REVIEW OF VARIABLE SPEED DRIVE TECHNOLOGY

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Abstract - **Variable speed drive technology has advanced dramatically in the last 10 years with the advent of new power devices and magnetic materials. This has given rise to substantial confusion by users and specifiers of variable speed drive equipment. Add to that the difficulty in evaluating efficiency and power factor and the subject of drive selection becomes a daunting task indeed. There is no single type of drive system which is perfect for all applications, therefore the purchaser must choose the most appropriate system for the job to be done. This paper will identify the drive types available in the industrial marketplace in integral horsepower sizes from 1 to 500 hp which covers the greatest majority of general industrial applications. Various characteristics of each type will be described including performance, size, ease of application, performance, maintenance, efficiency, power factor, and cost. Finally, comparisons will be made by type as to relative advantages and disadvantages since each type will be better suited for some types of applications than others.**

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

Eddy Current, magnetic reluctance, and other types are available but are not widely used and have various qualities making them unsuitable for widespread general use and are not discussed in this paper.

II. History of Brush type DC Drives

The brushed 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 efficiently 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 AC Variable Frequency

The induction motor (as well as the syncronous and split phase motors) was developed by Nikola Tesla in 1924 and has the endearing characteristic that it can be run by direct connection to a three phase power source. The motor speed is directly proportional to the applied frequency and is determined by the formula $n = 120f/p$ where n is the synchronous speed of the motor in rpm, f is the frequency of power applied and p is the number of poles on the rotor. Therefore a 2 pole induction motor running at 60 Hz will run at 3600 rpm synchronous speed less the slip required to produce the induction effect at full load. This slip is variable depending on the motor design but for the "standard" NEMA design B motor it is 3 to 5 % making the typical 2 pole motor run at 3500 rpm at full load at 60 Hz. Soon after the AC motor was developed, the idea of varying the speed was considered and the only practical way of doing this at the time was to provide the motor with a variable frequency obtained by using a DC motor turning an AC alternator which allowed a variable frequency. This was done on a wide range of applications in the 50s, 60s, and 70s. Since the much simpler Ward-Leonard system existed for DC motors, however the major use for such lines was in precision controlled multimotor lines where synchronous AC motors were used for each section and when the master alternator frequency was varied, all the motors would follow together with synchronous accuracy. Such systems were still being installed on new machines as late as the mid 80s when static variable frequency controls became widely used. Static AC variable speed drives that were readily available were of the six step, variable voltage design. Later, when Phillips/Signetics came out with a sine coded PWM chip set, sine coded PWM drives became the norm and six step variable frequency faded into non-use except for unusual applications where the slightly lower loss at full speed, full load was an advantage.

V. Characteristics of AC Drives

Of the several types of AC variable frequency drives available, only the PWM voltage source, sine-coded type is commonly in use. For general purpose drives over 5 Hp they are essentially the only type available. The current source type is fairly common at 100 hp and higher and does offer some advantages. These two types will be discussed. One universal aspect of induction motor speed control is that slip is required in order for the motor to produce useful torque [4]. The various means for improvement in performance such as voltage boost, energy savings by voltage reduction, slip compensation, "scalar" control, vector control, etc. do nothing to prevent the slip which is inherent in the motor design. At full speed, full load, an AC motor will slip an amount roughly equal to 3% of it's synchronous speed based on the motor design and this is not affected in the least by the design of the controller. This slip represents energy loss in the rotor of the AC motor and converts directly to heat inside the motor which must be dissipated. This one fact alone makes the AC machine relatively limited in terms of full torque thermal speed range. The standard induction motor cannot produce full torque over more than a 2 to 1 speed range without overheating if subjected to continuous duty. Energy efficient types can stretch this speed range to approximately 3 to 1 and special designs can extend this to 10 to 1 [4,3]. Dynamic response of the standard variable frequency drive is very limited with bandwidths of 1 to 3 Hz typical [7]. The PWM AC drive is the drive of choice for applications not requiring high starting torques, high continuous torque at low speeds, or fast dynamic response. Such applications are pumps, fans, some types of conveyors, and similar applications. It should be noted that by judicious use of a combination of high efficiency or special design motors, much higher torques can be achieved but at higher cost. One of the most compelling reasons to use such a variable speed drive is price (in the small hp sizes particularly). Another reason why AC drives are very nearly universally used in fan and pump applications is the ability to run a standard AC motor (if the application allows it) which can be bypassed, or operated from the AC line in the event the controller might become inoperative. The ability to do this in a municipal pumping application where sewage or water is pumped is imperative and in many cases, the locations where this equipment is located is remote and controlled by computer or PLC and the sensing of controller malfunction and bypassing it is all done automatically without human assistance. The problem is annunciated and is later fixed by maintenance personnel.

VI. History of the AC Vector Drive

AC vector technology was known as early as 1970 but practical devices employing the technology in industrial applications did not become available until the early 80s and first units were generally limited to current source inverter technology. The current source inverter, however is only practical for general purpose use at 75 to 100 hp and up and virtually no progress was made with the technology until the PWM sine coded inverter became a reality in the middle 80s. At this point in time, vector AC drives have still not had a significant effect in the general industrial market primarily due to the complex algorithm (formula) the controller uses to locate the flux vector and the fact that the controller must be "programmed" with the motor parameters. As more manufacturers are bringing these drives to the marketplace, they are being used in more general purpose applications. The vector drive is used in large numbers in the machine tool industry where it's high speed and wide constant torque range capabilities are key benefits.

VII. Characteristics of the AC Vector Drive

The most significant characteristic of the Vector Drive is that full inner current loop control of the AC motor is possible which cannot be done with the conventional AC variable frequency drive. This aspect of control means that if the bandwidth is high (which it is in most good vector drives), very tight velocity and or position loop control over a standard induction motor is available. Vector drives typically use a full wave diode bridge "front end", an intermediate capacitance storage bank and out output power section using either bipolar power transistors, GTOs, or FETs. All three of these are high speed power switching devices that can be turned on and off (commutated) at will. The controller uses these devices in a Pulse Width Modulated (PWM) mode of voltage control. Very nearly all Vector drives require that an encoder or tach generator be added to the induction motor in order to determine rotor slip. It is possible to run an induction motor without the feedback device but the result is that very tight dynamic response and position holding is not possible around zero speed and accurate speed range is reduced to 30 to 1 from the otherwise available 100 to 1. The vector control allows control of an induction motor such that performance is as good as (or even better in some cases) any brush type DC drive presently in general purpose use. Since the torque-to-inertia ratio of the induction motor is better than the brush DC motor, the potential for very high acceleration/deceleration rates exists. The induction motor however has one characteristic that limits the effectiveness of the vector drive in some applications. The conventional AC motor, even with substantial modification cannot run continuously at full torque at very low speeds due to the thermal losses in the rotor due to slip. No motor is being currently advertised that will provide speed ranges over 10 to 1 (operation from full speed to 1/10 of full speed) continuously at full torque due to this limitation.

VIII. 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 size range and one company 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.

IX. 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 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 any of the other three technologies. Disadvantages are similar to those for the vector drive in that it is not widely available from a large number of manufacturers and the technology is more complex than Brush DC or simple AC variable frequency. The performance and efficiency advantages however should make it worth considering in most general purpose applications.

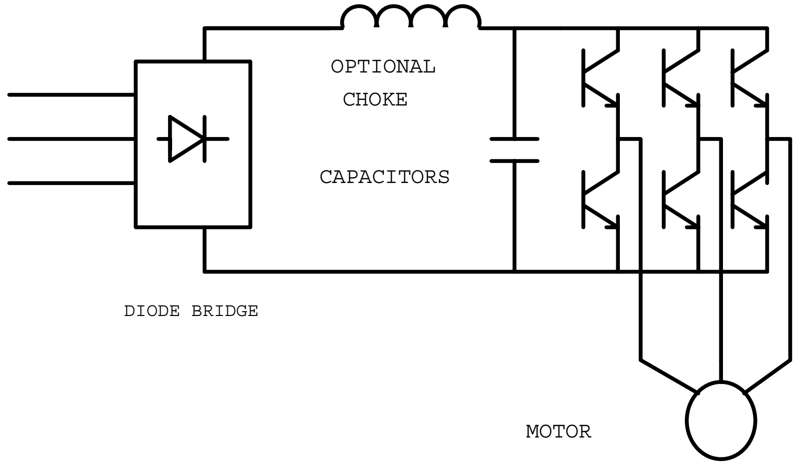
X. Power Factor

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]. Basically it is the ratio of real power (watts) to apparent power (kva). As an example, if a machine required 100 amperes, three phase 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 switchgear, fuses, wire, etc.) would have to be twice as large for the 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 it is 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. AC variable frequency, AC vector and DC Brushless all use the same basic 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 cannot be added to the AC input side and therefore must be bought built in to the equipment.



TYPICAL PWM CONTROL FOR AC, VECTOR, AND BRUSHLESS DC

XI. Advantages/Disadvantages Summary

BRUSH TYPE DC

ADVANTAGES	DISADVANTAGES
ESTABLISHED TECHNOLOGY	LOWER ACCURACY
SMALL CONTROLLERS	POOR POWER FACTOR
HIGH EFFICIENCY	BRUSH WEAR
WIDE SPEED RANGE	REQUIRES LARGE BLOWERS
LOW INITIAL COST	FIELD WINDING NECESSARY
WIDELY AVAILABLE	COMMUTATOR LIMITS O-LOAD

AC VARIABLE FREQUENCY

FAIRLY SIMPLE CONTROL	POOR ACCURACY
ESTABLISHED TECHNOLOGY	LOW STARTING TORQUE
USES STANDARD INDUC MTR	POOR SPEED RANGE
LOW INITIAL COST	POOR DYNAMIC RESPONSE
GOOD EFFICIENCY	POOR POWER FACTOR
WIDELY AVAILABLE	LARGE CONTROLLER

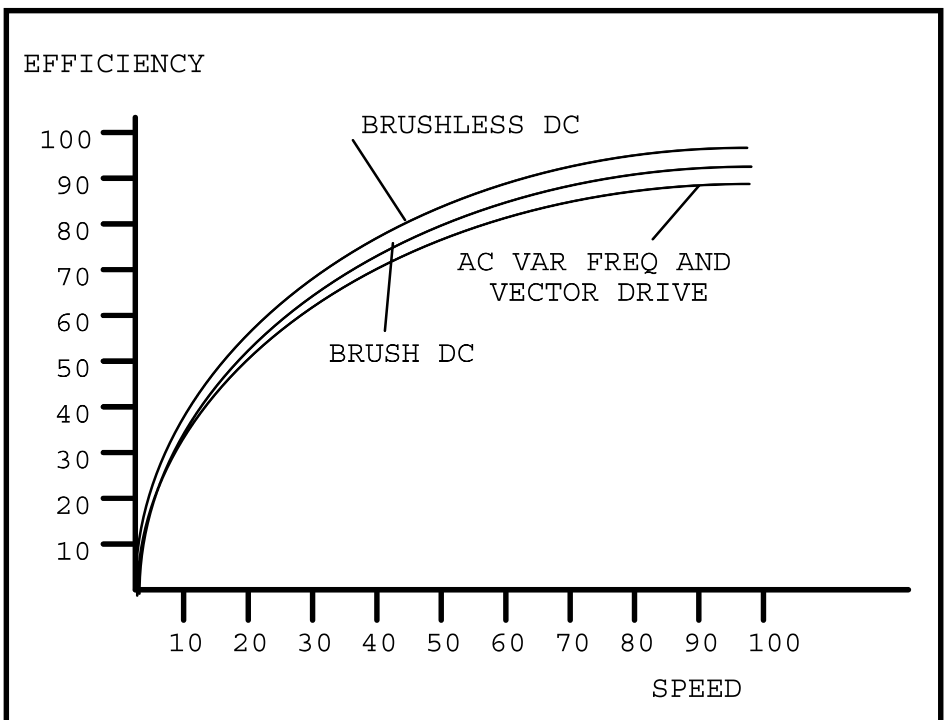
AC VECTOR

HIGH DYNAMIC RESPONSE	HIGHLY COMPLEX
USES STANDARD INDUC MTR	HIGH COST
HIGH ACCURACY	USUALLY NEED SPECIAL MOTOR
VERY WIDE SPEED RANGE	MOTOR COOLING PROBLEM

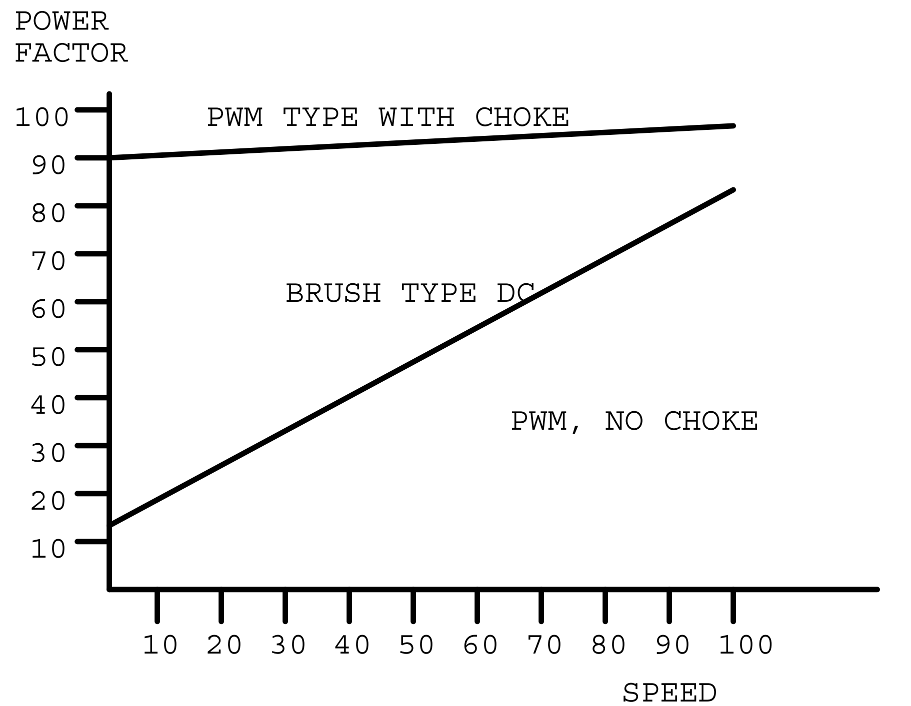
VERY HI STARTING TORQUE	NEEDS MOTOR TACH
GOOD EFFICIENCY	MAY HAVE LOW POWER FACTOR
LOW CONTROLLER LOSSES	HIGH MOTOR LOSSES
CONTROL TO ZERO SPEED	LIMITED HP AVAIL

DC BRUSHLESS

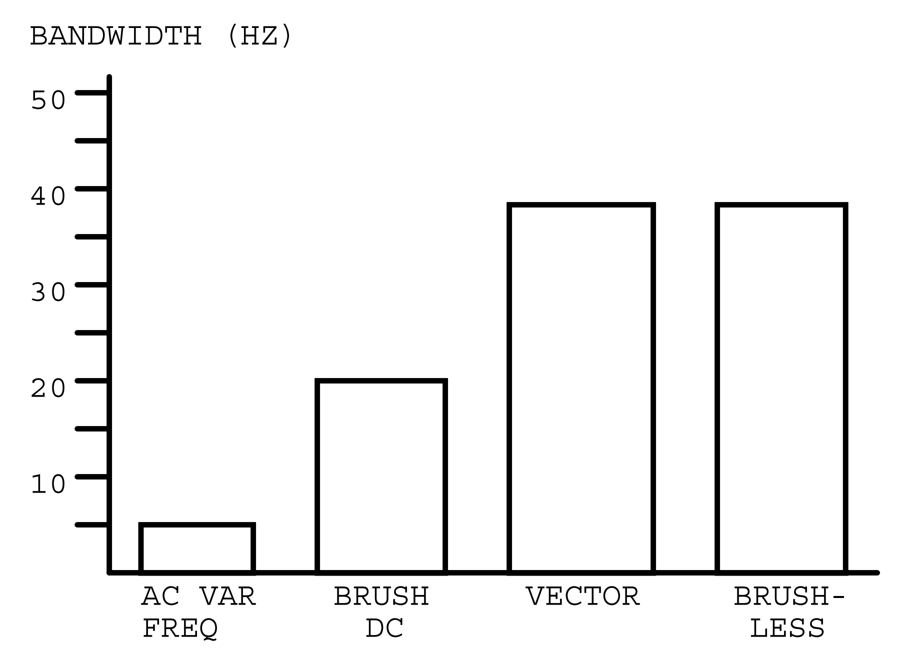
HIGH DYNAMIC RESPONSE	SOMEWHAT COMPLEX
0% SPEED ERROR	REQUIRES SPECIAL MOTOR
VERY WIDE SPEED RANGE	NEEDS ENCODER (FOR BEST PERF)
EQUAL COST TO BRUSH DC	LARGE CONTROLLER
COOL RUNNING MOTOR	FEWER MANUFACTURERS
HIGHEST EFFICIENCY	
LOW CONTROLLER LOSSES	
LOW MOTOR LOSSES	
CONTROL TO ZERO SPEED	
VERY HIGH POWER FACTOR	
HAS ENCODER INSIDE MOTOR	



TYPICAL EFFICIENCY/SPEED CURVES AT FULL LOAD



POWER FACTOR VERSUS SPEED



COMPARITIVE BANDWIDTH
(DYNAMIC RESPONSE)

XII. References

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