Soft Starters vs. Variable Speed—or Both?

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Management Summary

In water applications, centrifugal pumps are driven by an induction motor directly fed from the network. Flow regulation is accomplished by a few different means, namely:

- ***Throttling***—A highly inefficient method, as hydraulic losses increase dramatically when the flow is strangled by a valve.
- ***Variable-frequency drives (VFDs)***—Recommended as an effective means of saving energy—that ensure flow regulation by controlling the rotational speed of the motor shaft.
- ***Alternatively, on-and-off pump operation following a precise duty cycle***—The pump is not operated continuously; rather, it is activated when needed for pumping the target water volume and is disconnected for the rest of the time.

Given that many different hydraulic systems recommend the use of either frequency converters or cyclic control (soft starter technologies), the question must be asked—Which one of these solutions is the most cost-effective in reducing energy consumption and providing the most satisfactory payback time?

Introduction

Energy efficiency is key for customers seeking products and systems, and something that suppliers work hard at in improving their product offerings. In fact, the general view held is that the investment linked to the purchase of electrical equipment—as well as the downtime cost incurred from installation and commissioning—is offset by a decrease in electricity consumption due to energy-efficient operation.

Low-voltage solutions in the form of frequency converters and soft starters are especially suitable for maximizing energy savings in water pump and waste applications.

By reducing the applied voltage, a soft starter allows smooth starting of AC motors. During pump stop, water hammer—i.e., a pressure surge or wave resulting when a fluid in motion is forced to stop or change direction suddenly—in the hydraulic system is avoided by a controlled decrease in torque enabled by a dedicated algorithm in the soft starter. Water hammer commonly occurs when a valve is closed suddenly at an end of a pipeline system and a pressure wave propagates in the pipe.

As throttling is highly inefficient, which one of the two technical solutions—variable-speed or cyclic control—is the most cost-effective in reducing energy consumption (Fig. 1). In fact, the nature of the hydraulic system in which the centrifugal pump is to operate is the determining factor in

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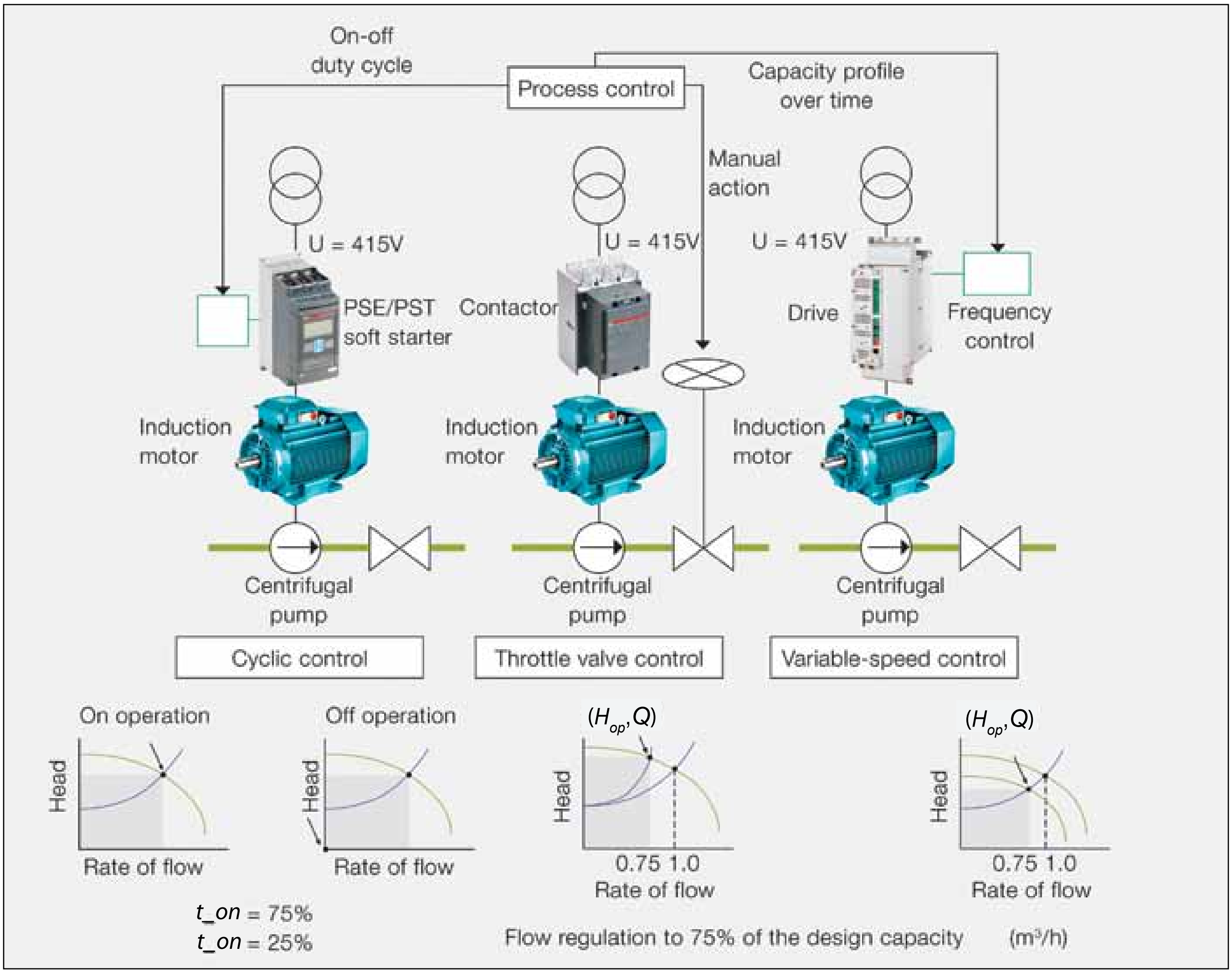

Figure 1—System illustration for cyclic, throttled and VFD (variable frequency drive) flow control methods.

Nomenclature

H_{bep} (m)	Hydraulic head at the best-efficiency point of the centrifugal pump.
Q_{bep} (m^3/s)	Capacity at the best-efficiency point of the pump.
H_{st} (m)	Total static head—i.e., the vertical distance the pump must lift the water. If pumping from a well, for example, it is the distance from the pumping water level in the well to the ground surface—plus the vertical distance the water is to be lifted from the ground surface to the discharge point. If pumping from an open water surface, it would be the total vertical distance from the water surface to the discharge point.
Q_{op} (m^3/s)	Capacity at the system design point. In practice, this is determined for the occasional peak flows arising—about 5% of the time—in water treatment plants.
H_{op} (m)	Hydraulic head at system design point.
H_{opid} (m)	Hydraulic head at the design point in an ideal system.
H_t (m)	Hydraulic head associated with a generic capacity Q (m^3/s) in fixed speed and throttled flow regulation.
H_d (m)	Hydraulic head associated with a generic capacity Q (m^3/s) in variable frequency flow regulation.
H_{max} (m)	Maximum height at which liquid can be lifted by a given pump.
Q_{max} (m^3/s)	Maximum capacity for a given pump.

Figure 2—ABB's PSE compact soft starter range, used primarily for pumping applications.

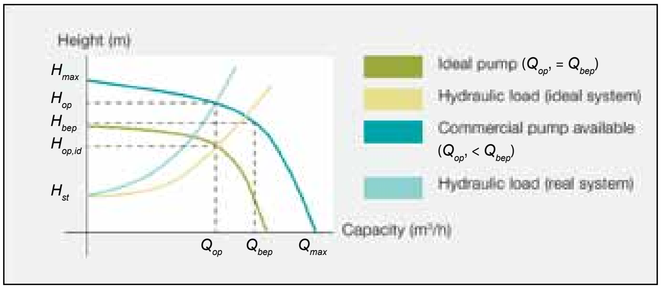

Figure 3a—Pump selection for an industrial installation.

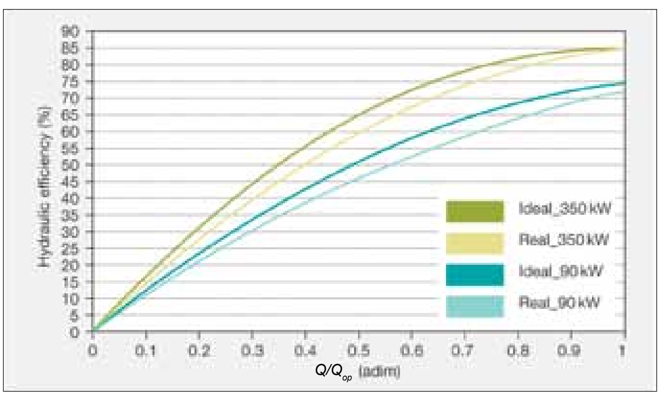

Figure 3b—Hydraulic efficiency loss in 90 kW and 350 kW pumps due to 15% over-sizing.

Manufacturer	Power (kW)	H_{max} (m)	H_{bep} (m)	Q_{bep} (m³/h)	η_{max} (%)
Aurora	90	43.0	27.8	575	74.9
Aurora	350	62.7	38.8	2 500	84.5

Figure 4—Characteristic data of the two pumps studied.

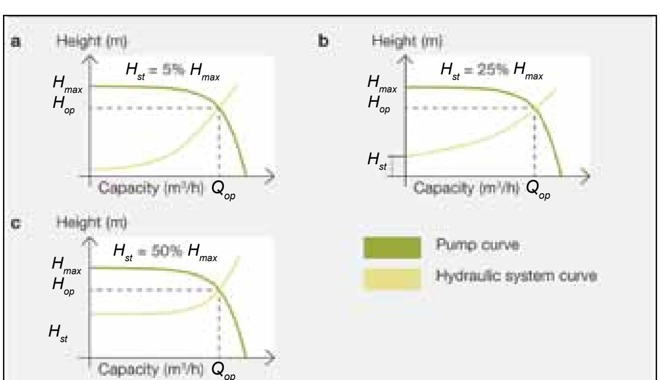

Figure 5—Hydraulic systems selected for energy-saving potential analysis. a: Friction head dominated, b: Mixed head dominated, c: Static head dominated.

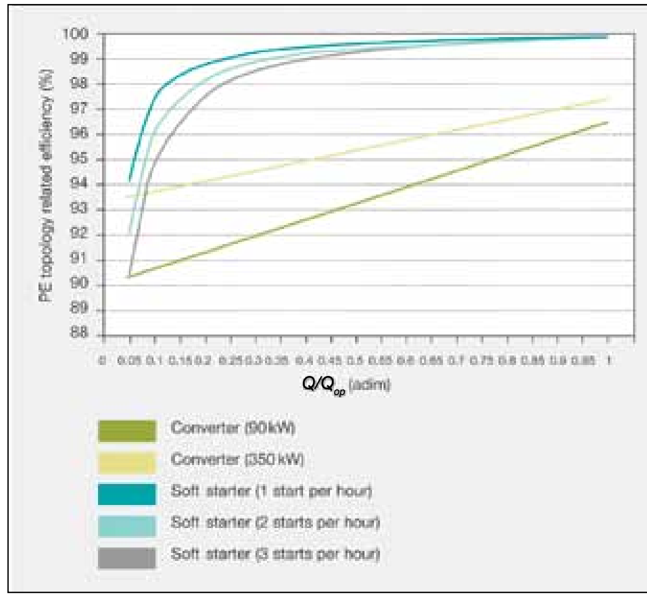

Figure 6—Variation of electrical efficiency (%) in the power electronics circuit (soft starter and converter) with hydraulic load.

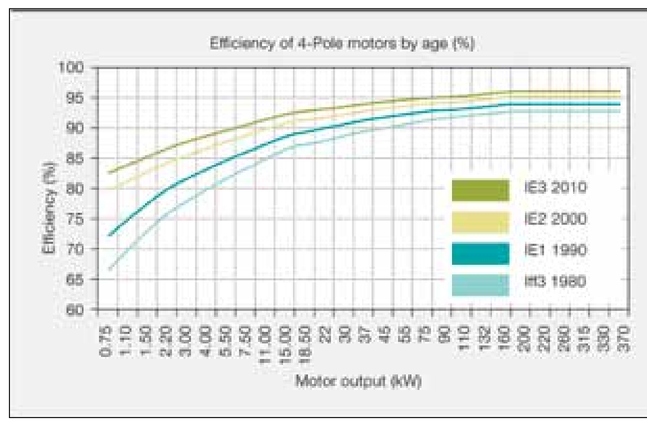

Figure 7a—Impact of class type on motor efficiency.

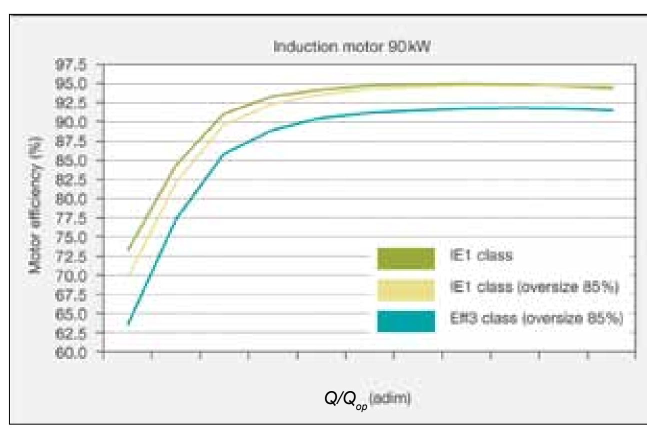

Figure 7b—Variation of motor efficiency with hydraulic load.

selecting one or the other control method.

In wastewater processing, for example, the on/off operation of the centrifugal pumps is, in general, process-control based. Residual water (effluent from residential or commercial buildings) is commonly collected in septic tanks or sewage basins until it is pumped to municipal treatment plants (Ref. 1). Owing to several start events, the use of soft starters significantly reduces the risk of pump clogging due to sludge in the water (Fig. 2). In general, cyclic control is an attractive alternative to the variable-frequency drive (VFD) strategy, despite losing flexibility in flow regulation. In other words, a soft starter is seen as a suitable and competitive technology that preserves the induction motor from electrical strain, mechanical shock and vibration during start-up, and prevents water hammering as the pump stops. Additionally, the motor is used at its best efficiency point and switched off when not needed.

In the following sections, energy savings and payback of variable-speed and cyclic-control solutions are analyzed for two centrifugal pump systems: 90 kW and 350 kW.

A Typical Pump System

When a pump system is assembled, a target flow Q_{op} (m^3/h) must be guaranteed. In an ideal system, the selected pump has a coincident Q_{bep} (m^3/h) with Q_{op} (m^3/h). In reality, however, a larger pump is chosen (Fig. 3). As a result, the pump works under reduced hydraulic efficiency for most of the capacity range. This point is illustrated in Figure 3b for two Aurora centrifugal pumps with power ratings of 90 kW and 350 kW, respectively (Fig. 4; Ref. 2).

To analyze the potential for energy savings in these pumps, three different hydraulic systems were taken into account (Fig. 5):

1. ***Friction head-dominated***—the ratio (υ) of static head H_{st} (m) to maximum hydraulic height H_{max} (m): 5%
2. ***Static head-dominated***: υ is 50%
3. ***Mixed***: υ is 25 %

Converter, Soft Starter and Motor Performance

Frequency converters have a high efficiency (h_{conv}) that drops naturally when the output power decreases with respect to the rated value. The efficiency of soft starters is practically 100% when the motor bypass is activated. Their efficiency decreases noticeably with the number of starts-per-hour and shorter operating time intervals owing to additional joule losses during motor start-and-stop (Fig. 6).

Today's tighter IEC standards guarantee high motor efficiency—in general, greater than 90%—for loads (Refs.3–4; Figs. 7a–7b). This efficiency, which is strongly dependent on its graded class, is affected by the use of either a frequency converter or soft starter. It decreases when supplied by a fast-switching converter due to harmonic current and voltage distortion, but is not altered when the motor is bypassed after soft starting, due to a purely sinusoidal supply.

The impact of system-oversizing, motor class and harmonic losses (drive control) in a real system is shown in Figure 8.

Energy Savings

Energy savings made using VFD and cyclic control in a 90 kW and 350 kW pump system are illustrated in Figures 9a and 9b, respectively. In friction-head-dominated systems (υ = 5%), VFD control ensures higher energy savings across almost the entire operating range, or 7 to 98% in both pump systems. In a 90 kW pump and static-head-dominated system (υ = 50%), cyclic control is a better technical solution than VFD control for all working points, while for the 350 kW system, VFD control guarantees slightly higher energy savings but only between 75 and 92% pump capacity. When a combined hydraulic system (υ = 25%) is considered, VFD control only ensures a larger economic benefit for pump

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	Load (%)				
Efficiency drop (%) caused by	5%	25%	50%	75%	100%
1 – Oversized pump (by 15%)	-1.3	-3.8	-6.0	-4.5	-2.1
2 – Oversized motor (by 15%)	-3.2	-1.2	-0.4	-3.0	0.2
3 – Motor class (Eff 3)	-9.5	-3.4	-3.0	-3.0	-3.0
4 – Harmonic loss	-7.0	-2.1	-2.4	-1.9	-1.3
Increase in power consumption (%)	26.5	11.7	13.3	10.3	6.6

Figure 8—Effect of system over-sizing, motor class and harmonic losses on electric power consumption (*Pn* = 90 kW; switching frequency 4 kHz).

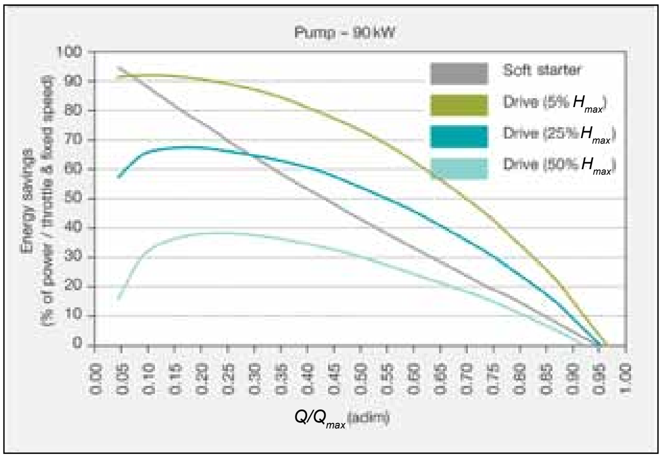

Figure 9a—Energy savings (%) of VFD and cyclic control in the 90 kW pump system.

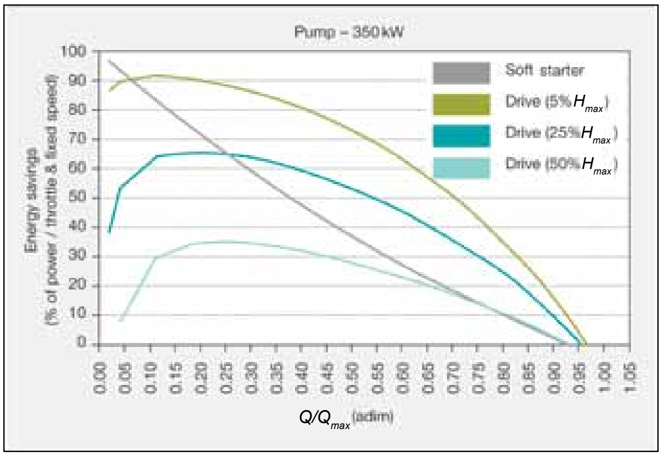

Figure 9b—Energy savings (%) of VFD and cyclic control in the 350 kW pump system.

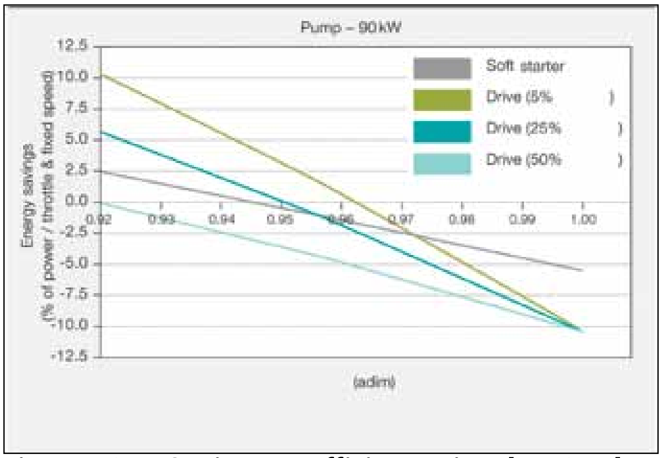

Figure 9c—Optimum efficiency in the 90 kW pump due to soft starter bypass capability at high loads—90–100% of design capacity.

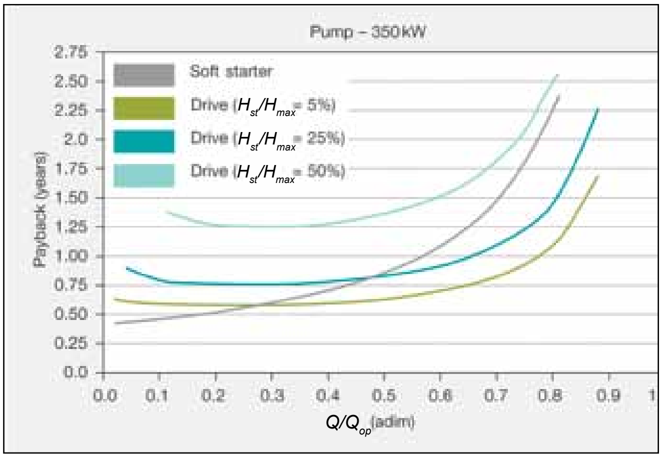

Figure 11b—Payback time of VFD and cyclic (soft starter) solutions for the 350 kW pump.

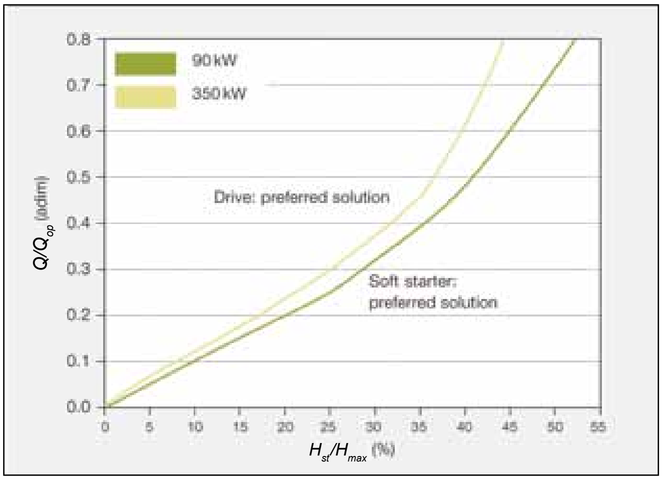

Figure 10—Breakpoint where economic savings with cyclic control (soft starter) exceed a VFD solution.

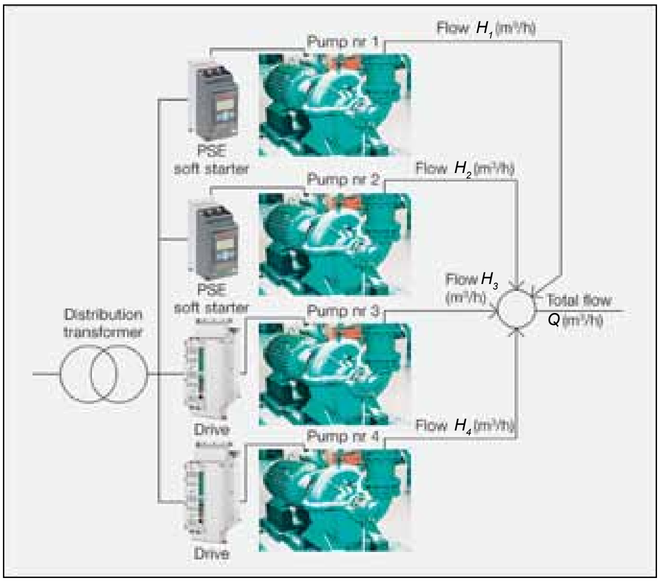

Figure 12—Recommended power electronics solution for a four-parallel pump system (friction-dominated hydraulic system).

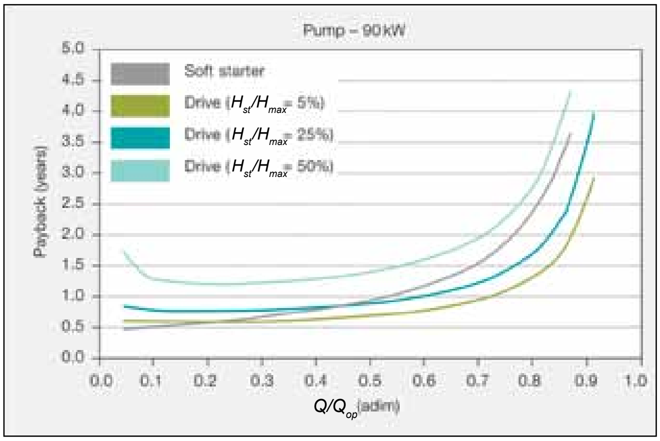

Figure 11a—Payback time of VFD and cyclic (soft starter) solutions for the 90 kW pump.

	Pump 1	Pump 2	Pump 3	Pump 4
PE	Soft starter	Soft starter	Drive	Drive
Flow control	Cyclic	Cyclic	VFD	VFD
Flow Q (m³/h)				
[illegible]	[illegible]	[illegible]	Off	Off
[illegible]	Off	Off	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	Bypass	Bypass	[illegible]	[illegible]
Higher than [illegible]	Bypass	Bypass	[illegible]	[illegible]

Figure 13—Flow control scheme in a four-parallel pump system (friction-loss-dominated).

capacities above 28% (for the 90 kW system) and 24% (for the 350 kW system). In fact, the highest gain with VFD control is found at between 15 and 20% capacity.

Unlike frequency converters (characterized by semiconductor losses at nominal load), soft starters operate in bypass state at nominal load (Fig. 9c). No additional losses in the thyristors are thus accounted for. The operating and system conditions—when either cyclic control or VFD is the preferred solution for pump flow regulation—are illustrated in Figure 10. (*Authors' note: Converting percentage energy savings—with respect to fixed speed and throttle—into economic benefits assumes that the pump works for 8,760 hours per year (330 x 24) at a price of $0.065 for 1 kWh of electricity; see also Ref. 5*).

Return on Investment

Customers will inevitably want to know when they can reasonably expect a return on their investment—which, keep in mind, includes the additional costs incurred by production downtime while the drive or soft starter is being installed and commissioned.

For pumps with a power rating of around 25 kW, the price ratio of converter to soft starter is around three, and reaches an approximate value of five for 350 kW pumps (Ref. 6). The total initial investment associated with VFD and cyclic solutions is calculated as the sum of the cost of the drive or soft starter plus a percentage of the lifecycle costs to cover production downtime (Ref. 7). For both power electronic topologies, a value of 7.5% is used.

Too, cost of individual components may vary for a number of reasons. Primarily, low-voltage VFDs operate on a continuous—rather than stop-start basis—and enable more sophisticated control. However, they use insulated gate bipolar transistors (IGBTs) and so must be designed with sufficient cooling capability, making them more expensive when compared to soft starters with the same power rating. Soft starters, on the other hand, which operate during reduced time intervals of up to 15 seconds, incorporate robust and cost-competitive thyristors and benefit from natural cooling.

The payback times for VFD and cyclic flow control are shown in Figures 11a and 11b—for the 90 kW and 350 kW pumps, respectively—for the three hydraulic systems: υ = 5%, 25% and 50%.

Parallel Pump System Solutions

In many hydraulic systems, optimum energy savings and a good return on investment can be achieved using parallel pump solutions (*Authors' note: For optimal flow regulation in parallel systems, one individual pump is operated until a breakpoint in the target flow is reached, at which time two pumps simultaneously share the hydraulic load—see Ref. 8. When a second breakpoint is attained, three pumps become active, and so on.*) that combine both drives and soft starters.

For example, in a friction-dominated hydraulic system (υ = 5%), a recommended power electronics solution for a four-parallel pump system—each pump with a power rating of 350 kW (2,500 m^3/h)—consists of two converters and two soft starters (Fig. 12). The scheme providing the optimum solution in terms of payback time and control functionality equips Pump 1 and Pump 2 with a soft starter, and Pump 3 and Pump 4 with a frequency converter (Fig. 13). Pumps equipped with a soft starter are directly connected to the network at high capacity; by increasing the rotational speed in a pre-defined range—over 50 Hz—pumps driven by converters can deliver a peak flow if occasionally required.

In a mixed hydraulic system (υ = 5%), the scheme providing an optimum solution in terms of payback time and control functionality uses three pumps—the first two of which are equipped with soft starters, the third with a drive (Figs. 14–15).

For both systems the initial investment in power electronics solutions is translated into economic profit in less than 1.5 years, provided the regulated flow is below 80% of the total capacity (Fig. 16).

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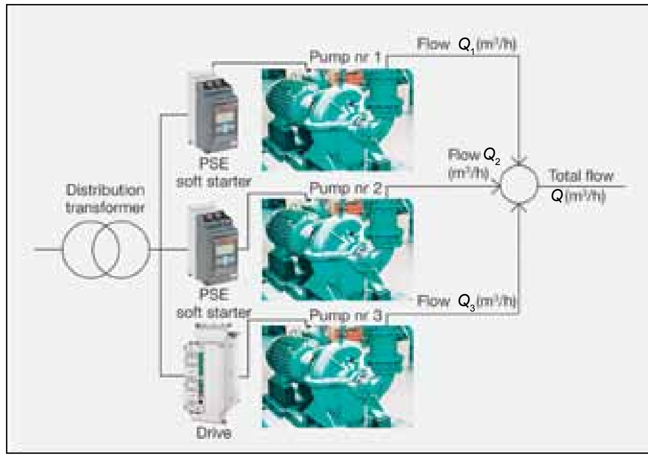

Figure 14—Recommended power electronics solution for a three-parallel pump system (static head-, friction-dominated hydraulic system).

	Pump 1	Pump 2	Pump 3
PE	Soft starter	Soft starter	Drive
Flow control	Cyclic	Cyclic	Variable frequency
Flow Q(m^3/h)			
0–2,500	On-off (0–50%)	On-off (0–50%)	off
2,500–4,500	On-off (50–80%)	On-off (50–100%)	On (40–100% Fn)
4,500–5,750	[illegible]	[illegible]	On (60–80% Fn)
5,750–6,330	Bypass	[illegible]	On (65–80% Fn)
6,330–7,500	Bypass	Bypass	On (85–100% Fn)
> 7,500	Bypass	Bypass	On (> 100% Fn)

Figure 15—Flow control scheme in a three-parallel pump system (mixed hydraulic system).

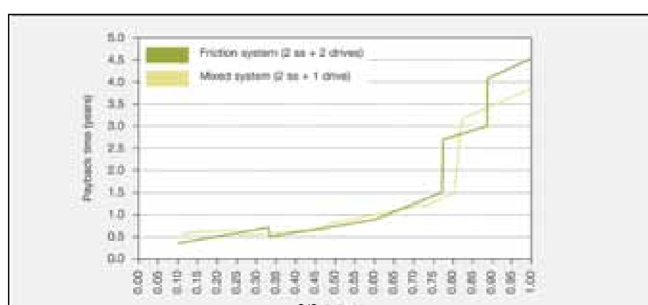

Figure 16—Estimated payback time for two installations consisting of parallel pumps and different power electronics solutions.

Would an Integrated Control System Benefit Your Business?

Switching your automation or motion control platform requires careful consideration. Ultimately, the decision may come down to risk management—whether the benefits of a PAC controller with integrated, high-performance motion control outweigh any potential risks. Some questions to ask in assessing the potential benefits of an integrated control system include:

- Are your customers getting the machine through put they desire with current motion controls? What is the bottleneck in your current machine?
- Does adding more axes to your system degrade system performance?
- Is the throughput of your machine limited by the slow servo update rates, the ability to respond to motion events quickly enough, or long program scan time resulting from sharing a single processor for motion and logic control?
- Does your motion control solution allow you to make changes to end position, velocity acceleration or jerk to active motion profiles at any point along the profile?
- Are you able to synchronize the position loop of all axes in the system to eliminate position phase errors?
- Are you able to instantly reconfigure your machine or line to handle different products? Can you programmatically change master/slave axis assignments and scaling, electronic gear ratios, cam profiles, and engineering units (e.g., English to metric) on the fly?
- Could your solution benefit from the reduced wiring, improved noise immunity and reliability provided by distributing servo amplifiers and motion-centric machine I/O via a fiber optic link?
- Does your solution include multiple programming software packages and/or different programs for logic, motion and operator interface control that require synchronization?
- Would an integrated programming environment reduce risk or improve engineering efficiency?
- Would your engineering resources benefit from an integrated environment?

Figure 17—Pump system in a water treatment installation.

Conclusion

The suitability of variable-speed and cyclic-flow regulation in centrifugal pump applications has been analyzed for two pumps (90 kW and 350 kW) in the low-voltage range. The data show that variable-frequency control is the best solution in friction-loss-dominated hydraulic systems (fluid transportation without height difference) while cyclic control is recommended for static-head-dominated systems. Speed control in systems with very flat pump and load characteristics should be avoided due to the risk of instability and pump damage (Ref. 9).

Soft starters are a very competitive technical solution, especially for water and waste applications in which the regular on/off operation for emptying a tank and pumping up fluid for further treatment are common practice. They are robust, have good bypass capability and dedicated control algorithms for start (kick boost) and stop (no water hammering) sequences. However, optimum energy savings and good payback times can be achieved in a wide range of hydraulic systems by employing parallel-pump schemes that use a combination of drives and soft starters (Fig. 17).

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