APPLICATION OF BRUSHLESS DC DRIVES IN BLOW MOLDING

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Abstract: **Variable speed drives used in Blow Molding have changed little in the last 20 years or more even though substantial technology advances have taken place in other areas of the Blow Molding process. A new variable speed technology has become available in the last 5 years and several blow molding manufacturers and users have taken advantage of this advancement and are using Brushless D.C. drives for the extruder function as well as for rotating molds. This paper addresses the advantages this new Brushless technology brings to variable speed drives in general and Blow Molding Machines in particular. Areas specifically addressed include efficiency, accuracy, power factor, size, harmonics, and speed range. A basic description of how Brushless D.C. works and a comparison to other types of variable speed is given. With increasing emphasis on product quality at lower costs, the need for modernizing the Blow Molding Machine becomes ever more important.**

I. Introduction

The first variable speed drives were certainly mechanical and were based on adjustable pitch diameter pulleys. Such systems are still in use but for obvious reasons are not in general use in industrial applications today. There are four basic types of electrically adjustable speed drives being installed in today's modern industrial machines:

- DC Brush type motors and controllers
- DC Brushless motors and controllers
- AC Variable frequency controllers and induction motors
- AC Vector controllers and induction motors

Historically, the brush type D.C. motor has been nearly the exclusively used variable speed drive on blow molding machines. The use of AC variable frequency and AC vector drives on blow molding machines has been almost nil and will not be covered in this paper [1]. A rather unique type of brush motor called a brush shifter was popular on early machines . The Brush rigging was moved mechanically by a small servo motor to control the speed. Electronically it was quite simple but the motor itself was quite complicated to manufacture and repair and most of the machines using such motors in the US. have had the motors replaced by conventional brush D.C. machines with speed changed by the use of a thyristor controlled armature voltage controller. The Brushless D.C. drive can be a direct replacement for the brush DC drive and is the subject of this paper.

II. History of Brush type DC Drives

The brush DC motor was invented in 1856 by Werner Von Siemens in Germany. Variable speed by armature voltage control was first used in the early 1930s using a system involving a constant speed AC motor driving a D.C. generator. The generator's DC output was varied using a rheostat to vary the field excitation and the resulting variable voltage DC was used to power the armature circuit of another DC machine used as a motor. This system was called a Ward-Leonard system after the two people credited with it's development. The Ward-Leonard method of DC variable speed control continued until the late 1960s when Electric Regulator Company brought to market a practical, general purpose, static, solid state controller that converted the AC line directly to rectified DC using SCR (thyristor) devices. That technology was adopted by virtually all manufacturers and still is in use today. It is a very simple power control concept and uses the fewest number of parts possible to produce variable speed from an electric motor.

III. Characteristics of DC drives

The DC motor works on the principle that speed of the shaft is a direct function of the applied armature voltage. To a lesser extent, field control can be used for speed control but it is not widely used except for winders and constant HP applications and will not be discussed here. At zero volts applied to the armature, the motor will run at zero speed, while at rated voltage (500 vdc for most industrial motors over a few hp), the motor will run at rated speed (1750 rpm has developed as a "standard"). The motor will produce torque based on a similar relationship with current. The torque produced by a DC motor will vary directly with armature current. These two simple characteristics make the DC motor continue to be the most popular means of variable speed control in use today for constant torque industrial applications. DC motors are very efficient in converting electrical energy to mechanical energy with typical values of 90 to 92 % for sizes from 10 to

75 hp. Controller efficiency is very high and averages 98% making the overall efficiency 88 to 90 % for the range of 5 to 75 HP. Unfortunately, the SCR, while being an efficient power conversion device, does so by varying the point on the AC voltage waveform at which current begins to flow. This means at mid to low output voltages, the power factor at which the power is used is very low [5]. While some years ago, this was not such a cause for concern, power companies are becoming more insistent that industrial users keep power factors up to at least .8 or higher. There are selfish reasons for the industrial user to keep power factors high as well since it reduces the size of transformers, breakers, fuses, and conductors in the power system. See the summary section on power factor.

IV. History of Brushless D.C.

The earliest evidence of a Brushless D.C. motor was in 1962 when T.G. Wilson and P.H. Trickey made a "DC Machine with Solid State Commutation". It was subsequently developed as a high torque, high response drive for specialty applications such as tape and disk drives for computers, robotics and positioning systems, and in aircraft where brush wear was intolerable due to low humidity. Unfortunately, the technology to make such a motor practical for industrial use over 5 hp simply did not exist until a number of years later. With the advent of powerful and permanent magnet materials and high power, high voltage transistors in the early to mid 80,s the ability to make such a motor practical became a reality. The first large Brushless DC motors (50 hp or more were designed by Robert E. Lordo at POWERTEC Industrial Corporation in the late 1980s. Today, almost all of the major motor manufacturers make Brushless DC motors in at least some horsepower sizes and POWERTEC makes Brushless DC from 1/2 to 300 hp as a complete product line (had has announced 500 Hp available in October, 1992). Brushless DC has had a substantial impact in some industry market areas, primarily Plastics and Fibers and most recently a mining company has put several of these drives at 300 hp ratings operating coal conveyors in underground mines. The drives work on the same principle as all DC motors but the motor is built "inside out" with the fields (which are permanent magnets) on the shaft of the motor and the "armature" on the outside. The fields turn and the "armature" stays stationary. To duplicate the action of the commutator (which no longer needs to exist since the winding is now stationary), a magnetic encoder is mounted to the shaft of the motor to sense the magnetic position of the fields on the shaft. The controller "sees" the magnetic position information and determines through simple logic which motor lead should have current going to a winding and which motor lead should return the current from the winding. The controller has power devices which connect the voltage on a capacitor bank to the correct motor lead at the correct time when the shaft encoder demands it. In this way the motor and controller act in the same way as a brush DC motor but without the brushes. The controller is built in a very similar way to the controller used in an AC variable frequency drive or in an AC Vector drive because all three types use a PWM type of variable voltage control to their respective motors.

V. Brushless DC Characteristics

Voltage on the motor determines speed and current in the motor determines torque. These relationships are linear and nearly identical to a standard Brush DC drive. The application of the product then is essentially like the more familiar brush machine. Speed accuracy is very high, in fact with the most widely used Brushless drive, the accuracy is synchronous (0% speed error) due to a digital encoder and drive controller position regulation. Torque to inertia ratios are very high providing high accel/decel rates and excellent dynamic response. Controller bandwidth (30 to 40 Hz) is 5 to 8 times higher [7] than the Brush DC drive. Motor thermal characteristics is the major advantage of Brushless DC in that a thermal speed range of 100 to 1 at full rated torque is available on the standard motor and totally enclosed motors are available in very small frame sizes. Motor efficiencies range from 90 to 96 % and controller efficiency is 97% giving overall efficiencies better than brush DC systems.

VI. Blowmolding Applications Advantages

In general, the characteristics of Brushless D.C. that are most advantageous to the blow molding process are:

- Very precise average speed control over a very wide speed range.
- Precise instantaneous speed control due to high dynamic response
- Constant power factor means lowest possible input current.
- Small physical size of motor compared to brush type.
- No recurring motor maintenance (brush replacement)
- Feedback device (encoder) is inside the motor not outside.
- Higher efficiency overall.

The blow molding process always involves an extruder of some kind and the variable speed drive on the extruder has to provide an output sufficient to allow the parison to be formed in time to meet the cycle requirements. Since the final product may require more or less volume of plastic for different shapes and because the cycle time varies, hence the requirement for variable speed. The result of inconsistent speed control is simply that more (or less !) material than is necessary to make the part will be extruded. Speed control consistency therefore is important to the production of a consistent product. Speed that either drifts slowly from the setpoint speed over a long period of time or speed that changes rapidly as a function of load, line voltage, AC line voltage, and/or other effects changes the process and ultimately either affects product quality or waste.

In the cases where rotary (wheel type) molds are used, the wheel drive must be coordinated with the extruder so the parison is the right size when the mold is ready to clamp. If the average rotational speed of the wheel is incorrect, the result is the same as if the extruder were running the wrong speed since the relationship of parison size to mold position would be off. One factor not necessarily considered however, is that even though the average rotational speed may be correct, the instantaneous speed of the wheel may be varying substantially. This is due to the fact that the torque loads seen by the motor vary as a function of the angular position of the wheel since the wheel operates the mold opening and closing cams. This reciprocating load will cause problems with some parts because it will directly affect the instantaneous speed of the wheel and therefore the "timing" of mold close and release relative to the parison formation. At least two blowmolding manufacturers have looked at this effect and the results are as follows.

Machine A: Machine had 12 stations making a large bottle. The machine was geared for approximately 80 bottles per minute at a motor speed of 1750 rpm. One test was run with a brush type D.C. motor and conventional Thyristor controller with tachometer feedback. Using a stroboscope synchronized the average speed of the motor shaft, the variation in the motor shaft position as the cam loading occurred could be observed. A shift of something between 180 degrees and 270 degrees of motor shaft rotation could be observed at every mold closing point. The average speed was also being affected causing a "drift" from the reference shaft position. See figure [1]. The brush drive was then removed and a Brushless D.C. drive was installed on the same machine and the tests were repeated. This time the change in shaft angle at the motor was approximately 18 to 20 degrees at every mold closing point and there was no change in the reference position. In other words the shaft average speed was being held synchronous to the set speed in the average sense and within 18 to 20 degrees in the instantaneous sense.

To explore the potential accuracy further, an external, high count (600 ppr) encoder was added to the Brushless D.C. drive and the test was repeated. This time the shaft angle change with load was less than 4 degrees ! The relationship of motor shaft angle to the wheel angle is 360 degrees of motor rotation equals 16 degrees of the wheel. This relates to approximately 0.056" of circumference of the wheel at its largest diameter per degree of motor shaft rotation. Table 1 shows these data.

DRIVE TYPE	FEEDBACK	DEGREES	ERROR AT DIAMETER
Brush D.C.	tach gen	180 degrees	10"
Brushless D.C.	120 ppr	18 degrees	1"
Brushless D.C.	600 ppr	4 degrees	.25"

TABLE 1: CIRCUMFERENCE ERROR DUE TO LOAD

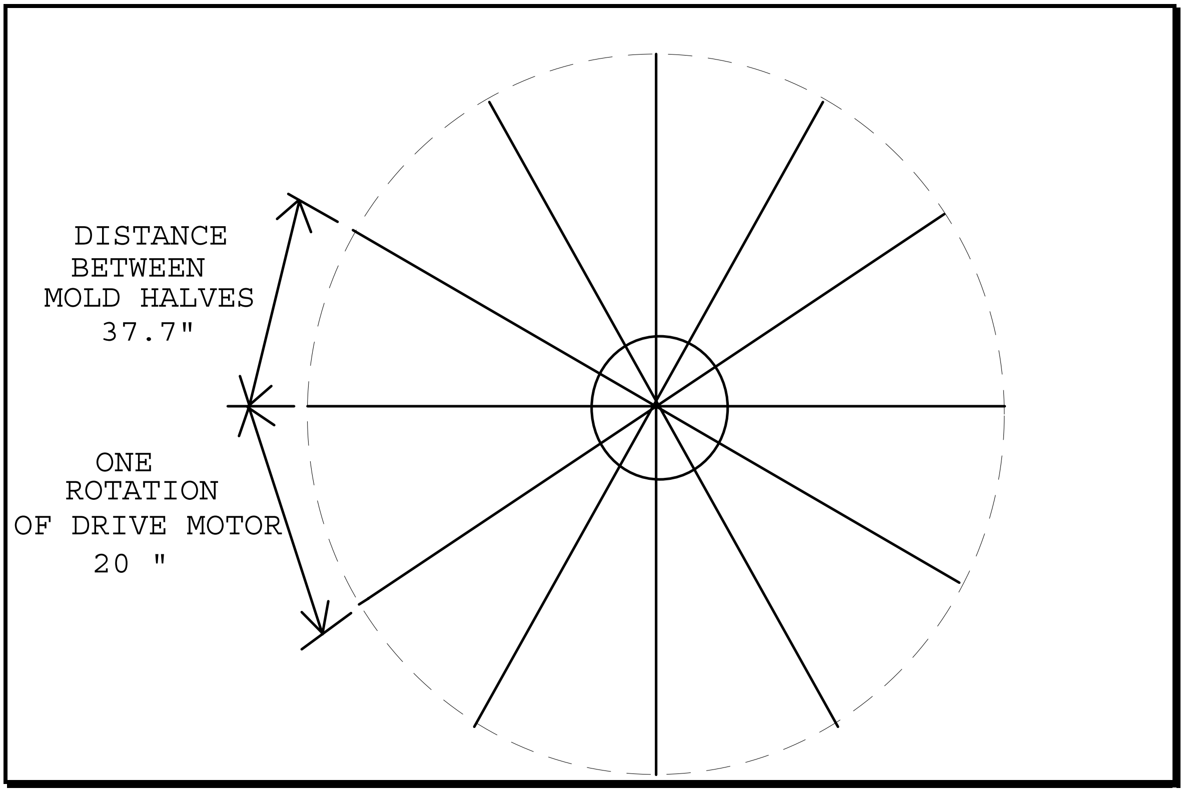


FIGURE 1: WHEEL MOLD

Machine B: A machine by another manufacturer has a very large diameter wheel measuring 108" in diameter. 1750 rpm equals 6 rpm of the wheel. The wheel has 12 stations. An investigation to determine the best drive to minimize any instantaneous or average speed change was made and both brush type DC as well as AC type drives were used. The manufacturer settled on a Brushless D.C. drive. The final results of a stroboscopic study showed that the ring gear with a 108" pitch diameter with 3-pitch teeth (.33 in/tooth) did not vary either in long term average or instantaneous position by more than 1 tooth. Variations of several inches were noted with other drive types.

VII. Power Factor

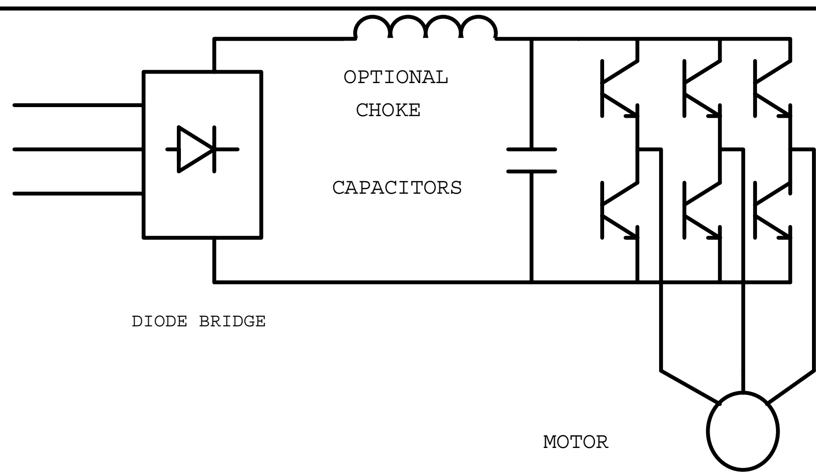
In addition to the speed regulation and dynamic response characteristics of Brushless DC, the efficiency and power factor can be major considerations. Efficiency differences are not dramatic since brush D.C. is already a high efficiency technology. Since the differences are small (about 2%), the potential savings due strictly to efficiency are not great taken by themselves except on large machines or a large number of smaller machines. Power factor differences however are very large and the potential savings due to the combination of efficiency and power factor can be quite large since blowmolding machines typically run 24 hours a day, seven days a week.

Power factor is a term recently being given a considerable amount of press, primarily due to the increased pressure by utilities on users to improve the operating power factors of industrial plants. Closely related to power factor is harmonic currents. Both of these are becoming very important terms because of penalties, extra charges, and outright refusal to allow connection to AC power sources unless controlled within certain parameters.

Power factor is a measure of how much real current is required to operate a certain load (usually inductive) relative to the current to operate the same load if it were a pure electrical resistance [5,6]. It is defined as the ratio of real power (watts) to apparent power (KVA). As an example, if a machine required 100 amperes to operate with a perfect power factor (1.0, pure resistive load), the same machine would draw 200 amperes to do the same work if the power factor were .5. While the watts are the same in both cases, and the power meter would read the same in both cases, a demand meter or power factor meter would see the difference and the power company would obviously rather deliver the 100 amps than the 200 amps at the same cost ! It matters to the user however, even if the power company doesn't care because a transformer, for instance (same for switch gear, fuses, wire, etc.) would have to be twice as large for the poor power factor machine.

Usually directly associated with this problem is a companion problem involving harmonic currents. When AC current is drawn from the line in other than a sinusoidal waveform, harmonic currents result that cause significant power losses and disruptive effects on the power source [6]. Large harmonic currents cause both the user and the utility problems and should be avoided when possible.

Brush type D.C. drives create both low power factor and high current harmonics due to the way in which power is converted. Little can be done, within practical cost constraints to prevent it. DC Brushless drives use power control circuitry involving a full wave diode bridge, capacitors, and output switches. A key item in the design relative to both power factor and reduced harmonic currents is the choke which is shown as a option in the diagram below. This choke must be fairly large (in the range of 2 to 5 millihenries) to have the best effect and some kind of choke must be present [5] or the resulting power factor and harmonic current draw can be even higher than the brush type drive at some speeds and loads. The user should take care to insure that an appropriately sized choke is provided in the equipment design he is considering since the use of such a choke is not widespread. These chokes add a measurable cost to the equipment and since it is not necessary to operation, there is significant pressure on the equipment supplier to not include the choke in the design. Be aware that this choke, in order to be effective in increasing power factor MUST BE DOWNSTREAM OF THE DIODE BRIDGE, [6] it will not work when added to the AC input side and therefore must be bought built into the equipment.



TYPICAL PWM CONTROL FOR AC, VECTOR, AND BRUSHLESS DC

FIGURE 2: Choke location in power bridge

Table 2 shows the result of calculations involving a typical extruder running at 80 of rated load and 80% rated speed (a common operating condition) continuously using a brush type drive versus a Brushless D.C. drive with the appropriate buss choke. The figures are based on a 150 hp drive.

80% SPEED, 80% LOAD ENERGY USAGE FIGURES FOR 150 HP DRIVE AND MOTOR

	SCR	**BLDC**	
TORQUE OUTPUT	360	360	lbs-ft
SPEED	1400	1400	RPM
POWER OUTPUT	71616	71616	WATTS
MOTOR VOLTAGE	400	206	VDC/VAC
MOTOR CURRENT	196	206	ADC/AAC
FIELD POWER	1000	0	WATTS
POWER TO MOTOR	79400	75845	WATTS
MOTOR EFFICIENCY	90.2	94.4	%
CONTROLLER LOSS	1007	1562	WATTS
INPUT POWER	80407	77407	WATTS
AC LINE CURRENT	160	102	AAC
POWER FACTOR	0.63	0.96	
KVA PER KW	1.59	1.05	
NORMALIZED POWER	1.04	1.00	

51.44%	MORE KVA REQUIRED
3.88%	MORE KW REQUIRED
26,280.76	MORE KWH PER YEAR REQUIRED BY DC/SCR
$ 2102.46	SAVINGS USING BRUSHLESS DC AT $.08/KWH

TABLE 2: Efficiency Comparison brush DC to Brushless DC

The dollar savings above are figured based only on the efficiency differences and do not account for the power factor related savings due to extra losses in wire, transformers, etc. which add another $ 1000 per year and that does not include any penalties or correction costs for poor power factor. A detailed derivation of these numbers is not included here but can be obtained from POWERTEC Industrial Corporation. See the references at the end of this paper [8].

VIII. Summary and Conclusions

While there are several options available to the manufacturer and user regarding the type of variable speed drive to use on the Extruder and rotating mold applications of the blow molding machine, there are some distinct advantages in the use of the Brushless D.C. drive while other types of drives may become available in the future that may provide these advantages, they are not yet available for general use in the HP sizes necessary for most blow molding machines. The Brushless DC technology is here and in wide use in various extrusion and related applications in the plastics industry.

IX. References

[1] T.G. Wilson, P.H. Trickey, "D.C. Machine With Solid State Commutation", AIEE paper # CP62-1372, Oct 7, 1962.

[2] NEMA Publication # MG 1, ref MG-1.41.2, table 12.6B

[3] Eaton Dynamatic Electric Drive Applications Guide page M-37.

[4] Dennis P. Connors, Dennis A. Jarc, Roger H. Daugherty, "Considerations in Applying Induction Motors with Solid-State Adjustable Frequency Controllers", IEEE Transactions on Industry Applications, Vol 1A-20, no. 1, January/February 1984.

[5] John B. Mitchell, "Inverter Power Factor and Noise", Power Transmission Design magazine, page 45, 46.

[6] Derek A. Paice, "Harmonic Issues and Clean Power Controllers", Westinghouse Electric Corp, Presented at PCIM '90, Oct 25, 1990.

[7] Frank J. Bartos, "Reliability, Ease of Use Widen AC Drives' Application Horizons", Control Engineering News, page 55, February 1992.

[8] Robert E. Lordo, "Comparison of the 150 HP Brushless DC and conventional DC/SCR motor/Control", June, 1992, POWERTEC Industrial Corp. Box 2650, Rock Hill, S.C. 29732, phone 803-328-1888.