SAVING ENERGY WITH VSD SYSTEMS

Freddy Gyllensten and Alessandro Castagnini, ABB Motors and Generators, outline how variable speed drive (VSD) systems and synchronous motor technologies can provide significant energy savings in the petroleum and chemical industries.

Energy efficiency is essential for today's industrial systems. A large number of low voltage (LV) motors used in the petroleum and chemical industries – in pumps, fans, blowers and compressors – offer significant potential for energy savings. In applications where the flow rate has to be adjusted, overall efficiency can be increased by using variable speed drive (VSD) systems and switching to the latest synchronous motor technologies.

VSD control

Pumps are at the heart of many processes and a large chemical plant or refinery can have thousands of pumping systems. This article focuses on pumps because their large numbers provide great potential for improving energy efficiency. However, it should be noted that the same principles apply to fans, blowers and compressors driven by LV motors.

Like many other process-intensive sectors, the petroleum and chemical industries have a high base production flow, which can be managed by pumps operated at constant speed. However, there is almost always a need to regulate the process flow over time. The most commonly used methods for controlling the flow of a pump that transfers a liquid from a location of lower pressure to one of higher pressure are throttling, bypassing, on-off control and VSD control. Throttling is the least efficient of these methods, yet it is the one that is most frequently used. Meanwhile, VSD control is a more efficient method but is used less frequently.

The potential for improving energy efficiency depends on the type of pumps used, specifically on the relationships between the pumps' performance variables. These relationships, for pumps and other applications, are shown in Table 1. Applications with a cubic relation of power vs speed (i.e. centrifugal pumps, fans, blowers and compressors) offer the greatest scope for energy saving with variable speed control. When the process requires a lower rate of flow and the VSD reduces the speed of the application, this has a much greater impact on the amount of power consumed than in applications where the relationship is linear.

VSD control vs throttling

Empirical work with real pump data and system measurements has shown the scale of the energy savings that can be expected when VSD control is used in place of throttling.[1,2] Throttling controls the flow rate by decreasing the effective area for the flow. This increases the pressure, leading to inefficient operation. In the case of a VSD, the cross sectional area for the flow remains unchanged and so there is no bottleneck to impede flow. Instead, the speed of the pump is adjusted so that it delivers exactly the required flow rate.

Data for throttle valve control was taken from a US Department of Energy publication.[2] The test setup involved a centrifugal pump with throttle valve control that was operated with negligible static head (i.e. pressure associated with lifting a fluid against gravity), as in a closed circuit. The pump was driven by a four pole motor, rated at 37 kW, connected direct-on-line and run at constant speed. The nominal flow rate of 273 m^3/hr corresponded to a motor output power of 33.6 kW.

Data for an equivalent pump system but with VSD rather than throttle control was taken from measurements performed in an ABB test facility (and maintaining the same conditions with regard to static head and closed circuit).

The input and output power requirements vs flow rate for the two pump systems are shown normalised on nominal flow rate and output power in Figure 1. The upper dashed curve shows the measured motor output power for the pump with throttle control at constant motor speed; the lower dashed curve shows the motor output power for a VSD controlled pump system where power varies with the cube of speed and flow rate. The dashed curves (i.e. pump system curves) also indicate that even if it were possible to produce motors with 100% efficiency, the power consumed by the throttle valve controlled system would still be much higher than for the VSD controlled system (except at the nominal flow rate). The curves with markers show the input powers required by an IE3-class induction motor operated at constant speed, and by the same motor with a VSD.

Table 1. Relationships between performance variables for different motor driven applications

Application	Flow vs speed	Pressure or torque vs speed	Power vs speed
Positive displacement pumps[a], positive displacement blowers, screw and piston compressors	Linear	Constant	Linear
Centrifugal pumps, fans, blowers and compressors	Linear	Quadratic	Cubic

[a] Including piston, screw, gear and progressive cavity types

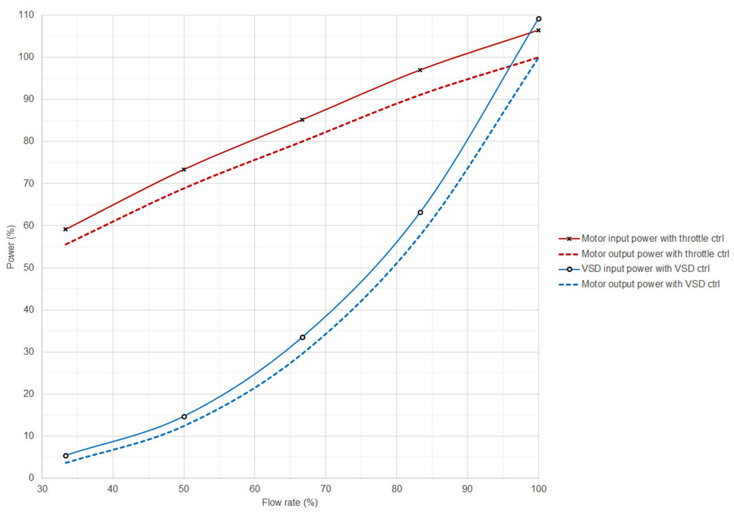

Figure 1. Input and output power requirements vs flow rate for two different pump systems controlled by a throttle valve and a VSD.

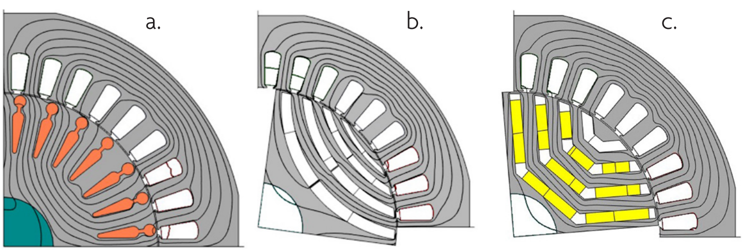

Figure 2. Lamination shapes for (a) an induction motor, (b) a SynRM motor, (c) a ferrite-assisted SynRM motor.

Figure 1 highlights the advantages of VSD control at partial flow rates. Electricity (input power) usage is reduced by 80%, 61% and 35% at flow rates of 50%, 67% and 83%, respectively, compared to throttling valve control. However, it is important to note that at the nominal flow rate (where the throttle valve is deactivated), the throttle valve controlled system is more efficient and uses 3% less electricity than the VSD system. This is due to extra losses induced by the VSD and is illustrated in Figure 1 by the difference between the two input powers at a flow rate of 100%. For this reason, VSD control is not recommended for pumping systems that are almost constantly operated at the nominal flow rate.

VSD control vs on-off control

In on-off control, pump flow is adjusted by turning a constant speed motor on and off according to whether flow is required or not. VSD and on-off control were compared using two independent pumping systems, each comprising two similar centrifugal pumps with negligible static head.

In one system the pumps were on-off controlled and in the other they were VSD controlled. Assuming that a flow rate of 50% nominal is required, the first system can respond by shutting down one motor and keeping the other running. This gives a power usage of 50% compared to the nominal flow rate. The second pump system can keep both motors running but at 50% speed; because the relationship of power to speed is cubic for centrifugal pumps,[1] the power usage is only 12.5% compared to the nominal flow rate. The energy saving is, therefore, 75% for this particular case (leaving aside relatively minor differences in component losses).

Energy savings potential

Applications such as centrifugal pumps, which have a cubic power relation vs speed, offer high energy saving potential with variable speed control because throttling, bypassing and similar control methods use constant full speed when in operation. This generally results in a tremendous amount of wasted motor work and much higher energy consumption for the same required process work. These flow control methods could be compared to a car driver who keeps one foot firmly on the accelerator at all times, and slows down by pressing the brake pedal with the other foot.

In spite of the benefits that VSDs provide, it is estimated that only around 12% of the total worldwide installed base of industrial electric motors are VSD controlled. So why are VSDs not used more commonly? It probably comes down to the higher initial investment for a VSD controlled system. When making investment decisions, organisations often go for the option with the lowest purchase price, even though a slightly higher initial outlay could secure significant energy savings over the equipment's lifetime. The payback time for the VSD can be extremely short. For a centrifugal pump application driven by a direct-on-line connected induction motor where the flow is regulated by throttling, for example, switching to variable speed control could result in a payback time for the VSD of five months or less.

Table 2. Motor and drive system comparisons

Motor data[a] (from tests in VSD operation with network voltage 400 V)			
Motor product (ABB)	M3BP160MLA	M3BL160MLA	n/a
Type	IM	SynRM	FA-SynRM
Output power (kW)	11	11	11
Speed (RPM)	1500	1500	1500
Voltage (V)	380	380	380
Current (A)[b]	21.8	24.2	18.4
Power factor (–)	0.845	0.737	0.953
Efficiency (%)	91.8	94.2	95.6
VSD and system data (from tests with network voltage 400 V)			
VSD product (ABB)	ACS850-035A	ACS850-035A	ACS850-035A
Comparison cases with induction motor and drive system as reference			
Constant torque (75%) duty			
Annual electricity consumption (kWh)	55 011	54 027	53 274
Annual electricity cost (US$)[c]	8912	8752	8630
Annual electricity savings (kWh)[c]	0	983	1737
Annual electricity cost savings (US$)	0	159	281
Average system efficiency (%)	88	89.6	90.9
Quadratic torque duty			
Annual electricity consumption (kWh)	44 121	43 366	42 803
Annual electricity cost (US$)[c]	7148	7025	6934
Annual electricity savings (kWh)[c]	0	755	1317
Annual electricity cost savings (US$)	0	122	213
Average system efficiency (%)	89	90.5	91.7

[a] Data from tests at nominal working point
[b] Currents scaled from measured values to equal voltage of 380 V for simple comparison
[c] Industrial electricity price in Germany of US$0.162/kWh

Efficient synchronous motor technologies

Induction motors have established themselves as the 'workhorses of industry'. They are relatively inexpensive and robust, and the lack of a commutator and brushes means they are reliable and fairly maintenance-free. Their main drawback is their asynchronous speed, which causes losses in the rotor conductors. These losses reduce efficiency and increase heat production in the bearings, leading to shorter bearing lifetimes.

In synchronous motors, the rotor moves at the same speed as the driving magnetic field, eliminating most causes of rotor losses. Therefore, the motor can run at a lower temperature, which promotes longer lifetimes for components such as the

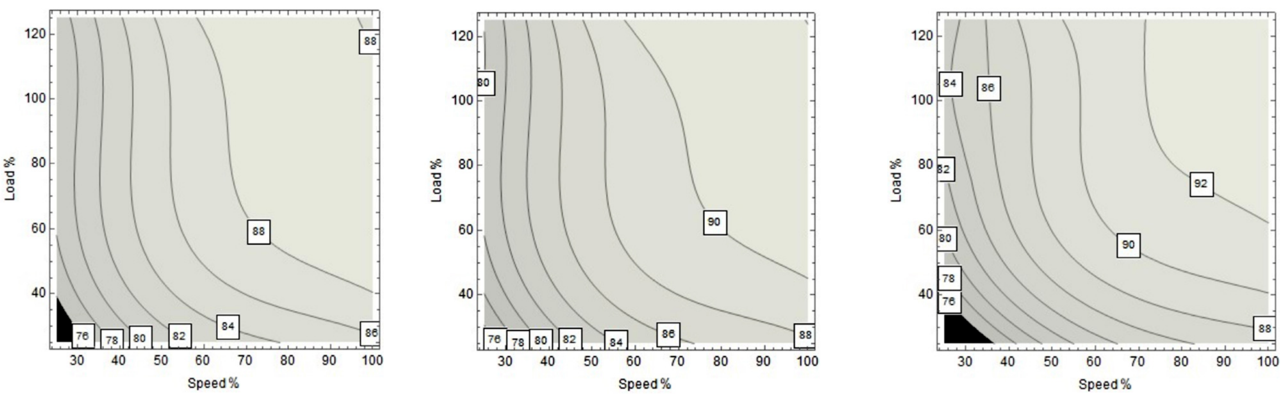

Figure 3. Measured combined motor and drive efficiency vs speed and torque, given as a contour plot. The plots show the values for the induction (left), SynRM (middle) and FA-SynRM motor (right).

Table 3. Average speed, torque and power, by duty cycle, for calculation of economic impacts

Duty cycle	Average speed	Average torque	Average power
Constant torque	67%	75%	50.5%
Quadratic torque	67%	50.5%	40.8%

bearings and insulation system. This section describes three types of synchronous motor: permanent magnet (PM), synchronous reluctance (SynRM) and ferrite-assisted synchronous reluctance (FA-SynRM). Typical lamination shapes for induction, SynRM and FA-SynRM motors are shown in Figure 2.

PM synchronous motors use magnets mounted on the surface of the rotor or embedded under it, and deliver high performance. The optimal material for the magnets, from the performance point of view, is considered to be neodymium-iron-boron (NdFeB). This enables production of highly efficient, compact motors; the IE5 efficiency level can easily be achieved using this material. However, Nd and similar 'rare earth' elements are relatively expensive and have been subject to availability issues and erratic price movements.

SynRM motors do not require PMs and have no local magnetisation source in the rotor. They use a special rotor design that exhibits preferred paths for the magnetic flux, and the rotor is driven by the stator-generated magnetic field. These motors provide good reliability and performance, enabling more compact or higher efficiency motors to be produced. SynRM motors in efficiency class IE4 are available. As PMs are not used, there is no risk of induced voltages on the motor terminals when a disconnected motor is rotated. A drawback of SynRM motors is that they have a relatively low power factor, and this can make a larger VSD necessary.

FA-SynRM technology can be considered as a hybrid: they combine SynRM technology with low cost magnets. The magnets are made from ferrite or iron oxide (Fe_2O_3), which is widely available. The process of manufacturing the rotor is more complex than for a SynRM motor, but these motors can provide higher output torque and power factor. They are also more compact in size and have lower stator losses because of the smaller current, which enables better efficiency levels, and smaller sized VSDs.

Measuring motor drive system efficiency

In order to compare the efficiencies of the different technologies, three motor drive systems were set up using an induction motor (as reference) and a SynRM and FA-SynRM motor. The product types and ratings are shown in Table 2. The induction and SynRM motors were commercially available products and controlled by the same type of commercial drive. The FA-SynRM was a prototype, which was paired with a laboratory drive for the tests. To ensure that the comparison of the efficiencies would be valid, the efficiency of the laboratory drive was calculated based on empirical data obtained from the other two systems, and the drive losses were deliberately modelled in a conservative way so they were slightly exaggerated for the FA-SynRM system.

Efficiencies were measured using the direct input-output method. This involved using precision power analysers to measure the electrical power before and after the variable speed drive, and a precision torque transducer to measure the mechanical motor shaft power. Figure 3 shows the measured combined motor and drive efficiencies. The FA-SynRM system is the most efficient, followed by the SynRM and then the induction motor system.

The potential economic impact of the efficiency differences was then quantified. This necessitated a number of assumptions about the performance variables of applications, the time distribution of different operating speeds, and the industrial price of electricity. Normalised quadratic and constant torque profiles vs speed, as well as the associated power profiles for typical industrial loads were used. An annual time distribution for different operating speeds was created on the basis of broad application experience. This assumed that for speeds of 100%, 75%, 50%, 25% and 0% of nominal the motor would operate for 20%, 40%, 30%, 8% and 2% of the time, respectively. The performance variables and time distribution were combined to produce the average speed, torque and power figures shown in Table 3. The industrial electricity price was taken as US$0.162/kWh for Germany. Table 2 shows the test results and calculated energy cost savings.

Short payback times

Compared to the reference induction motor, which was a high performance IE3 efficiency class product, the SynRM and FA-SynRM motors provide additional annual energy cost savings of US$159 and US$281, respectively, for the constant torque duty profile; the savings are US$122 and US$213, respectively, for the quadratic torque duty profile. These values correspond to payback times well below two years, which means that these motors deliver significant cost savings over their lifecycle. Compared to less efficient induction motor drive systems, the energy savings could be considerable if the average annual output power was higher than in the examples described.

Summary

Switching to variable speed operation can provide significant energy savings in LV motor applications where flow is regulated by throttling, bypassing, on-off control or other conventional methods. This is especially true for applications such as centrifugal pumps and fans, where the load has a quadratic torque profile as a function of speed. Energy savings of more than 50% are a realistic prospect in applications that run at partial flow rates for most of the time.

The energy savings can be further increased by replacing induction motors with advanced synchronous motor technologies, such as SynRM and FA-SynRM. Synchronous motors not only improve energy efficiency, but they also typically operate at lower temperatures, which contributes to improved safety and higher reliability.

References

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2. 'Energy Tips – Pumping Systems, Pumping Systems Tip Sheet #12', US Department of Energy, (May 2007).