SMC Controllers with Pump Control

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Surges or pressure transients occur in centrifugal pumping systems when any sudden change of flow is introduced. These surges can result from starting and stopping a pump, opening or closing valves, and many other sources in a particular system. There are a number of mechanical surge reduction techniques, but these tend to be costly and complex. Electronic starting and stopping of the pump motor are a cost-effective solution that reduces problems that are caused by surges or hammering.

Overview

You can directly relate the percentage of change in pump speed to the percentage of change in flow output from the pump. From the affinity law for pumps, we see:

$$\frac{Q2}{Q1} = \frac{N2}{N1}$$

Where: N = pump speed
Q = Flow [cubic feet per minute (CFM)]

Centrifugal pumps are coupled directly to the shaft of an electric motor. When you start the motor by applying full line voltage, the pump accelerates from zero speed to full speed quickly—less than 1/4 second is not uncommon. This means that the flow out of the pump also increases from zero to total capacity in less than 1/4 second. Because fluids are only slightly compressible and have momentum, this large change in flow over a short time results in high- and low-pressure surges and cavitation while the system seeks equilibrium. This can cause many undesirable effects.

Pressure surges stress the walls of the pipe and cause audible noise. The sound is as if the pipe was struck with a mallet repeatedly. The noise is responsible for the term "water hammering" or "hammering". The sound that is created is trivial when compared to the physical damage that pressure surges can cause. High-pressure transients can cause the pipe to burst while low transients can cause pipes to collapse. Cavitation produces zones of highly agitated liquid and partial vacuums whereby the pipe lining may be eroded and the liquid may be boiled off. These effects also damage the valves and fittings.

Because a rapid change in flow causes hammering, you can minimize the hammering when you start and stop the pump by controlling the acceleration and deceleration of the pump motor. To understand how fluid flow is affected during the starting and stopping of a pump motor, review the various starting and stopping methods available.

The methods of starting and stopping a pump motor are as follows:

- Direct-on-line (closing a contactor and applying full voltage to the motor)
- Solid-state reduced voltage starting
- Smart Motor Controllers (SMCs™), including SMC™ Flex and SMC™-50 controllers with pump control option
- SMC-50 controllers with linear acceleration/deceleration

Before comparing the methods of starting, you must establish the relationship between the pump system and pump motor.

Pump System and Pump Motor Relationship

Figure 1 - Pump Curve Versus System Curve

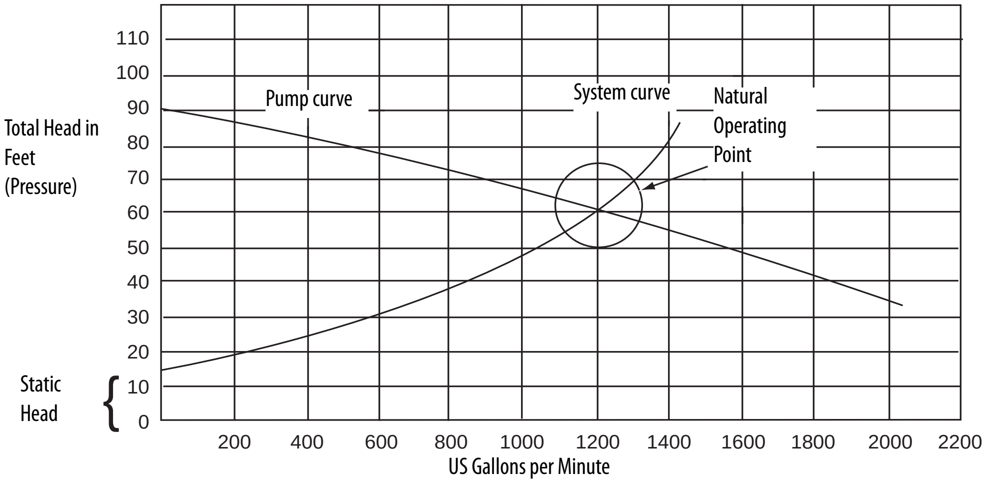


Figure 1 shows two independent curves. One is the pump curve, which is solely a function of the physical characteristics of the pump.

The other is the system curve, which is dependent on the pipe diameter and length, the number and location of elbows, and many other factors. The intersection of these two curves is called the natural operating point.

Another affinity law states:

$$\frac{P2}{P1} = \left(\frac{N2}{N1}\right)^2$$

Where: N = pump speed
P = Pressure (feet of head)

Therefore, we can say that the change in pressure is proportional to the square of the speed.

For a pump motor (AC induction motor) that drives a variable torque load, such as a centrifugal pump, the following is true:

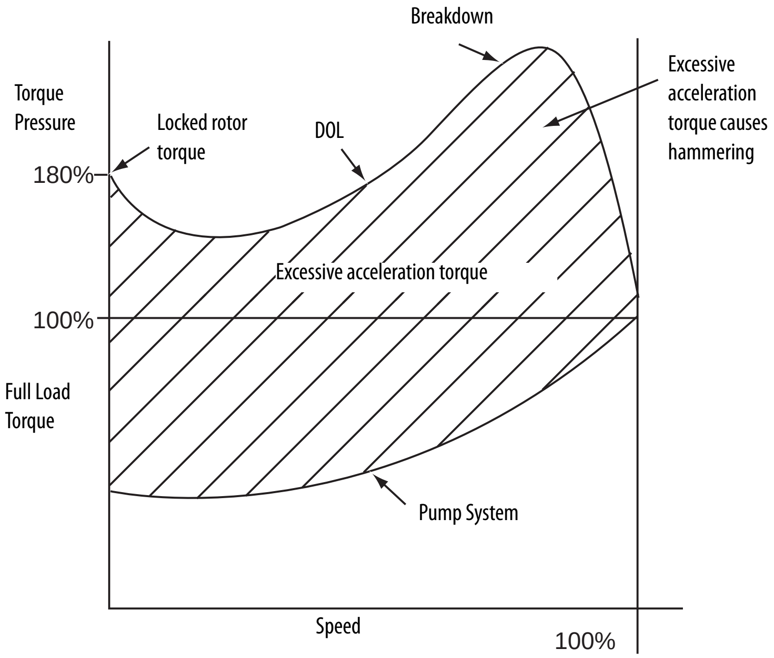
$$\frac{T2}{T1} = \left(\frac{N2}{N1}\right)^2$$

Where: N = motor speed
T = motor torque

Direct on Line Starting (Across-the-line Starting)

Figure 2 shows the speed torque characteristics of a pump (AC induction) motor started direct on line (DOL) with the load requirements of a centrifugal pump superimposed. At 100% speed, the two curves intersect. The motor meets the full load requirements of the pump system. Motors are selected to meet the pump load requirements based on this single point in the two curves.

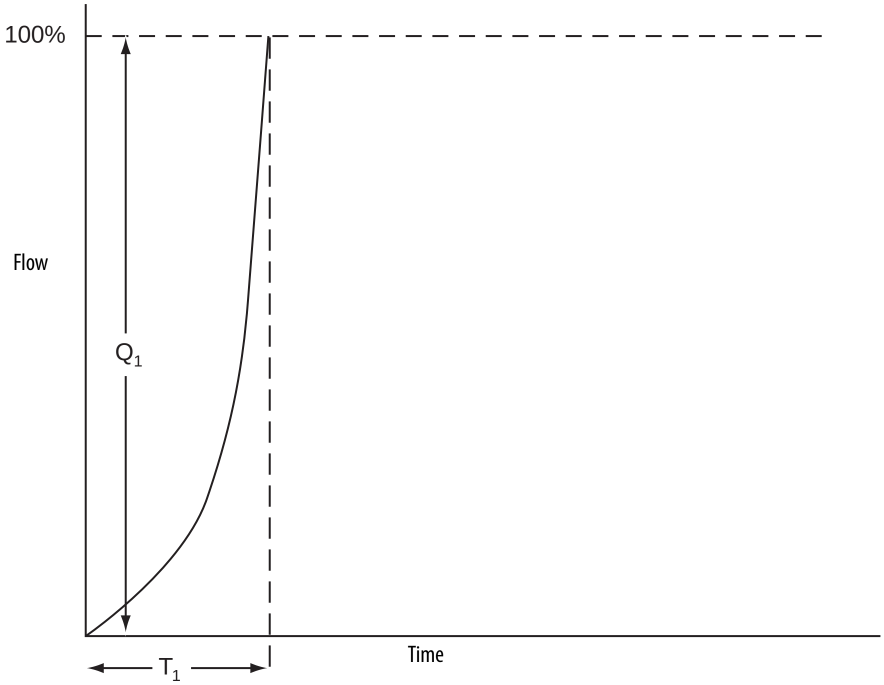
Figure 2 - Direct on Line/Pump Speed Torque Curve



Unfortunately, the motor torque output exceeds the requirement of the pump during the start cycle. Locked rotor torque (LRT) is the torque that the motor develops the instant that full voltage is seen at the motor terminals at zero speed. LRT can be as high as 180% of the torque the motor produces at full speed. Breakdown torque (BT) is the highest amount of torque the motor can develop. BT can be as high as 250% of full load torque. The difference between the torque that the motor produces and the torque that is required by the load is called acceleration torque.

Acceleration torque is the torque that causes the motor to rotate the connected load. In the case of the pump, the excessive acceleration torque that is produced by starting the motor direct on line causes the pump to come up to speed quickly, typically in less than 1/4 second. The result of this sudden change in speed (and therefore flow) is "surges" or "hammering" in the pipe system.

Figure 3 - Change in Flow Versus Time — Direct on Line Starting



To examine the problem another way, as shown in Figure 3, there is a large change in flow (Q_1) in a short time (T_1). The change is due to the large acceleration torque shown in Figure 2 on page 3, which results in system hammering during starting of the pump motor.

Solid-state Reduced-voltage Starting

If you can increase the time that is required for the flow to go from zero to 100%, you can reduce hammering by reducing the amount of acceleration torque delivered by the motor. Less acceleration torque means less force to turn the load and, therefore, more time is required to change the speed of the pump. You can reduce the torque by using a solid-state reduced voltage starter to slowly ramp the voltage that is applied to the motor from zero to full voltage over a preset time (adjustable from 2…30 seconds).

The formula for torque in an induction motor is:

$T = V^2$ Where: T = motor torque
V = voltage

From this equation, we see that the torque that is produced by a motor varies by the square of the voltage. Therefore, reducing the voltage by 50% reduces the torque to:

0.5 x 0.5 = 0.25 or 25%

25% of the initial torque is now available. If the locked rotor torque was 180%, then:

180% x 0.25 = 45%

The new value of initial torque is 45% of the full load torque.

Figure 4 - Solid-state Reduced-voltage/Pump Speed Torque Curve

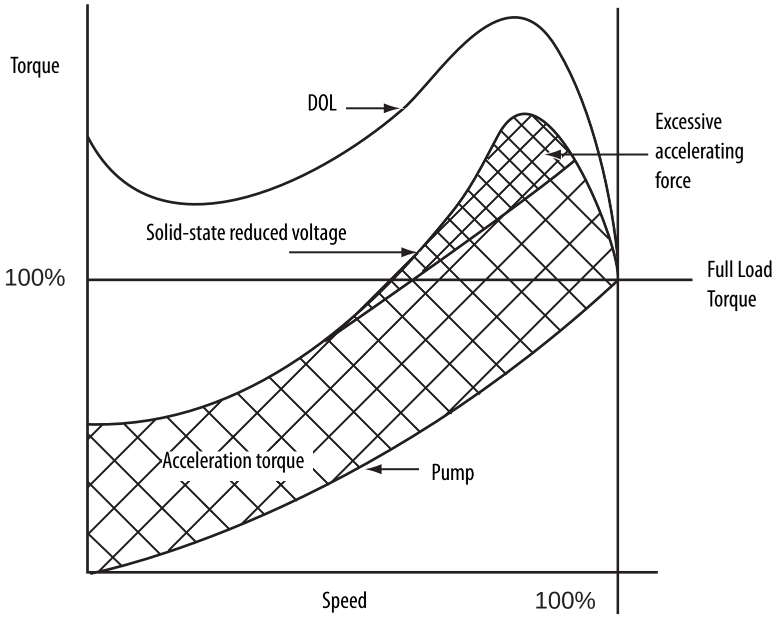
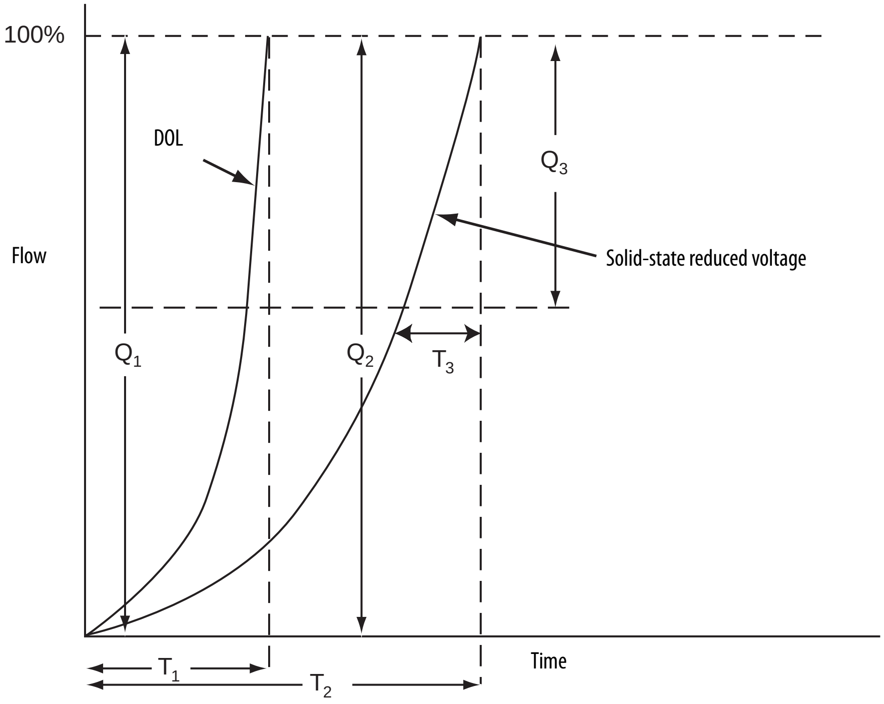


Figure 4 compares the speed torque characteristics for DOL starting and solid-state reduced voltage starting of an induction motor. The acceleration torque has been greatly reduced versus the Direct on Line method of starting the pump motor. The reduction is caused by the solid-state motor controller’s ability to start at a lower value of initial voltage and to ramp up to the full voltage value over an adjustable time period. The torque that is applied to the motor also ramps up.

At the end of the ramp, however, there is an excessive acceleration torque as shown in Figure 4. This sudden change in torque generates a corresponding burst of speed (flow) at the end of the start cycle and results in hammering.

Again the nature of fluids comes into play. In Figure 5, flow (speed) versus time is compared for the two methods. Note the ultimate flows (Q_1 and Q_2) are the same, but the time varies. T_2 is longer than T_1 so there has not been a sudden surge on the system. However, when observing Q_3 versus T_3 there is still a rapid change in flow (Q_3) versus time (T_3). There is still excessive acceleration torque as the pump motor rapidly approaches 100% speed. This is a result of the breakdown torque, which is still present when using a solid-state reduced voltage starter. This sudden surge in pump motor torque at the end of the start cycle results in a flow surge.

Figure 5 - Change in Flow Versus Time



The sudden surge in torque is due to the characteristics of the motor. It occurs because solid-state reduced voltage starting ramps up the voltage without regard to the motor's performance. In centrifugal pumping applications, the result is hammering.

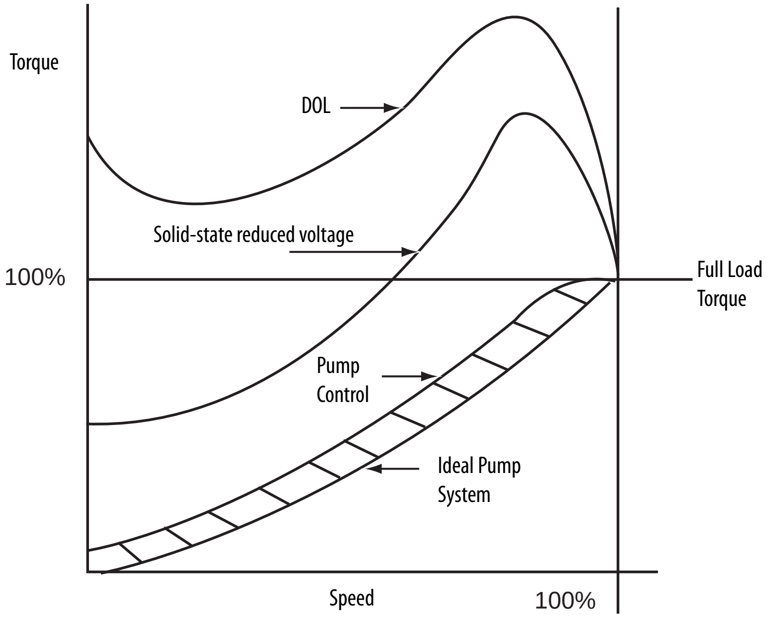
As shown, solid-state reduced voltage starting improves starting torque characteristics of the pump motor, but cannot control breakdown torque, which causes surges.

Innovative pump control options from Rockwell Automation resolve this problem.

SMC Controller with Pump Control for Starting Pump Motors

Figure 6 compares starting speed torque curves for direct on line starting, solid-state reduced voltage, and pump control.

Figure 6 - SMC Controller with Pump Control/Pump Speed Torque Curve

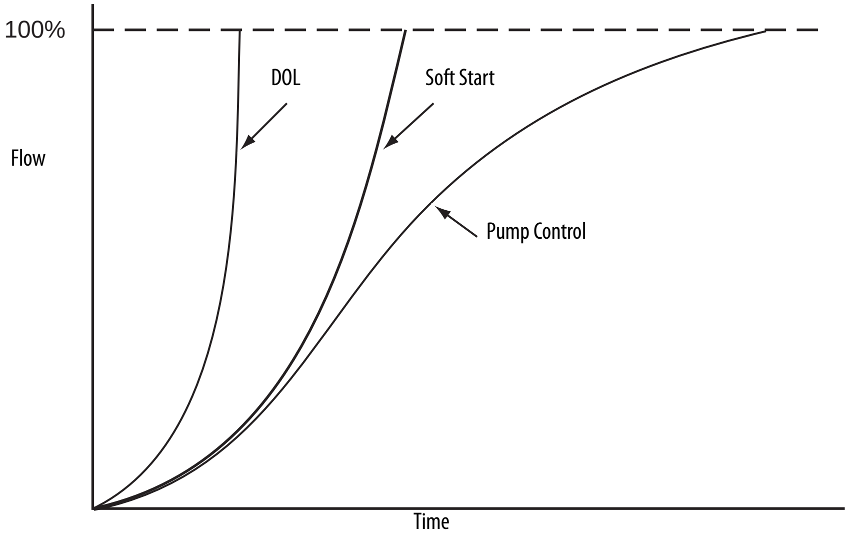


Pump control greatly reduces the surge that is produced during DOL and solid-state reduced voltage starting by using the microprocessor in the SMC controller to carefully control the torque output of the motor.

Because there are no sudden changes in torque, this translates into a smooth acceleration of the motor, which minimizes surges, or hammering, in the system.

Figure 7 compares flow versus time for the three starting methods.

Figure 7 - Change in Flow Versus Time



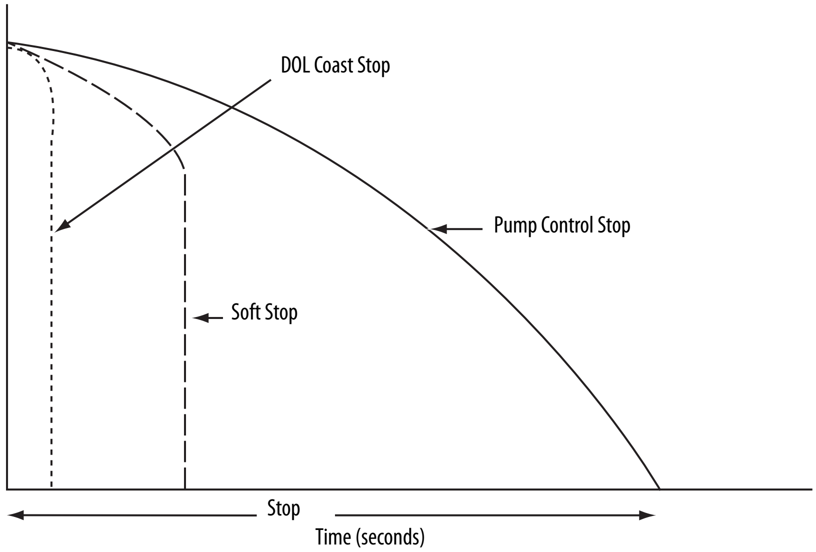
Pump control reduces sudden change in flow by controlling the acceleration torque of the pump motor and extending the time to produce a 100% flow, which minimizes hammering. This is the key to the pump control option: there are no sudden changes in torque. This is what is needed to reduce surges and, therefore, hammering is reduced in the pumping system.

SMC Controller with Pump Control for Stopping Pump Motors

So far, we have only discussed starting techniques. Stopping the pump is as critical in reducing surges and hammer as starting. In this discussion we limit the examples to speed (flow) versus time. See Figure 8.

When direct on line starting is used, stopping is accomplished by removing power and the pump motor coasts to a stop (see Figure 8).

Figure 8 - Rockwell Automation Pump Control for Stopping Pump Motors



The system head quickly overcomes the motor inertia and the pump comes to a rapid stop. The fluid, which is in motion and has momentum, must come to a complete halt as well. This action causes pressure surges on the pipes and valves and causes damage to the system.

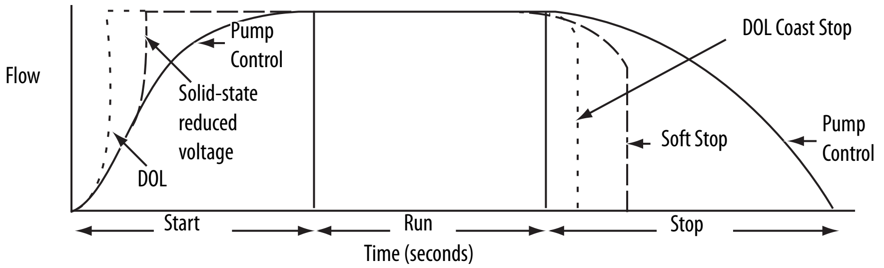
Many control manufacturers are promoting a solid-state reduced voltage starter with a soft or extended stop as a solution to surge or hammering problems. In most applications, a soft stop cannot prevent sudden changes in motor torque required on pumping applications. When a soft stop is initiated, the voltage is ramped from full voltage to zero volts over a time selected by the user (see Figure 8). Reduction in voltage results in reduction of torque and the pump begins to slow down. However, a point is quickly reached where the load torque demand exceeds the motor torque supply and the motor stalls. The effect, though not as severe, is the same as slamming a valve closed, and hammering occurs.

The SMC controller with pump control enabled controls the deceleration of the pump motor in a method similar to the control of the acceleration. When a stop command is initiated, the controller reduces the motor speed to help prevent any sudden changes in torque, minimizing surges in the system. The SMC controller continues to reduce the torque of the pump motor resulting in a speed characteristic as shown in Figure 8. This type of pump motor deceleration curve results in minimal surges or hammering in the system as there are no sudden changes in flow.

SMC Controller with Pump Control for Starting and Stopping Pump Motors

Figure 9 compares flow versus time when different starting/stopping techniques are employed. SMC controllers with pump control produce the most desirable flow characteristics when starting and stopping centrifugal pump motors. There are no sudden peaks or breaks in flow which result in surges or hammering in the system.

Figure 9 - Rockwell Automation SMC Controller with Pump Control for Starting and Stopping Pump Motors



When analyzing possible solutions for a hammering problem, an electrical solution should be considered before a mechanical solution. The initial cost for the electrical solution is typically less than that of a specialized control valve, and less complex. The frequent maintenance/system shutdown that is required with the specialized valve is not required with an electrical solution.

SMC controllers with pump control are the preferred starting and stopping method for centrifugal pump systems.

SMC Controller with Linear Acceleration and Deceleration

While pump control and soft starting are great for most pump applications, sometimes the system dynamics require more control.

An improvement to control of pumping applications is the utilization of linear acceleration and deceleration. This method is not as load dependent as pump control or soft start method. Figure 10 through Figure 12 compare starting methods using a 10-second start time, 0% initial torque, and 65% load on a centrifugal pump. Typically, starting current is lower and longer. The linear acceleration on pumps allows for smooth torque ramps, which reduce water hammer.

Figure 10 - Soft Start and Soft Stop in Pump Application

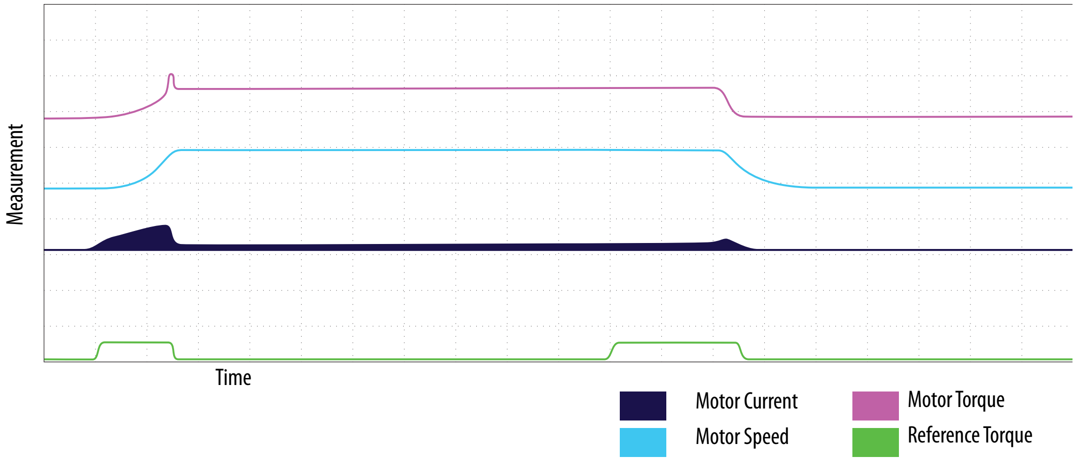


Figure 11 - Linear Acceleration and Linear Deceleration in Pump Application

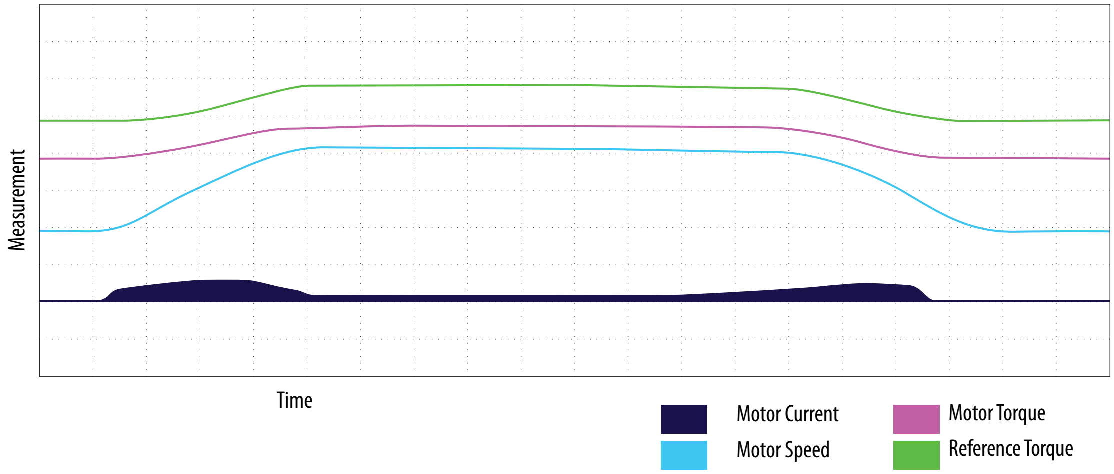
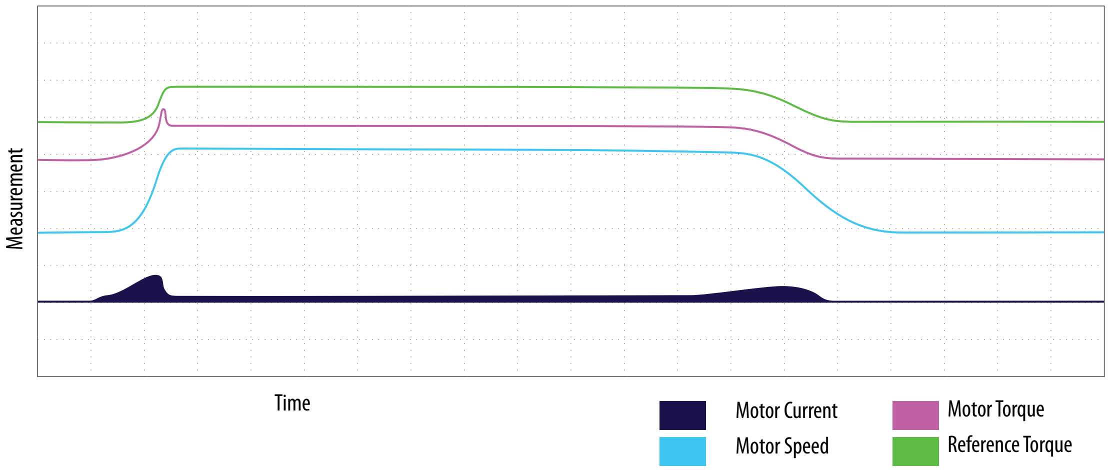


Figure 12 - Pump Control in Pump Application



You can compare these methods by overlapping the stopping profiles, as shown in Figure 13 and Figure 14.

Figure 13 - Torque Comparison

Load: Centrifugal Pump
% Load: 65%

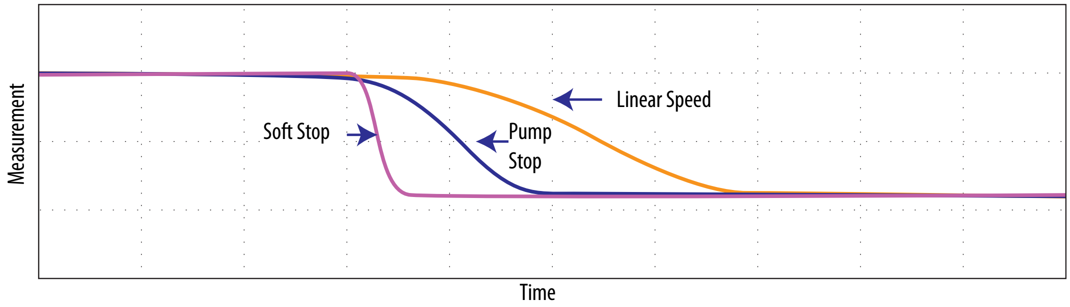
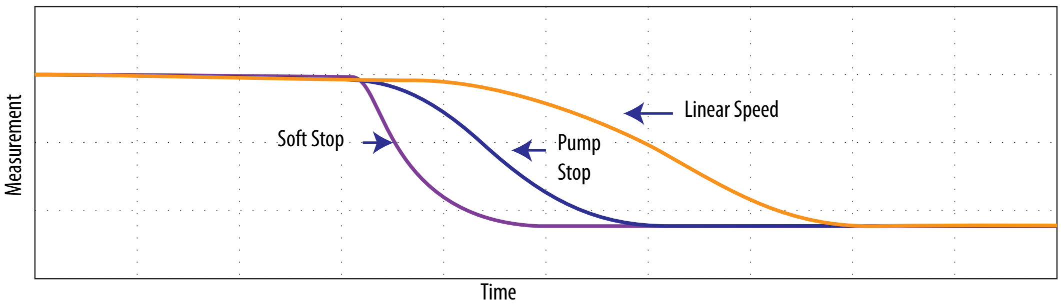


Figure 14 - Speed Comparison



Notice the characteristics of the motor torque and motor speed while stopping. In this specific example, soft stop mode, in comparison to the motor speed, the torque drops to minimum torque at about 1/4 the deceleration time. During pump stop, the torque drops off in approximately 1/2 the deceleration time. Linear Deceleration during the stop provides the most torque control for approximately 2/3 the deceleration time. The ability to maintain control of the motor and load much longer into the stop cycle translates directly to reductions in water hammer, fluid surge, and mechanical shock.

It is important to note that actual time differences in the torque and speed curves of different stopping modes varies depending on the system dynamics and the load. In almost all cases, Linear stopping mode boasts a torque curve that better "follows" the profile of the load.

Other Pumping Issues

Dry Runs

A dry run is a situation in which a pump is run without sufficient fluid. It could be caused by a closed suction valve or other blockage in the suction line. Running dry can cause thermal and mechanical failures within the pumping system.

Low or No Flow Discharge

Blockage or partial blockage on the discharge side can cause vibration and may reduce the minimum required flow rate of a given pump. The reduction in flow rate may cause damage thermally and mechanically to the system, because most pumps have a recommended operational range. Operating outside of the range may damage the pump.

Overload Conditions

Jammed impellers, oversized impeller, improper fitting of system components, bearing failures, and improper head pressure for the pump size are just a few examples of situations that can cause overload conditions on a pump. An overload can cause thermal and mechanical damage.

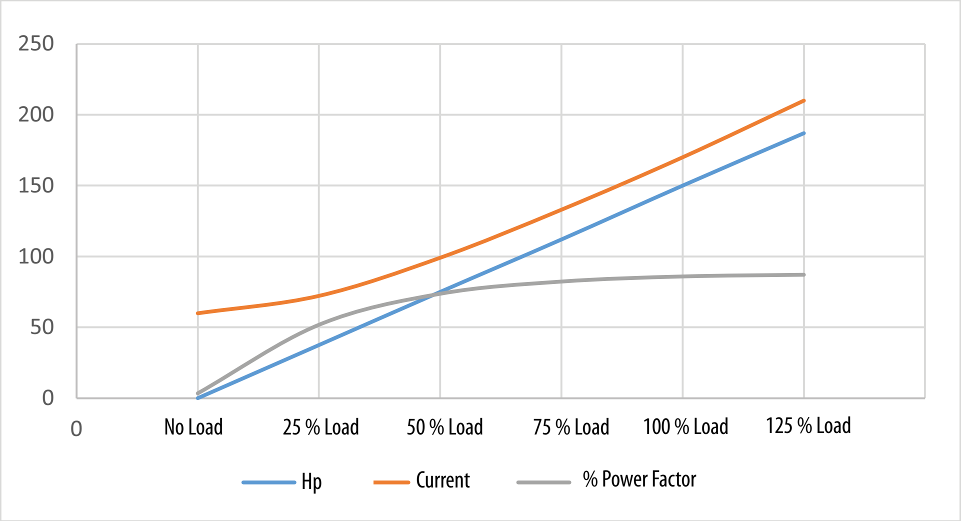
What Are Some Available Preventive Options?

Some options available are relays that are marketed as being suitable to detect cavitation and help prevent dry running. Some of these only monitor a single phase and have to work in conjunction with an externally mounted Current Transformer (CT). In some cases, a toroid is also used in conjunction with a CT to bring current feedback in the case of larger motors. Other components, such as resistors, may also be needed to fine-tune or maintain the voltage/current for appropriate range when using some standalone devices. This means that you need extra components and wiring to measure the current.

While it appears a lot of devices use current to help diagnose cavitation and help to prevent a dry running pump, a better way maybe to use power measurement.

You can use power measurements such as power factor and real power. Figure 15 shows the motor performance from no load to approximately quarter load; the current rise is slight, almost flat. At this load, using current only as a monitoring metric has limited usefulness, outside of monitoring for overload. Above quarter load, the current begins to increase substantially.

Figure 15 - Motor Load Performance for 150 Hp Motor



Power factor and horsepower rise significantly for the same duration starting at no load. The combination of the power factor and horsepower may be a better indication of cavitation or some other issue going on with a pump application.

Properly sizing the motor for the application benefits the protection of the pump system. Oversizing the motor too much reduces the range of opportunity to detect an issue with the system. For example if the motor is 50% loaded nominally, current has barely changed in Figure 15. The lower the percentage of loading on the motor, the more of an indicator it is that you should use something other than measuring current to detect pump issues.

Horsepower (or Watts) ranges from zero, where no work is done, to the rating of the motor, or slightly higher, depending on the load. This appears almost as a straight line.

The equations for 3-phase power are as follows:

$$\text{kW} = \frac{\text{Volts x Amperes x Power Factor x } \sqrt{3}}{1000} \qquad \text{Hp} = \frac{\text{Volts x Amperes x Efficiency x Power Factor x } \sqrt{3}}{746}$$

As calculated in the preceding equation, current is a function of voltage and power. Many factors produce the no-load current, including the number of poles of the motor and magnetizing current. Maintaining the magnetic field of the motor is the main reason why current does not drop to zero with no load.

Power Factor ranges from 0.0…1.0. A 1.0 power factor is a purely resistive load. A value of 0.0 is purely inductive. The lower the PF, the lower the efficiency of the system. Real power (kW) performs the actual work of the motor. In the case of a PF value of 0, no real power is present.

Reactive power (kVAR) is the power that is needed to magnetize the motors.

$$\text{Apparent Power x } \sin \Theta = \text{VIsin } \Theta$$

Apparent power (kVA) is the combination of real and reactive power. For typical loads with reactance, the equation is:

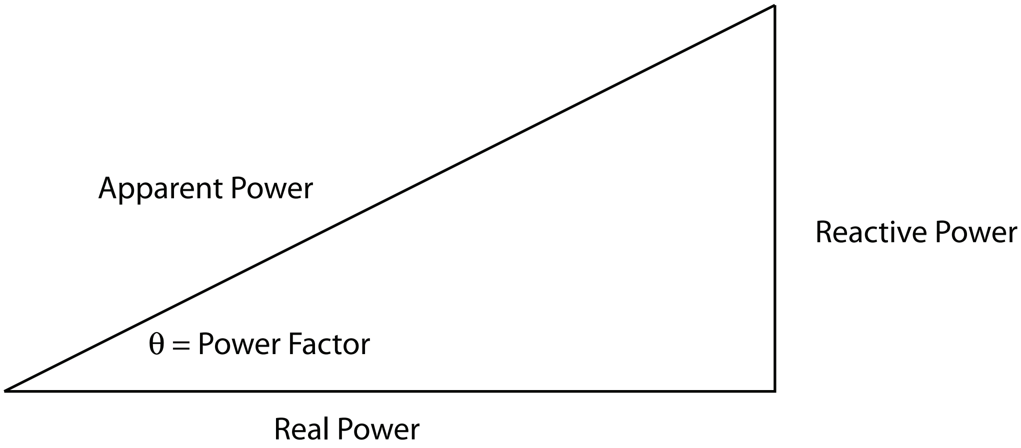
$$\sqrt{(\text{Real Power}^2 + \text{Reactive Power}^2)}$$

Power Factor is the ratio of real power to apparent power.

$$\text{PF} = \frac{\text{Real Power}}{\text{Apparent Power}} = \cos\theta$$

Figure 16 illustrates this graphically and geometrically in the power triangle.

Figure 16 - Power Triangle



For overload conditions, different types of standalone devices are used based mainly on an increase in current. Devices like soft starters may have the overload functionality built in.

Real, reactive, and apparent power for each phase with alarms and faults for each is part of the SMC-50 parameter structure. Because motor magnetizing current does not change much when changing loads to the motor, real power is a better method of detecting cavitation or low loading conditions.

Remembering Figure 15, the best indication of an issue with underload conditions is monitoring and using these values, especially when cavitation or a dry run is possible. Using current alone is not accurate enough.

SMC Controller Features

The SMC Flex and SMC-50 controllers can be used on applications other than pumps for controlling the starting and stopping of AC induction motors. During starting, the SMC controller minimizes mechanical shocks to the system. It can also be applied to minimize line disturbances that occur on the power system when a motor is started direct on line.

The SMC Flex and SMC-50 controllers provide microcomputer-controlled starting for standard three-phase squirrel cage induction motors and wye-delta motors with the inside-the-delta wiring configuration.

While the SMC Flex and SMC-50 controllers incorporate many new features into their design, they remain easy to configure and operate. You can use as few or as many of the features as your application requires. The following modes of operation are available within a single SMC-50 controller and as options with the SMC Flex controller:

- Linear Acceleration/Deceleration (SMC-50 controllers only)
- Torque Control (SMC-50 controllers only)
- DeviceLogix™ (SMC-50 controllers only)

- Standard Soft Start with Selectable Kickstart
- Current Limit with Selectable Kickstart
- Full Voltage
- Dual Ramp with Selectable Kickstart
- Preset Slow Speed (adjustable on the SMC-50 controllers, fixed on SMC Flex controllers)
- Linear Speed Acceleration with Selectable Kickstart
- Soft Stop
- Pump Control Option (standard on SMC-50 controllers, optional on SMC Flex controllers)
  - Pump Control with Selectable Kickstart
- Brake Control Option (standard on SMC-50 controllers, optional on SMC Flex controllers)
  - SMB™ Smart Motor Braking
  - Accu-Stop™
  - Slow Speed with Braking

The SMC Flex and SMC-50 soft starters are compact, modular, multi-functional solid-state controllers used that are used to start three-phase squirrel-cage induction motors with wye-delta motors and to control resistive loads (fully solid-state SMC-50 controllers only). The SMC Flex controller contains, as standard, a built-in SCR bypass and a built-in overload. The SMC-50 controller offers a fully solid-state power structure or internal bypass with built-in overload protection. Both product lines cover voltages of 200…690V, 50/60 Hz and are available as a non-combination and combination enclosed controller.

Additional SMC-50 Controller Features for Pumping Applications

Using the pump application control methods inherent to the SMC-50 soft starter, it may be possible to use the slow speed reversing function to unclog a blockage when something has been pulled into the pipes; for example, a blockage in a sewage influent pump. Once the blockage is detected by the appropriate power parameters, the slow speed function could be used to reverse the flow for a short period of time with the intent of unplugging the intake and not requiring manual intervention.

Additionally, using option cards such as the 150-SM3 Analog I/O Module would allow feedback from a flowmeter to the SMC-50 soft starter. You could possibly use the analog data with the included DeviceLogix™ capabilities programming for control. You can download free Connected Components Workbench™ software to create the DeviceLogix program in addition to programming the SMC-50 soft starter. See the Slow Speed Applications Using A Soft Starter White Paper, publication 150-WP009, for more information.

Overload protection is also standard with the SMC-50 soft starter, which covers the overloading issues the pump may have. An adjustable overload trip class is used to dial in the appropriate setting for the given pump system, potentially preventing further damage to the motor, pump, and system.

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