REDUCING ELECTRICAL ENERGY COSTS FOR EXTRUSION PROCESSES

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Abstract

The rising cost of energy is one of the largest challenges facing domestic plastic manufacturers today. Energy costs in certain parts of the country have risen more than 25% in the last two years, squeezing plant profitability. Unfortunately, many plant managers feel their only option is to negotiate with energy providers and have not focused their attention on how they can improve energy efficiency in the extrusion process. Principles and strategies are presented here that show how to reduce electrical energy costs for the extrusion process. Case studies and examples are provided as learning tools.

Introduction

For most plastic extrusion manufacturing facilities, approximately 1/3 of the energy consumed can be attributed to extruder motors. If the line is more than five years old, it is more than likely that a direct current (DC) motor is being used as the extruder motor. Today, the majority of extruder machinery manufacturers are now installing alternating current (AC) vector motors and drives on their extruders instead of DC systems. There are multiple reasons that they are making this change, but the biggest reasons are lower costs and better performance of the AC alternative. Manufacturers prefer AC motors because of the reduced maintenance as compared to DC motors; i.e., DC motor brushes require a high level of maintenance. Most manufacturers however, are unaware of the additional benefits associated with energy savings for AC motors.

Efficiency

Efficiency data for DC and AC motors provided by the manufacturers are shown in Table 1. At full speed and full load the efficiency of a DC motor is about 90%. Similar information for AC vector motors have efficiencies of about 95%, providing an improvement of at least 5% over the DC motor.

Table 1. Published manufacturer performance data for a 125 hp AC and DC motor of similar ratings taken at full speed and various loads [1,2].

TYPE	RPM	Efficiency at 100% Load	Efficiency at 75% Load	Efficiency at 50% Load
DC	1750	89.7	90.3	89.8
AC	1785	95.0	95.4	95.0

Although valuable, performance data does not match the demands created by flexible manufacturing that require manufacturers to operate extruders at different speeds and different loads depending upon the various types of material combinations and products that are required for production on a single extrusion line. Although a DC motor can be as much as 90% efficient at full speed and full load, it becomes less efficient as it is reduced in both speed and load. Measured efficiencies of a DC motor taken with an AEMC Model 3945-B Power Quality Meter, shown in Figure 1, at half speed and half load have recorded efficiencies as low as 75%. Thus, the DC motor can have an efficiency reduction of 15% when it is operated at a lower speed and load. Measured efficiencies for an AC vector motor under the same reduced speed and load conditions have been recorded at 85%, resulting in a reduction of 10% in efficiency.

Figure 1. AEMC Model 3945-B Power Quality Meter.

To determine the input power of a DC drive and motor system, measure the input power going into the DC drive with a power quality meter. The output power can be calculated from measurements taken with a clamp-on ammeter and a digital voltmeter of the armature voltage and current.

In a DC motor, the armature voltage is directly proportional to speed and the current in the armature is directly proportional to load, assuming the field is at rated voltage and current. From these readings percent speed and percent load can be determined when compared to the nameplate reading of the motor. Using these readings the output power can be calculated using Equation (1).

$$\text{Power}_{out} = (\text{hp})(0.746)(\%\ \text{speed})(\%\ \text{load}) \quad (1)$$

hp = motor nameplate horsepower
0.746 = kilowatts per horsepower

After the input power to the DC drive is measured and the output power is calculated, the total system efficiency for the DC drive and motor can be calculated. Efficiency is defined as Power out versus Power in as illustrated in Equation 2.

$$\%\ \text{Efficiency} = \frac{\text{Power}_{out}}{\text{Power}_{in}} \times 100\% \quad (2)$$

In order to perform a proper analysis between the efficiency of the DC system as it compares to the AC system, similar operating conditions must exist. Current and load are not linear functions with an AC motor as with the DC motor, therefore Equation (1) does not apply. If the extruder is operating at the same speed producing the same product, it can be assumed that the output power is the same as calculated for the DC motor. The input power can be measured with a power quality meter and the percent efficiency can be calculated.

An AC drive and motor system is at least 5% more efficient than a DC system with the efficiency difference becoming wider as the speed and load decrease as shown in Figure 2.

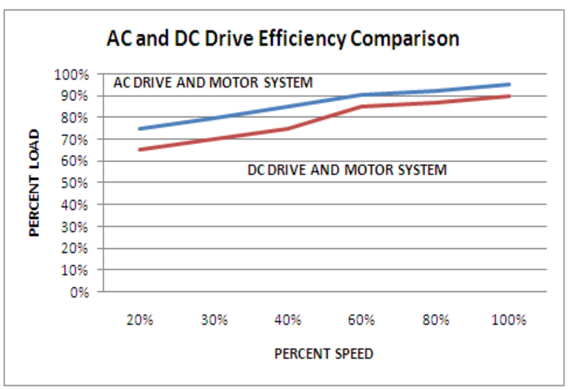

Figure 2. Efficiency comparison between AC and DC drive and motor systems with various speeds and loads.

In situations where the DC motor and drive are more than ten years old, efficiencies can be less than what is represented in Figure 2. Poor efficiencies in DC systems are a result of poor brush and commutator maintenance, multiple motor rewinds, improper field settings, or weak Silicon Controlled Rectifiers (SCR) in the DC drive.

Power Factor

In addition to efficiency, another concern surrounding energy costs is the power factor. The power factor can be defined in two ways, displacement power factor and true power factor.

Displacement power factor illustrated in Figure 3, is the relationship of the voltage and current waveforms and calculated by using Equation 3.

$$\cos \emptyset = \text{Displacement Power Factor} \quad (3)$$

$\emptyset$ is the angle of displacement in degrees between voltage and current.

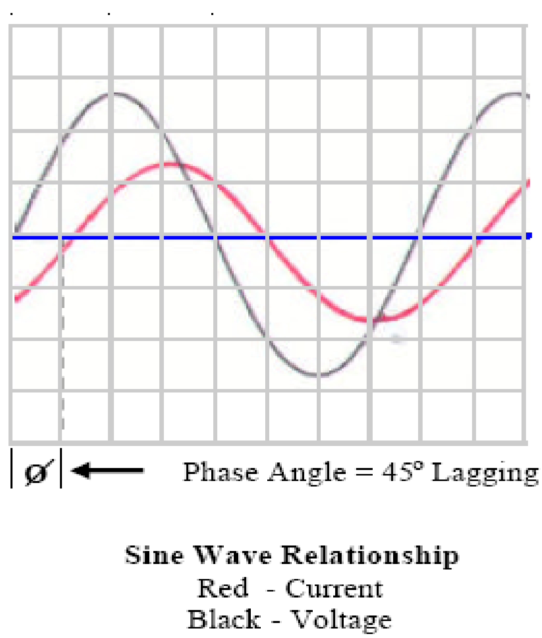

Figure 3. Displacement power factor as defined as the angle of displacement between voltage and current.

True power factor is defined as the ratio of true power (kilowatts) to apparent power (kilovolt amperes) as calculated in Equation (4).

$$\text{True Power Factor} = \frac{(\text{True Power (kW)})}{(\text{Apparant Power (kVA)}} \quad (4)$$

Energy providers are very concerned about manufacturers operating with a good power factor and many penalize industrial manufacturers by adjusting their billing upward if it falls below 0.9 or 0.95. The reason they don't like poor power factors is that the current and power factor are inversely proportional. In other words, more current is required to do the same amount of work with a poor power factor. Therefore, the energy provider usually bills for kilowatt-hours (kWH) and peak kilowatts (kW) with and adjusted charge to the peak kW for a poor power factor.

The displacement power factor of a DC drive and motor system is directly proportional to speed. As the DC motor is slowed in speed the power factor is also reduced. The speed of a DC motor is proportional to the voltage applied to the armature using SCRs, which are the main power component in all DC drives. As the speed of a DC drive is reduced, the SCR's fire further down the voltage waveform, thereby displacing the current and voltage waveform as illustrated in Figure 4.

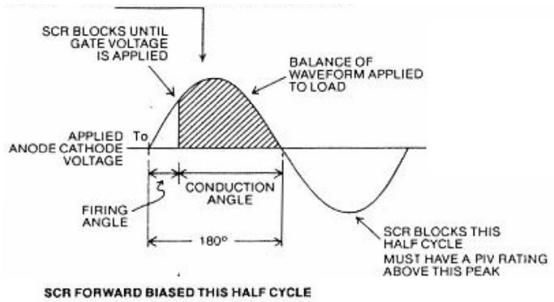

Figure 4. Voltage Waveform illustrating a 45 degree firing angle displacing the current waveform [3].

The best means of measuring the power factor for a DC motor and drive system is with a power quality meter although it can be calculated using Equation 5 and 6 [4].

$$V_{dm} = \frac{((3\sqrt{3}))V_m}{2\pi} \tag{5}$$

$$\text{Power Factor} = \frac{V_{dc}}{V_{dm}} \tag{6}$$

V_m = Peak phase voltage = 1.414 ($V_{AC\text{-}rms}$)
V_{dc}= Measured armature voltage

Example 1.

A DC motor with a 500 V_{dc} armature is operating at 75% speed and its measured armature volts is 375V_{dc}. The line voltage measured at the DC drive terminals is 480 $V_{AC\text{-}rms}$. The power factor for this example is calculated using Equations (5) and (6) as follows:

$$V_{dm} = \frac{\left(3\sqrt{3(480)(1.414)}\right)}{2\pi} = 562\text{ V}$$

$$\text{Power Factor} = \frac{375V_{dc}}{562V_{dm}} = 0.67$$

The input section of a Pulse Width Modulated (PWM) AC Vector drive is a three-phase diode bridge. The diode-bridge rectifies the AC into DC and it is stored in capacitors. In this circuit, the voltage and current waveform are in phase with each other resulting in a higher power factor. The power factor of an AC Vector drive ranges between 0.90 and 0.98. If an AC drive and motor were operating under the same conditions as the previous example, there would be more than a 20 % difference in power factor between an AC and a DC drive and motor. A chart comparing the power factor performance between AC and DC drives is shown in Figure 5.

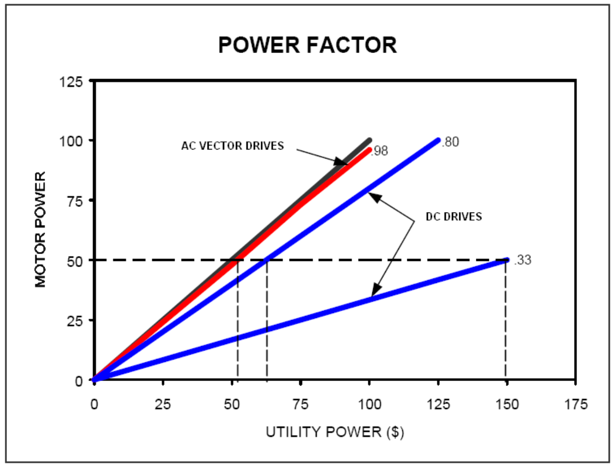

Figure 5. Chart comparing power factor between an AC and DC drive [5].

The installation of an AC drive system will improve the overall power factor and reduces the need for power factor correction capacitors, thereby reducing utility penalty charges from the energy provider.

Hidden Costs (I^2R Losses)

A lower power factor requires more current to do the same job. Since the power factor and current are inversely proportional, potential current reductions can be estimated for an AC motor and drive retrofit. Current reduction can be estimated by calculating the power factor of a DC motor as described earlier and subtracting that number from 0.9 and then multiplying the result by the incoming AC current to the DC drive.

In this example, a clamp-on ammeter was placed on one of the incoming AC lines of a 200 hp DC drive and it measured 300 A. The calculated power factor of the DC motor was 0.57. The calculation for the current difference when using an AC drive is as follows:

Example 2.

Incoming AC Line = 300 A
DC power factor = 0.57
Current Reduction = (0.9 – 0.57) (300 A)
= 99A reduction

The reduction in current results in reduced I^2R heat losses that occur in the power distribution system. In Example 2 it is calculated that a DC drive and motor requires 99A more to do the same amount of work as that of an AC drive and motor. If it is assumed that there is 0.1ohm of resistance in the power distribution system, the resulting I^2R loss would be 980 watts in heat loss. At $0.09 per kWH over an entire year, the cost in heat losses would be approximately $770/yr.

Lower currents reduce the I^2R heat losses that occur in transformers and wires from the point of power distribution to the DC drive. Even if a company has installed power factor correction capacitors, the power factor from the DC drive to the capacitor bank is still low causing high current draws resulting in higher I^2R heat losses, and thus reducing the system efficiency.

Case Study Example

In order to reduce energy consumption on an extrusion line, a plastic sheet manufacturer made the decision to retrofit their existing DC motor and drive system used on their primary extruder with a 500 horsepower AC Vector Drive and an AC Vector motor. The line had three extruders with its own service from the power company so the result could not only be verified by the use of power quality meter but easily verified by analyzing the power bill. Preliminary measurements indicated that the extruder was operating at 60% speed and 79% load. The measured power was 225 kW true power and 431 kVA apparent power resulting in 0.53 power factor. The system was drawing 531A.

The retrofit was performed between billing cycles. The billing cycle prior to the retrofit showed an overall power factor of 0.49 with a peak power kW of 371 kW. After the retrofit, the power bill showed a power factor improvement to 0.86 and the peak power kW was reduced to 360 kW. It is clear that the retrofit had an impact on both the Peak kW, which demonstrates an energy efficiency improvement as well as a power factor improvement. In order to better compare the difference in operating power between the previous DC motor and drive system and the AC motor and drive system, a post installation measurement was made using a power quality meter. The results showed at similar speed and load that the AC motor and drive required 202 kW and 214 kVA with a resulting power factor of 0.945. The required current was 290A which was a reduction in current of 241A.

The energy savings in this application was estimated at $2500 a month equating to $30,000/yr. Combined with the maintenance costs associated with the DC motor the estimated return on investment for this application was 1.4 years. Return on investment for extruders drive systems can range from 2.5 to 1.4 years depending on horsepower and energy costs.

Planning to Cut Costs

It is often the case that the energy utility budget and the maintenance budget are difficult to combine in a cost justification in the minds of many plant managers, and the decision to wait for a catastrophic event to make a change seems to be the most convenient solution. There are several problems with this approach, such as the availability of product, high shipping and labor costs resulting in a higher overall capital expense as compared to a planned retrofit. It is best to plan a drive and motor retrofit around a maintenance schedule of the DC motor.

To properly maintain a DC motor, it is recommended that the commutator be turned down every two years and that the armature be rewound every four years. Many industrial manufacturers have good preventative maintenance programs that regularly schedule maintenance on their DC motors. If a retrofit is planned around a routine scheduled maintenance event, it would allow both production and maintenance crews to coordinate to reduce overall costs that would otherwise occur in a catastrophic event.

Drive and Motor Sizing

Torque is a key factor when considering an extruder retrofit. This means that the drive and the motor must be considered as a torque producing system. As mentioned previously, the performance of the AC Vector system has surpassed the DC motor technology in both constant speed range and speed regulation. Therefore, a horsepower to horsepower retrofit is possible assuming that you replace the DC motor with an AC Vector motor with the same base speed. In some extruder applications, the DC motors in use may have very low base speeds, such as 850 revolutions per minute (rpm). Since an extruder is a constant torque application, this motor would produce twice as much torque as a standard 1750 rpm motor as illustrated in Equation (7). Therefore, the motor horsepower would need to be increased if using a 1750 rpm base speed motor.

$$\text{Torque} = \frac{\text{hp(rpm)}}{5250} \tag{7}$$

This makes motor selection the most important part of the retrofit sizing. In some situations, right sizing can be done for the extruder that would reduce the overall cost of the system. A good rule of thumb is if the system is operating at less than 60% speed or 60% load a reduction in the base speed and horsepower is possible, lowering the capital expenditure and yielding a higher return on investment.

Physical Considerations as it Relates to the Drive

There are physical differences between the AC drive and motor and the DC drive and motor. The AC drive is often times larger than the DC drive and unable to fit inside the existing enclosure. In such cases, a pre-configured drive package from the drive manufacturer would be the best solution. These packages are available in NEMA 12 enclosures with circuit breakers or line disconnects along with various other options. Packages larger than 100 Hp, are usually free-standing and proper dimensions should be obtained to find a suitable place for installation within 300 feet of the motor.

When mounting AC Vector Drives in existing enclosures or a standard electrical enclosure, there are more considerations than just its physical dimensions. An AC drive produces more heat than a typical DC drive of similar ratings, therefore thermal considerations are important when placing a drive inside an enclosure. Heat is a result of the watt loss of the drive and this information can be obtained from the drive product manual. A complete thermal analysis should be performed to ensure that the drive can properly dissipate the heat that it generates, eliminating premature failure. In addition, all drives must be mounted vertically as specified by their manufacturers.

Physical Considerations as it relates to the Motor

AC and DC motors are built in different frames. DC motor frames are usually a lower profile with lower center shaft heights although they are longer than an AC motor. Most AC motors use NEMA frames as a standard which have a higher shaft height and are wider in diameter but shorter in length. In motor retrofits this can be a problem, especially if the motor is mounted underneath the extruder barrel. A possible solution if height is an issue is the use of the Reliance RPM-AC motor which is an AC vector motor constructed in a DC frame. This solution could eliminate extra cost that would be associated with machining down a base to fit the AC Motor. In the case of a frame size change, proper shaft alignment techniques should be employed to extend motor bearing life. Height is usually not an issue when a motor is belt-driven, although the AC Vector motors should have optional roller bearings to withstand the increased radial load in such applications.

Conduit side mounting is also an important physical consideration in retrofitting an Existing DC motor. All too often, this simple item is overlooked in emergency retrofits. The F-1 mounting of the conduit box is standard with AC motors and is on the left side of the motor facing the shaft. The F-2 mounting of the conduit box is optional and is on the right side of the motor. For blower-cooled motors, fan mounting should be noted as to whether it is on top or the side of the motor.

Electrical Connections

There should be no change required on input wiring if the horsepower and voltage rating is the same as before, although there are differences in the connections from the drive to the motor. The DC motor utilizes two armature conductors for the majority of the current and two smaller conductors for the field current. AC Motors have three phases and a ground connection for power. There is a possibility that some of the existing wire can be used for retrofit purposes, although it is important to note that any wire added to obtain the desired current rating per phase should be the same size as the existing wire. An audit of the existing wires and conduit or wire tray space available should be noted. Distances from the drive to the motor beyond 300 feet require load reactors. Load reactors minimize negative effects caused by a reflected wave generated through capacitance build up in the wire. If radio frequency interference of the instrumentation is a concern, then the use of shielded cable is recommended. Recommended wire sizes are usually within the product manuals although a good rule of thumb is 1.5 times the full load current of the AC Drive. Control wire should always be run in a separate conduit from power wiring reducing the chance for electrical noise.

Encoder Feedback

Many DC motors utilize DC tachometer feedback which can provide 0.5% speed regulation. Although Open-Loop AC Vector control can achieve as much as 0.2% speed regulation if properly configured. This would alleviate the need for an encoder feedback in the majority of extruder applications.

Start-up and Drive Configurations

Although AC vector drives can be wired up to turn a shaft without any programming, it doesn't guarantee good motor performance. Proper drive configuration and motor tuning would be required in order to maximize torque performance throughout the entire speed range of the motor. It is recommended that a trained service technician assist in proper drive configuration and tuning.

Discussion

From the case study and given examples it is apparent that there are energy savings possible in the retrofit of existing DC drives and motors on extruders with new AC Vector motors and drives. Savings are dependent on operating speed and load conditions as well as the cost of energy. In most cases, the return on investment is around two years when energy savings are combined with the maintenance costs of the DC motor.

The Vector AC motor and drive system will give better performance in speed regulation which will improve product quality as well as reduce raw material usage. In addition, it will require little to no motor maintenance which will improve production throughput by reducing required and emergency maintenance as it relates to the DC motor brushes and commutator.

The DC motor is the most expensive part of a DC drive and motor system representing as much as 65% of the total system cost. Therefore, motor replacement or high repair charges are a significant incentive to retrofit to an AC vector drive system. Many existing DC motors on extruders are over 15 years old and very expensive to repair because they are in larger frames. The decision to retrofit should be made in advance of any repair decision, based upon a proper savings analysis and a current AC Vector motor and drive quotation. AC motors rated at 480VAC are available up to 1000 hp.

A retrofit should be planned in advance to minimize any additional charges that may be associated with downtime and labor and shipping costs. As well as reduce the chance for mistakes that can occur during an emergency retrofit.

Conclusion

The AC Vector motor and drive is the best in current motor and drive technology for extruder applications and it yields significant energy savings as well as reduced maintenance costs which reduce overall operating costs of the system over a comparable DC motor and drive system.

The techniques presented here have been performed hundreds of times, providing cost analysis comparisons on extruders. The analysis have helped several plastic extrusion manufactures develop cost justifications and planned retrofits to help reduce operating costs on extruders.

References

1. Baldor-Reliance, Performance Data Sheet, 125 Hp, 1750 base speed, C2813ATZ frame, DPFG, straight shunt, DC motor
2. Marathon Electric, Certification Data Sheet, Model# T444THFN8046 EF, 125 Hp, 1785 base speed, 444T frame, TEBC, AC Vector motor
3. Elwood Gilliland, *Killowatt Classroom, SCR article,* 4 (2002)
4. Sharifah Azma Syed Mustaffa, *Controlled Rectifiers,* Chapter 10, slide 22
5. Wiliam A. Kramer, *Motors and Drives for Extrusion Applications,* 5, 1999

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