA
controller goes to a DI of the VFD. The signal from
the sensor, 4-20mA transmitter is wired into the VFD.

Notice in the example above, a DO on the SCADA controller, a relay
output, which has no power of its own, completes the circuit between
terminal 12, +24Vdc and terminal 18 of the VFD which is the start/stop input.
The pressure transmitter is wired directly to the VFD, which saves a point on
the controller, but limits the operational use and adjustments by the SCADA
System for the water supply. The operator must go to the VFD through its
keypad, to monitor the pressure in the water line and to change the setpoint.
Other information from the VFD, such as speed, temperature, alarms, etc.
displayed through the keypad would also be done locally at the VFD. In this
control arrangement, the SCADA system can only indicate if the VFD had
been enabled or disabled.

9) SCADA - Enable & Reference

A local controller sends an enable/disable (Start/Stop) command to the VFD by use of a Digital Output (DO); and it sends a reference (speed) command to the VFD by use of an Analog Output (AO).

9)   SCADA - Enable and Reference

On the example above additional connections or points are used to gather more information and send more commands from the SCADA controller. Notice that the controller sends a Start/Stop command and also sends a reference. The pressure sensor monitoring the water pressure in the line is sent to the SCADA controller. A closed loop inside this controller monitors the pressure and adjusts the reference to maintain the pressure setpoint.

The VFD, programmed for open loop, receives the reference and Start/Stop commands from the SCADA controller. In this arrangement, the water pressure and setpoint can be monitored and modified by the SCADA system. Additional connections can be made from the VFD back to the SCADA controller to confirm commands and monitor alarms. Each connection requires an additional hard-wire point from the SCADA controller.

9) SCADA - Enable & Reference
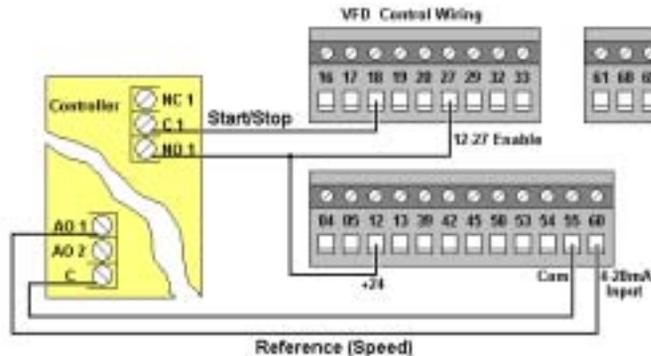
A Start/Stop command from a DO of the SCADA Controller goes to a DI of the VFD. A Reference or Speed command from an AO of the Controller goes to a AI of the VFD.

In the example above, the DO of the SCADA controller is wired to the VFD as in the previous example. Now, however, an AO from the SCADA controller which sends a 4-20mA signal, is wired directly to the current input, AI of the VFD. The 4-20mA pressure transmitter is wired directly to the SCADA controller, which is not shown above. More information and adjustments can be accomplished through the SCADA system using this control arrangement. For each piece of new information such as alarm status, current going to the motor, and energy usage, wires are needed between the VFD and SCADA controller.

10) Serial Communications
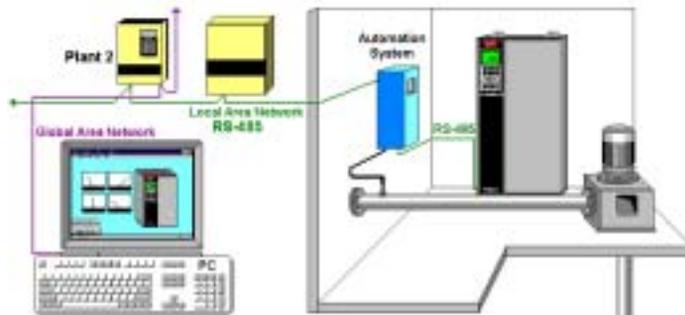
Here serial communications is used to enable the VFD and to give it a reference or speed. Verification of the VFD' speed and status is sent back to the Controller through the serial connection. This connection is usually an RS-485 connection.

10.   Serial Communications

Here is the last interface with a SCADA system. A serial communications protocol is used inside the VFD to talk directly on the Local Area Network or Bus. With this arrangement numerous bits of information can be seen at the SCADA controller as well as the entire SCADA system. This information includes the start/stop command, water pressure, and reference, as in the previous example; but it also includes information about energy usage, alarming, running hours, input status, internal temperatures, and motor information. This information is sent over a 2-wire, RS-485 connection.

In the example above, it can be seen that the VFD is wired directly to the same bus that connects the Local Area controllers. This bus connection could be a iCAN protocol. Local SCADA controllers operate specific devices, or areas in a water treatment plant.

The Local Controllers are in turn connected to a Global Area Controller. These Global Controllers operate separate plants or large parts of a plant. Global Controllers are wired together to form a Global Network. This connection could use an Ethernet protocol, which is becoming more popular. Notice that a PC is wired to the Global Network. This PC has a Graphic User Interface program which is also known as a GUI.

10) Serial Communications
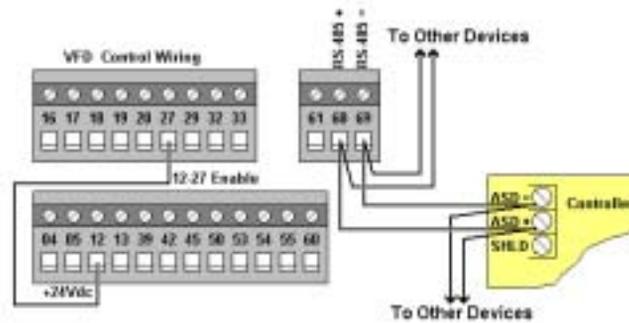
The Start/Stop command and reference command along with numerous other bits of information travel through the 2-wire, RS-485 connection.

In the example above, the 2-wire, RS-485 connection goes between a local controller and the VFD. Normally this 2-wire bus connection must be in a "Daisy Chain" arrangement. This arrangement only allows 2 ends. All the positive or + connections are wired together and all the negative or – connections are wired together. Addressing of each device must be unique, and can be accomplished with hardware switches or programmed in software, which is the case with this VFD.

This concludes Lesson 2. There is a Post Test to review this information.