POWER UP

Manish Verma, TMEIC, USA, details how using medium voltage adjustable speed drives can help plants save energy and improve power factor.

n its 'Annual Energy Outlook 2019, with projections to 2050', released earlier this year, the US Energy Information Administration (EIA) outlined that "the United States became a net natural gas exporter on an annual basis in 2017 and continued to export more natural gas than it imported in 2018."[1] While there are several technological advances in oil and gas extraction, transportation, and processing that have reduced the need to import energy, LNG exports have contributed significantly to the US' shift from being an importer of energy to becoming a net energy exporter. To export LNG, several types of complexes such as oil well drilling, gas separation/gathering plants, NGL pipelines or gas transmission pipelines, tanks and storage terminals participate, as well as LNG plants. Rotating equipment such as pumps and compressors are at the heart of each petrochemical complex. With easy access to electricity, medium voltage (MV) motors are now driving large rotating equipment, such as pumps and compressors, that were historically driven by mechanical prime movers. Electric adjustable speed drives (ASD) power several of these services.

This article covers two major MV ASD application areas. First, it provides a brief review of how drives are used for energy savings in a plant. Extensive literature exists in print and electronic media detailing case studies where ASDs save energy by running the driven equipment at below base speed and hence more efficiently while reducing wear, tear and extending the life of the overall service. This article will briefly touch on this aspect. With recent advancements in MV drive topology and economical power semiconductor switching devices such as insulated gate bipolar transistors (IGBTs), a new generation of drives not only provide motor speed and torque control, but also improve the power factor (PF) at the connected electrical bus or the overall plant; this is the second aspect this article focuses on. This is extremely valuable in an environment where the sources of electric power generation have shifted from coal and nuclear power to renewables, such as solar, that are power

electronics based rather than rotating machinery based and have limited ability to deliver the reactive power that is needed to improve PF. Monetary penalties are imposed in cases where the plant is unable to meet the PF criteria established by the utility provider. Hence, it becomes critical for the end user to find economical ways of generating reactive power within the boundaries of the plant that consequently improve the overall PF at the point of common coupling. The scope of the article is a MV drive (>1000 V) with ASD power ratings ranging from 500 hp to 6000 hp.

MV drives – energy savings

An MV drive converts fixed voltage and fixed frequency that is available from the utility (e.g. 4.16 kV, 60 Hz) to variable voltage and variable frequency. By converting from an alternating current (AC) waveform to direct current (DC) and then back into AC, the ASD controls not only the voltage but the frequency of the electric motor. Why is this important? Equation 1 determines the speed of an electric motor:

$$Motor\ Speed\ (RPM) = \frac{120\ x\ Motor\ Frequency}{Number\ of\ Motor\ Poles} \qquad (1)$$

Hence, there are only two ways to change the motor speed. One can change the number of poles or the frequency. Once manufactured, the pole number of an electric motor is fixed. The only option left to control the motor speed is frequency. Variable torque loads such as centrifugal pumps, fans and, to some extent, compressors (depending on the molecular weight of the gas) follow affinity laws, commonly
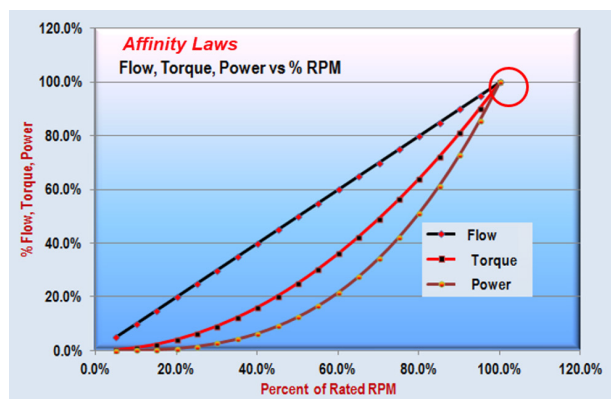

Figure 1. Classical affinity law curve plotting flow, torque and power vs speed.
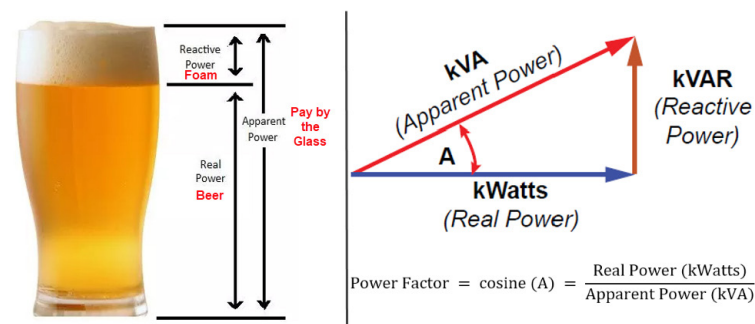

Figure 2. (a) Beer analogy for power factor, (b) power triangle.

known as 1-2-3 fan laws. From an electrical perspective, the following holds true:

$$Flow \propto (Motor\ Speed)^1 \qquad (2)$$
$$Torque \propto (Motor\ Speed)^2 \qquad (3)$$
$$Horsepower\ (HP) \propto (Motor\ Speed)^3 \qquad (4)$$

Consider a pump service in a petrochemical plant. When the pump is selected, it is designed for the maximum process capacity (MPC). Hence, the designed flow rate might be higher than what is currently required by the process. To reduce the output flow, either a valve can be added to restrict to a desired flow rate or the pump speed can be reduced, which holds a linear relationship, as shown in equation 2. For example, if 90% flow rate is required, the motor can be turned down to 90% of the nameplate speed. By doing so, the pump not only matches the flow rate required by the process, but it also reduces the amount of energy (horsepower) that is drawn by the electric motor. While several factors such as ASD efficiency, motor efficiency at part load, percent time the motor is running at reduced speed, etc., impact the net energy savings, a quick method to calculate estimated energy savings can be performed using equation 4. For a 10% reduction in speed, the energy demand is reduced by ~27% (hp = $(0.9)^3$ = 72.9% = ~27% energy saving). Figure 1 plots the flow, torque, and power vs speed of a variable torque load such as a pump.

MV drives – improving power factor

A simple definition of PF is the efficiency of energy utilisation. Non-electrical discipline personnel most commonly understand the principle using the famous beer analogy, as shown in Figure 2a. In three phase electric circuits, to deliver real power (W), reactive power is also needed. Reactive power is the non-working power and expressed in volt-amp reactive (VAR, kVAR, or MVAR). Inductive loads such as an electric motor require reactive power to operate.

A further explanation of reactive power and why it is needed is beyond the scope of this article, but there are a number of good primers on reactive power and PF.[2,3] However, it is important to know how real power and reactive power are related. The power triangle, as shown in Figure 2b, shows the trigonometric relationship between real and reactive power. The question that now arises is why an end user or a plant should strive in reducing if not eliminating the need for reactive power demand. Wasted system capacity is one key reason. Electric power generating and delivering apparatus such as generators, ASDs, and transformers are rated in terms of apparent power (kVA or MVA) and not real power (kW; see Figure 2b for relationship). A poor PF requires bigger equipment, heavier transmission lines, switching equipment and other power delivery apparatus that would otherwise not be required in the absence of reactive power demand. Hence, utility providers pass on the costs of maintaining larger equipment to the end user as PF penalties. In fact, in many places around the world, the end user is mandated by the utility to maintain a stipulated PF (such as 0.95) at the point where they are metered, thereby shifting the burden on to the end user and within the boundary line of the plant. Using the glass of beer as an example in Figure 2a – the beer is real power (kW),

the foam is reactive power (kVAR). For the same glass, more beer, less foam would be better.[4] Conventional methods of PF improvement have been to use switched capacitor banks. In a paper presented at the Minnesota Power Systems Conference, T. P. Speas mentioned that capacitors represent an effective and low-cost method for improving the PF and hence supporting the voltage on the bus.[5] However, switching untuned capacitors in and out of the circuit daily presents challenges with potentially setting up resonant circuits in parallel with the power system inductive impedance. Recent advancements in MV drive technology provide a viable alternative to inject reactive power to the system, thereby improving the PF. Note that if all reactive power is eliminated from the plant, then the apparent power is equal to the real power, and this is known as unity PF (cosine (0) = 1); a goal that is worth pursuing but might not be economical.

The principle of injecting or absorbing reactive power (VAR) with an MV ASD is similar in working principle to that of a synchronous generator. From basic circuits, electric current travels from a high potential to a low potential. Take, for example, a synchronous generator. The rotor field winding excitation current is varied so that the induced stator terminal voltage is raised or lowered with respect to the connected bus voltage. If the terminal voltage of the synchronous generator is higher than the connected bus voltage, reactive current starts

flowing from the generator to the bus and vice versa. Active front end voltage source inverter (VSI) ASD uses a similar concept. Figure 3 shows a typical electrical one-line illustration of an ASD that is set-up to do reactive power (VAR) compensation while motoring. The ASD converter's DC bus voltage (2) is raised with respect to the utility bus voltage to push reactive power (3) into the drive isolation transformer and the system. When current flows out to the utility by raising DC capacitor bus volts, it is effectively reactive current. The resulting current leads the voltage if the DC bus is higher than the system nominal and lags if the DC bus volts is less than the system nominal. The transducer (4) creates a feedback signal to regulate reactive power (VAR) and PF at the hold point (5), which is usually the bus or a point higher upstream of the ASD where the PF correction impacts the most to the end user. Note that diode front end converter-based drives such as 12-pulse, 18-pulse or 24-pulse, cannot push current back to the line since they are inherently non-regenerative.

The following example can be used to understand the practical benefits of an ASD that can inject reactive power back into the power system. Consider a pump service that calls for the electric motor to be rated at 1000 hp (Figure 4a). This is a typical induction motor with a 0.88 PF and 95% efficiency. The application also requires an ASD for reducing the motor inrush current and flow control. As mentioned before, ASDs are rated in terms of apparent power (kVA). Hence, to run this motor, a 1000 kVA drive is selected. After doing the power calculations (Figure 4a), at rated conditions, the motor requires 424 kVAR of reactive power. This power is supplied from the ASD and always takes priority. However, because the drive is an active front end converter and has capacitors as the DC link, the drive can also supply excess capacity back to the bus as reactive power. ASDs that can push reactive power to the system are known as regenerative drives. The amount of regeneration is limited due to ambient temperature and the drive power rating. In this case, the drive can regenerate up to 80% of its apparent rating (kVA) at 30°C ambient. Hence, as shown in Figure 4a, the ASD can supply up to 153 kVAR, assuming the drive is running at rated conditions. From practical experience, we know that the prime mover, such as an electric motor, is sized 10 − 12% more than the driven equipment, and the selected ASD matches the motor rating. Hence, the drive is usually oversized to
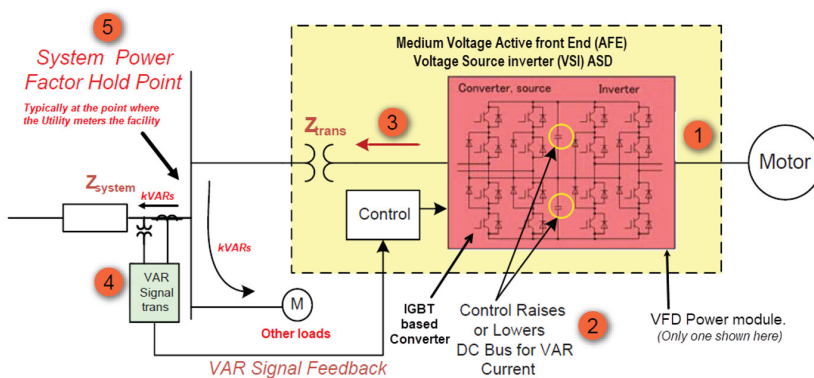

Figure 3. Electrical illustration of MV ASD for reactive power compensation.[3]

Motor Details
HP: 1000
Power Factor: 0.88
Efficiency: 95%

$Motor_{kVA} = \frac{Motor\ Power\ (HP)\ X\ 0.746}{Motor\ PF\ X\ Motor\ Efficiency} = \frac{1000\ X\ 0.746}{0.88\ X\ 0.95} = 892\ kVA$

$Motor_{kW} = \frac{Motor\ Power\ (HP)\ X\ 0.746}{Motor\ Efficiency} = \frac{1000\ X\ 0.746}{0.95} = 785\ kW$

$Motor_{kVAR} = \sqrt{(Motor_{kVA}^2) - (Motor_{kW}^2)} = \sqrt{892^2 - 785^2} = 424\ kVAR$

$Drive\ Export_{kVA} = 80\%\ of\ Drive_{kVA} = 80\%\ of\ 1000kVA = 800\ kVA$
$Drive\ Export_{kVAR} = \sqrt{(Drive\ Export_{kVA}^2) - (Drive\ Export_{kW}^2)} = \sqrt{800^2 - 785^2} = 153\ kVAR$

$Motor_{kVA} = \frac{Motor\ Power\ (HP)\ X\ 0.746}{Motor\ PF\ X\ Motor\ Efficiency} = \frac{1000\ X\ 0.746}{0.88\ X\ 0.95} = 892\ kVA$

$Motor_{kW} = \frac{Motor\ Power\ (HP)\ X\ 0.746}{Motor\ Efficiency} = \frac{1000\ X\ 0.746}{0.95} = 785\ kW$

$Motor_{kVAR} = \sqrt{(Motor_{kVA}^2) - (Motor_{kW}^2)} = \sqrt{892^2 - 785^2} = 424\ kVAR$

$Drive\ Export_{kVA} = 80\%\ of\ Drive_{kVA} = 80\%\ of\ 1380kVA = 1104\ kVA$
$Drive\ Export_{kVAR} = \sqrt{(Drive\ Export_{kVA}^2) - (Drive\ Export_{kW}^2)} = \sqrt{1104^2 - 785^2} = 776\ kVAR$
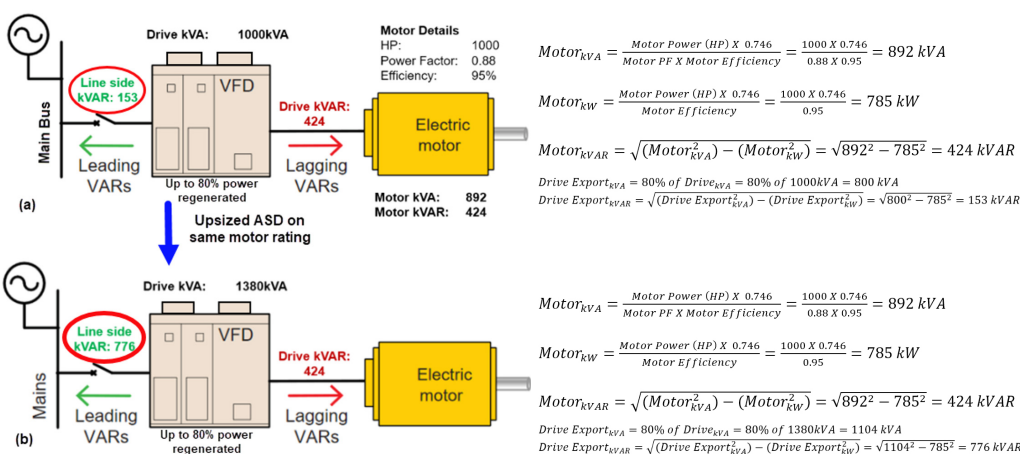
Figure 4. Example of using ASD for power factor compensation (a) ASD sized for motor rating, (b) ASD upsized relative to the motor rating.

begin with. Therefore, the reactive power compensation capability might be more than what the calculations suggest.

Taking the above example a little further, the next frame size of drive rating is selected and applied to the sample 1000 hp motor. After working out the calculations, the drive can deliver a lot more reactive power (776 kVAR) for a small increase in drive rating. This is beneficial to the end user since many times it could mean that an entire bank of capacitors can be eliminated from the system, thereby increasing the reliability and releasing power capacity in the plant (Figure 4b illustrates this configuration).

In the industrial world, MV drives are also used solely for starting large motors. Extending the above example, consider the case where the ASD is used as a starter for the motor. Figure 5 shows how the ASD can start the motor, synchronise with the line, and then compensate for the motor that it just started. Since the drive is no longer responsible for running the motor, the net regenerative capacity of the drive can be used for injecting reactive power. Hence, the ASD is doing work after starting the motor, thereby impacting the return on investment positively for this installation.
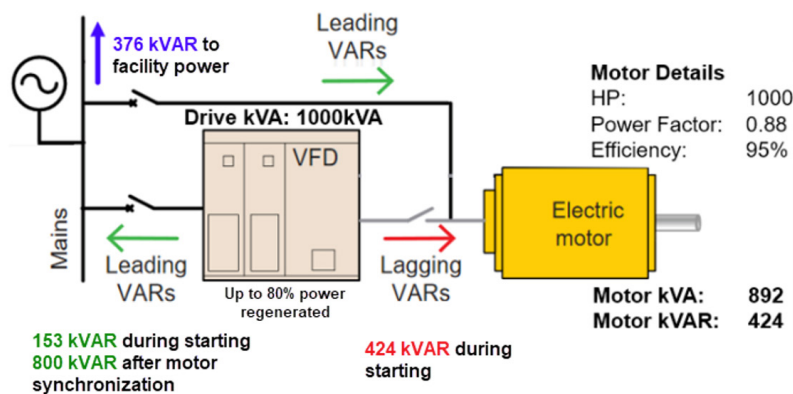
Now that the article has described how an MV drive can help in improving the plant PF, Figure 6 shows an evaluation chart when planning to apply an MV ASD for reactive power control at a facility.

Due diligence in gathering the mentioned data and providing this to the ASD manufacturer will help in selecting the appropriate drive and its rating. While using ASDs to provide reactive power is encouraging, a clear understanding of installation expectations is critical.

Takeaway

Energy savings, soft starting and reduced wear and tear on the motor have been key motivators for applying MV drives to large rotating machinery. While standard diode-fed drives help in improving the motor PF as seen by the utility, they are unable to do anything better than 0.95 – 0.97 PF. Several means exist to control the PF in a plant. Switched capacitor banks have historically been used, but issues with power system resonance and stability often occur. As power systems in several western countries become starved of reactive power availability, due to renewable sources of energy, the imposition of PF penalties are increasing rapidly. MV voltage source inverter (VSI) drives with active converter topology are now readily available to support the voltage, reactive power demand, and ultimately the PF. They provide dynamic variability that a plant might need and can work in concert with existing capacitor banks. This not only reduces the maintenance cost associated with maintaining cap banks but also help in realising cost savings related to reduced PF penalties and provide another reason to utilise an ASD for motor control and energy efficiency. An MV ASD that can provide motor and PF control is a convincing piece of the plant electrical apparatus from an application, total installed cost (TIC) and total cost of ownership (TCO) standpoint.

Figure 5. Example of using ASD for power factor compensation and as a soft starter for an electric motor.

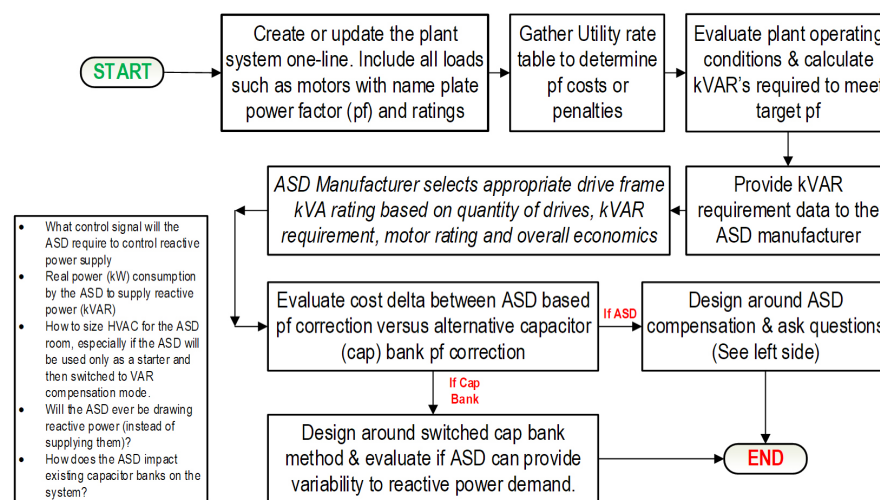**Figure 6.** Evaluation chart of selecting MV drive vs capacitor bank method of reactive power compensation and questions to ask.

References

1. 'Annual Energy Outlook 2019', US Energy Information Administration, https://www.eia.gov/outlooks/aeo/pdf/aeo2019.pdf.
2. EVANS, P., 'Power Factor Explained', https://theengineeringmindset.com/power-factor-explained/.
3. VERMA, M., PHARES, D., and DICK, B., 'Medium Voltage Adjustable Speed Drives: power factor correction & motor control – A beautiful combination', IEEE IAS/PCA Cement conference, (2019).
4. TMEIC, 'TMdrive-MVe2 Reactive Power Control: Exceptional by Design' https://www.tmeic.com/sites/default/files/assets/files/library/Exceptional%20-%20MVe2ReactivePowerControl-D0007-103Feb2019-web.pdf.
5. SPEAS, T. P., 'Capacitor Switching and Capacitor switching devices', Minnesota Power Systems Conference (MIPSYCON) 45th Annual, (2005).