A Comparison of the Characteristics of AC and DC Motors

CONTROLMATCHED
Variable Speed Solutions

Motors-9.1

Rockwell Automation
Allen-Bradley

Abstract

As AC motors continue to be used in applications traditionally served by DC motors, some comparisons of the characteristics of AC and DC motors seem appropriate. The aspects of AC and DC motors which will be reviewed include typical construction, torque production, equivalent circuits, ratings (power and torque density), speed ranges, load ranges, etc.

This comparison will also highlight some of the relative advantages and disadvantages of each type of motor in variable speed applications. In addition, looking at variable speed AC motors with a “DC motor mentality” can offer a more “user-friendly” understanding of these AC machines. This point of view can also suggest ways to optimize AC motors for variable speed applications.

Introduction

As AC motors continue to be used in applications traditionally served by DC motors, some comparisons of the characteristics of AC and DC motors seem appropriate.

This session will NOT provide a broad endorsement of one technology as being universally superior to the other. Rather, it is intended to provide specific comparisons of individual features and characteristics of AC and DC machines. Attempts will be made to point out when differences are “technology-based” (i.e. physics), as opposed to “history-based” (i.e. standardization, application, etc.). The basis for comparison will be for DC, a wound field (separately-excited) 4 pole machine, and for AC, a squirrel-cage induction, 3 phase, 4 pole machine.

Construction

Let’s quickly look at some of the basic constructions of AC and DC motors. As you will see, while some generalizations can be made regarding construction differences, there are many exceptions to these generalizations.

While a lot of AC motors use a cast iron frame, with mounting feet integral to the frame (Figure 1), there are also AC motors with mounting feet on the endshields (Figure 2).

Figure 1.

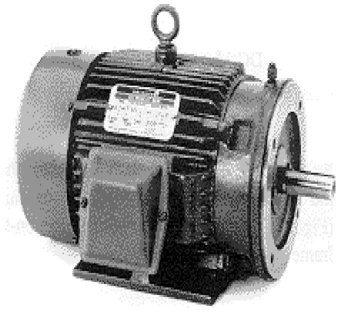
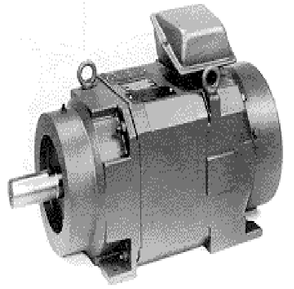


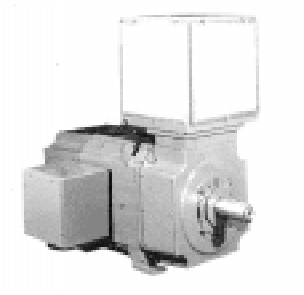
Figure 2.



By the same token, while many DC motors have the mounting feet as part of the endshield (Figure 3), other DC motors utilize feet-on-the frame construction (Figure 4).

Figure 3.

Figure 4.



With the proliferation of static power supplies (instead of MG sets) for controlling DC motors some years ago, the laminated frame construction (Figure 5) became popular. As more AC motors are being applied with electronic power sources, the laminated frame construction is seeing increased usage (Figure 6) for AC motors (especially for inverter applications).

Figure 5.

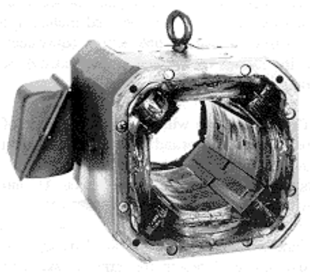
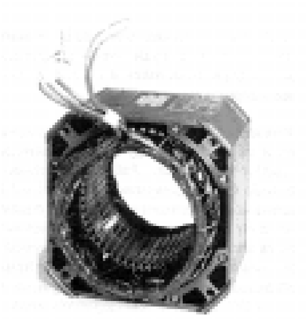


Figure 6.



In short, the basic construction features of AC and DC motors are less likely to be divided along AC versus DC lines, but rather application or manufacturer preference is more likely to influence construction type.

Terminology

As long as we’re looking at pictures of motors, this would probably be a good time to go over some terminology we’ll be using during this session - to be sure we’re all on the same page. I’ll refer to endshields (brackets, end-brackets), frames, stators, rotors, an-natures, main field poles and coils, commutating poles and coils (interpoles and coils), compensating (pole face) windings, commutators, and brushes. Each of these terms will refer to motor parts as indicated in Figures 7 - 10.

Figure 7.

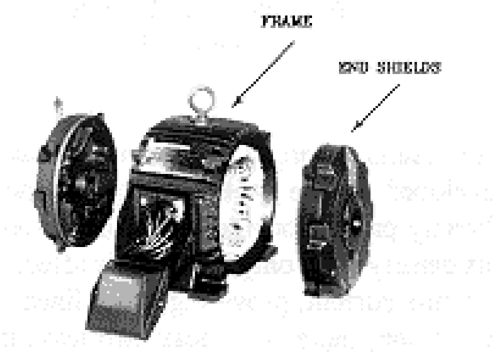


Figure 8.

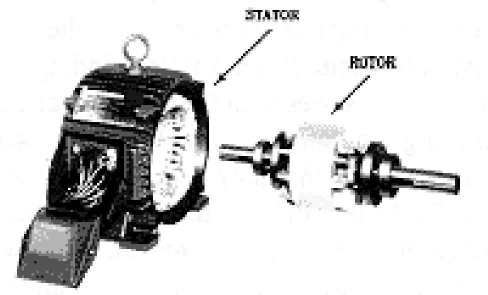


Figure 9.

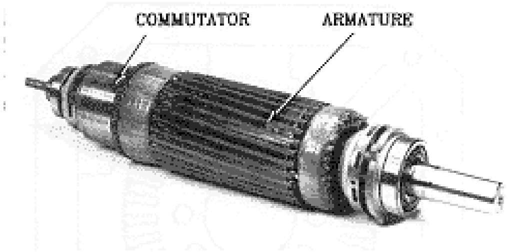
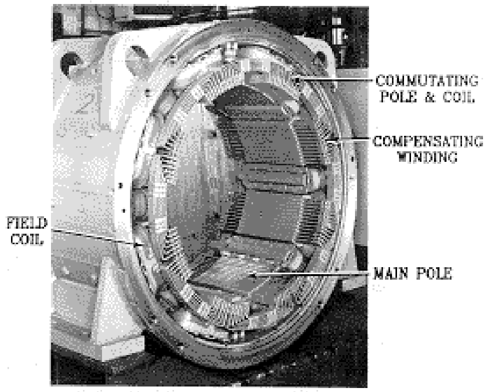


Figure 10.

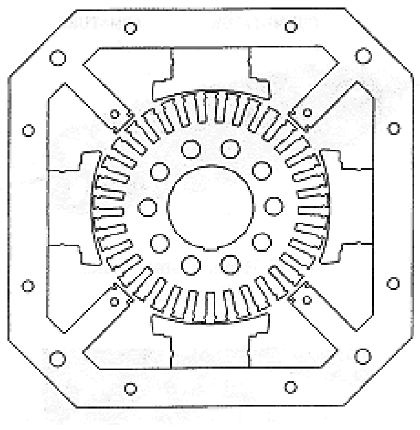


Torque Production

Moving closer to the "heart" of AC and DC machines, let's look at how torque is produced in converting electrical power into mechanical power in each type of machine.

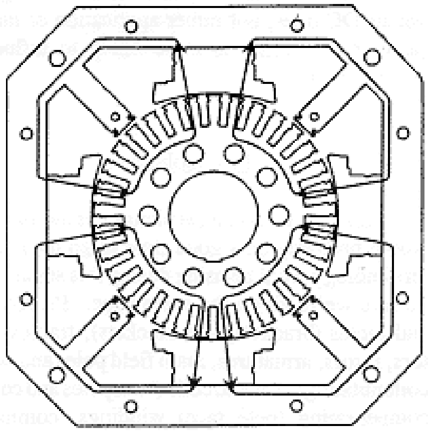
Starting with the conceptually simpler DC machine, a typical electromagnetic cross section is shown in Figure11. This particular embodiment shows a "4 pole" construction, which is typical for a range of about 20 BP to over 1000 BP. DC machines are typically manufactured with a fixed (single) number of poles as the construction for a given frame size. This still allows machines with a wide range of "base speeds" to be constructed within that frame size.

Figure 11.



The field windings (or permanent magnets) in a DC machine set up a magnetic flux pattern as shown in Figure 12. For the purposes of this session, we will assume that the field winding is supplied with current from a source separate from the armature supply, as is commonly done.

Figure 12.



When current flows in the armature windings, this interacts with the magnetic flux to produce forces based on the equation:

F = B x I x L (for a perpendicular orientation of the field and current). (Technically a ‘cross product’ of vectors.)

(F = force in N, B = magnetic flux density in webers/sq m,
I= current through the conductor in Amps, L= length of the current carrying conductor in the magnetic field in meters).

This results in torque (force times moment arm) developed in the motor which is linear with (directly proportional to) armature current. The flux density (B) is only secondarily affected by the armature current, providing a nice linear system. In addition, there are at least two ways in which even the second-order effects of armature current on flux density are mitigated.

The first of these is through the use of series (stabilizing) windings on the main field poles. These windings are concentric to the (normally separately excited) main field windings, but are connected in series with the armature circuit. For motoring operation, these windings would be connected such that they incrementally add to the main field strength by an increasing amount as the load (armature current) increases. A drawback to this type of winding is that for reversing applications, the series winding would be of the wrong magnetic polarity in the opposite direction of rotation.

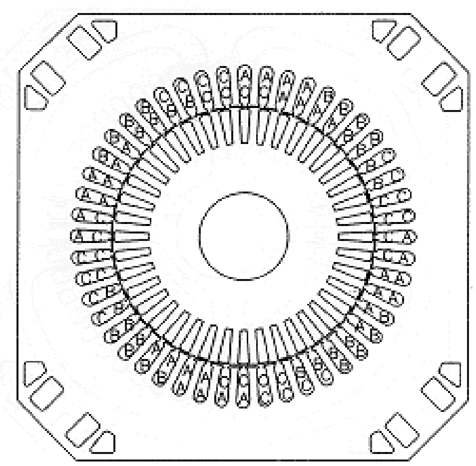
The other method of minimizing the effect of armature current on the motor flux is through the use of compensating, or pole face windings. These windings are also connected in series with the armature circuit, but are not wound concentric to the main field windings. Rather, these windings are inserted into the face of the main field poles (adjacent to the air gap) in such a way to be concentric with the commuting Interco windings. These windings provide a magnetomotive force (mmf) which is as closely as possible exactly opposite to the mmf of the armature windings. DC motors with compensating windings can be operated in all four quadrants of the speed/torque plane (forward and reverse, motoring and generating) with consistent performance.

The end result is, even without the use of either series or compensating windings, a DC machine usually has a sufficiently linear torque/current relationship that fairly simple control techniques can be employed. The differential equations describing both the electrical and mechanical performance are simple linear, first order differentials. Suffice it to say that this allows straightforward calculations of gains, stability, etc. to be made for drive systems employing DC motors. Another feature worth pointing out at this time is that the commuting Interco windings do not contribute at all to the basic function of producing torque in a DC machine.

AC Motor Torque Production

Moving on to torque production in AC induction machines, this is where it becomes harder to NOT sound like it's all hocus-pocus or magic. Obviously the enormous number of AC induction motors running various applications should be enough proof that it isn't all smoke and mirrors.

Figure 13.

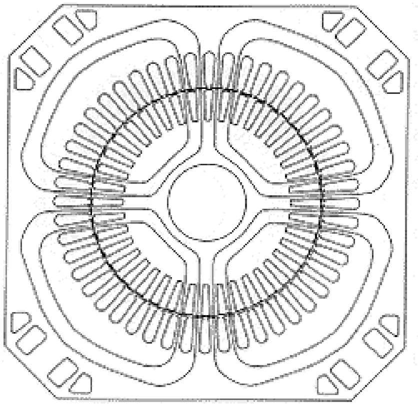


A typical cross section of an AC induction motor lamination (electromagnetic cross section) is shown in Figure 13. Various rotor slot shapes are frequently used to provide specific performance characteristics, but that will not be important to our discussions in this session. More will be said about that subject in a later session. The winding layout shown corresponds to a 3 phase, 4 pole configuration. For simplicity and also for consistency, we will use this arrangement for our comparisons to DC machines.

The first obvious difference between this AC lamination and the DC motor cross section shown earlier is that the AC windings are “distributed” around the air gap, rather than being “concentrated” coils. Also, there are only stator windings and rotor windings, whereas the DC machines may have armature and field windings-plus commutating, series, or compensating windings in addition.

The stator winding will, under no load conditions, set up a magnetic field as shown in Figure 14.

Figure 14.



Since the stator windings are carrying alternating current (AC), this magnetic field will be time varying in a sinusoidal fashion as viewed from a fixed point in the electromagnetic circuit. It can also be shown that the peak (or any other selected reference point) of the flux pattern “travels” in a rotational manner at a speed equal to: rev/sec = f/(p/2), where f is the frequency of the alternating current in the stator (in cycles/sec) and p is the number of poles.

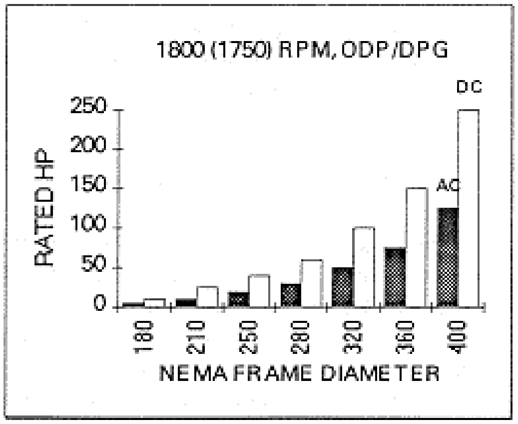
Without any load on the motor, the rotor will turn in synchronism with the rotating magnetic field. As load torque is required from the motor, the rotor speed will decrease relative to the rotating field. The difference in the magnetic field speed and the rotor speed (known as slip) induces current to flow in the squirrel cage rotor. This current interacts with the magnetic field it is in to produce force (and torque) just as described previously for a DC machine. The major difference is how the AC machine rotor current is developed versus how the DC motor armature current is supplied.

In the AC motor, it is via magnetic induction that the rotor current is caused to flow. In the DC motor, current is directly supplied to the rotating armature via the brushes and commutator.

Power and Torque Density

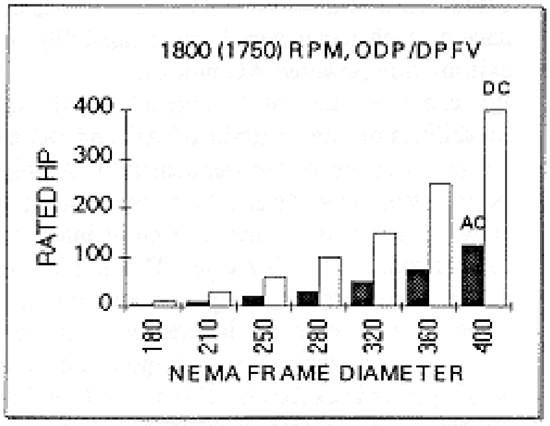
Based on historical usage of modem AC and DC machines in industrial applications, the DC motor would appear to have a distinct advantage in terms of either power developed per frame size, or torque per frame size. The comparisons of power density in Figure 15 are based on typical catalog offerings of open, self-ventilated AC and DC motors in NEMA frame sizes. There are some issues which make "typical catalog offerings" of these motors less than a perfect "apples-to-apples" comparison. The AC motors tend to be built in frame sizes as established by NEMA MG 13. These motors/ratings are based on Class B insulation, 1. 15 Service Factor, and operation on sodial power (not inverter power). The DC motors/ratings tend to follow a pattern of Class F insulation, 1.0 Service Factor, and rated for operation on static (rectified) power supplies.

Figure 15.



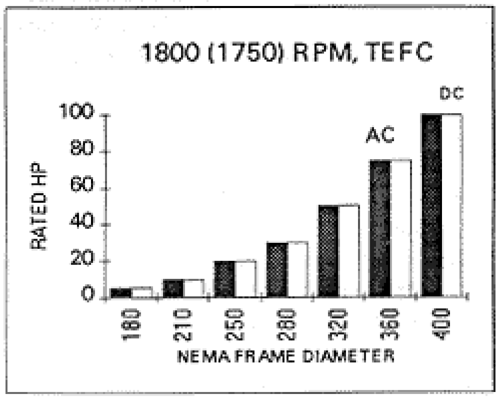
If this comparison is carried a step further in the direction of "typical motors" applied in industrial applications, the charts of Figure 16 would result. The DC motors/ratings in these comparisons are based on a "force-ventilated" (DPFV) enclosure, instead of the "self-vent" ratings of Figure 15. A dramatic apparent advantage of power density for "typical DC motors used in industrial applications" can be seen.

Figure 16.



If we next make these comparisons based on "totally-enclosed" motors (such as TEFC), but continue to base the comparison on "typical catalog offerings" of AC and DC motors, the data in Figure 17 are the result. This implies nearly identical power density for AC and DC motors in a TEFC configuration. Again, there are some less than apples-to-apples aspects of speed comparison. Similar to the comments for Figure 15, the AC motors/ratings tend to be B insulation, sinewave power, but may be 1. 0 Service Factor (rather than 1. 15) for TEFC motors. The DC motors/ratings in Figure 15 have the same assumptions stated for the open (DPG) ratings.

Figure 17.

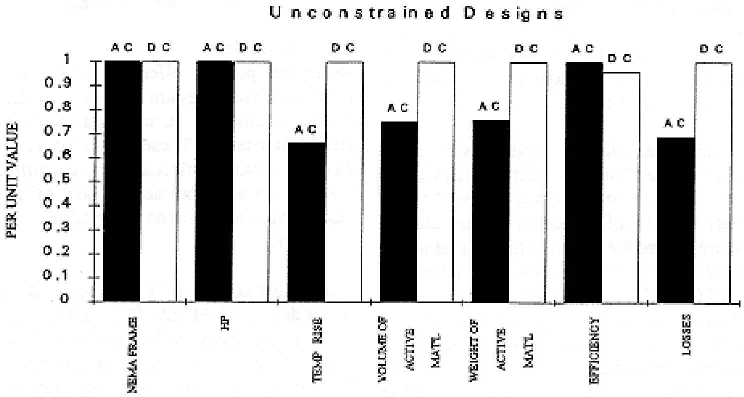


Power Density Comparison of Unconstrained Designs

The comparisons in Figures 15 - 17 are all based on typical product offerings of AC and DC motors. As such, they are influenced by historical considerations and standardization (including NEMA Standards). These comparisons therefore do not reflect any inherent differences based on the pure "physics" of how AC and DC machines convert between electrical and mechanical power.

In order to make a more "pure" comparison of the power density of AC and DC machines, designs were created from an "unconstrained" starting point. Designs for various ratings from 100-500 HP were utilized for the comparisons shown in Figure 18. The data in Figure 18 are based on designing an AC motor and a DC motor for a selected rating (HP and speed) in a specific frame size. Both were designed with the same DPFV cooling system. Both were rated based on use with static power supplies, i. e. AC PWM inverter power and DC rectified power. (Ms also allows the modification of AC rotor slots for optimal performance on adjustable frequency PWM power.)

Figure 18.



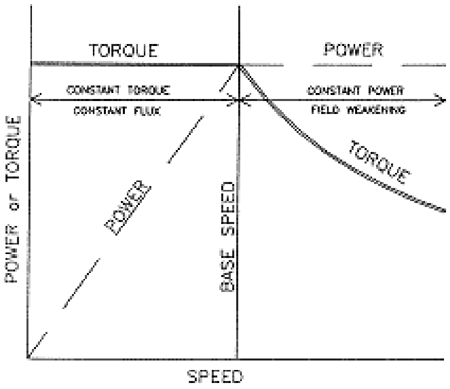
Various ratings in various frame sizes consistently followed the pattern of results shown in Figure 18. This chart shows that in an “unconstrained”' comparison of the basic technologies of AC and DC power conversion, the 3 phase AC induction motor has some distinct advantages in regard to power density. The fact that the DC motor is saddled with “non-torque-producing” components such as commutating coils is a major reason for this AC advantage. It is also interesting that Figure 18 (unconstrained designs) is so different than Figures 15 and 16.

Application Issues Speed Ranges

If we compare typical AC and DC motor products in use today, the DC motors (since they are in most cases applied across a speed range) are predominantly cooled by methods independent of motor speed. As a result, these DC motors will tend to have a much wider speed range capability than existing line-powered AC motors.

We can then look at “inherent” speed range capabilities of “unconstrained” AC and DC motors (as was done for “power density”). As might be expected, using a “clean sheet” or unconstrained design philosophy results in a more interesting comparison. For both AC and DC motors, the curves of Figure 19 apply. Below the “base speed,” these motors are inherently “torque producing”, while above the base speed a constant output power is expected. For both AC and DC machines, this corresponds to “constant flux” operation below base speed, and “field weakening” above base speed.

Figure 19.



Below Base Speed

As long as the motor cooling is dependent on motor speed, the low speed limit of the constant torque speed range is usually a thermal limit. The extent of this part of the speed range will then also be strongly influenced by any thermal margin which may exist at base speed. For both AC and DC motors, winding 12R losses remain constant (for constant torque) as speed is reduced below base speed. Iron losses (eddy currents and hysteresis losses in the magnetic core) are reduced as speed decreases with constant flux. These phenomena are essentially the same for AC and DC motors. In the very low speed area is where AC and DC motors have some distinct differences.

While DC motors (with speed-independent cooling) can provide constant torque to very low speeds, at a true “zero” speed localized heating of the commutator can cause problems. For that reason, DC motors are not typically rated for full torque at “stall,” or zero speed.

In the case of AC motors, a different phenomenon can limit speed capability at very low speeds. With DC motors, maintaining a constant flux condition while speed is reduced is quite straightforward. However, since AC motors do not have separate field and “power” windings, this becomes a more complex issue for AC. Constant flux in an AC motor can be viewed as a constant ratio of Eg./f, where Eg is the motor internal generated voltage, and f is the AC frequency applied to the stator. At speeds near base speed, the voltage is typically high enough that Eg is approximately equal to Vt (Vt = terminal voltage). At very low speeds, however, the terminal volts are low, and the stator IR drop becomes significant. If constant flux is not maintained, then the motor will not produce constant torque per amp, and will therefore not be able to provide constant torque.

Controlling the flux in an AC motor as the speed and load are varied is the reason for the development of “vector” or “field-oriented” controllers. If the flux is properly controlled, then an AC motor with independent cooling can provide constant torque down to zero speed.

Above Base Speed

At speeds higher than the base speed, with constant applied terminal voltage, both AC and DC motors would be expected to provide constant output power. As the speed is increased in this way, the flux level in the motor is reduced. This results in approximately constant losses (at constant output power) above base speed for both AC and DC motors. Friction and windage and stray load losses would eventually increase to a significant level as speed is raised further for both types of motors. What limits the maximum speed at constant power for each type of motor is as follows.

For DC machines, the most likely limitation on the constant power portion of the speed range is commutation. As the speed of a DC machine is increased, the rate at which current must be “commutated,” or caused to change direction in the armature windings is proportionally increased. At some speed, the DC motor will no longer have the ability to accomplish this without destructive sparking at the brushes. This is usually the first limitation on a DC motor constant power speed range. Often the next limitation is the dielectric strength against a flashover initiated bar-to-bar along the commutator.

To see what characteristics limit the constant power speed range of an AC motor, it is useful to look at what happens to the motor’s speed-torque curve as its flux level is reduced by increasing frequency. Figure 20 shows a family of speed-torque curves for an AC motor as the frequency is increased to raise the speed above base speed. Since it is constant power (not torque) that we expect from the motor above base speed, it is convenient to redraw these curves as seen in Figure 21. These curves show speed-power information for increasing frequencies.

Figure 20.

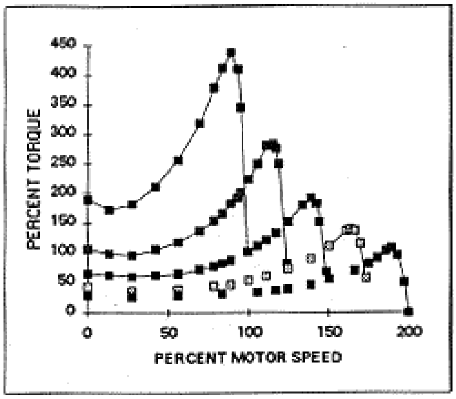
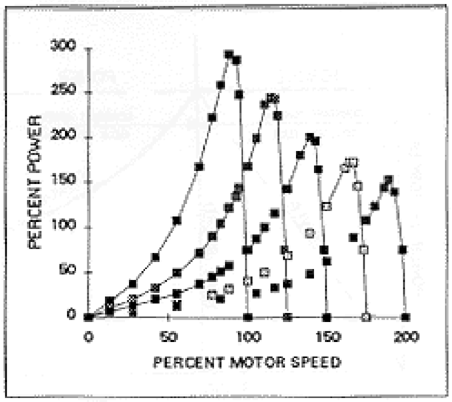


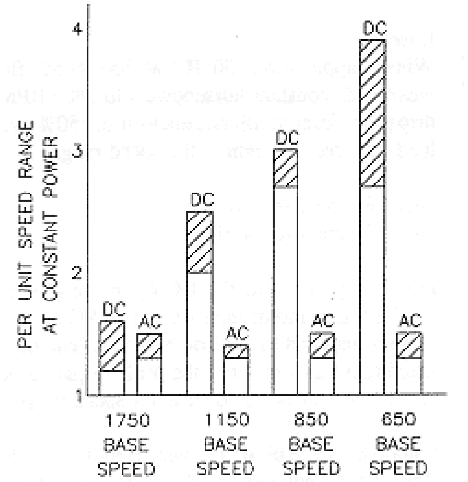
Figure 21.



As can be seen, the point of peak or maximum power available from the motor decreases as the flux level is reduced at higher speeds. As the peak power approaches the desired power output from the motor, the motor slip increases, torque becomes non-linear with current, and the AC motor constant power speed range is thereby limited. As an approximation, the peak power is proportional to flux, therefore above base speed peak power is essentially inversely proportional to speed.

In comparing the constant power speed range of “unconstrained” AC and DC motors, we can use the same designs considered for the power density comparison in Figure 18. The resultant speed ranges are as seen in Figure 22. This result is only one of many possible scenarios (utilizing 500 V DC motors and DPFV enclosures). If the nominal voltage of the DC motors is changed, or if the enclosure of either type of motor is changed, then dramatically different speed range comparisons can result.

Figure 22.



Miscellaneous Issues

Overloads

The basic overload capability of motors built with AC and DC technologies is not very different. Similar to speed ranges, the overload capability of a given motor will be affected more by enclosures, speeds, voltages, etc. than by AC versus DC technology.

Stability

Both AC and DC machines can exhibit ‘unstable’ characteristics in certain situations. DC machines can have a speed versus load characteristic which may be inherently unstable based on a loss of flux with increasing load. This is the same effect discussed in the section on “torque production.” Compensation for such a characteristic is typically accomplished by a feedback circuit, such as speed feedback, or by the use of stabilizing windings in the motor.

A type of instability which can be exhibited in AC motors is completely different than the potential speed/load instability described in the case of DC motors. AC motors can, depending on the applied voltage, frequency, and the driven load have regions of torque (current) instability. Multiple motors operated in parallel from a single power source can increase the “size” of these regions of instability (see Figure 23). Usually these instabilities occur only for lightly loaded conditions, so they are often innocuous, although annoying.

Control Complexity

The separation of field (excitation) and power circuits in a DC motor allows simpler control of DC machines. The straightforward “Phase control” circuitry for running DC machines forward, reverse, motoring, and regenerating (four quadrant operation) from three phase AC power is simpler than any equivalent AC control topology.

Particularly in the area of regeneration, this DC technology has a distinct advantage over the AC options. The use of three phase, phase control does, however, Emit some of the "performance" aspects of this type of drive relative to AC PWM drives. In order to achieve higher frequency response of the current (torque), a DC system would need to utilize a "chopper" supply. This is essentially the DC equivalent of an AC PWM control.

"Vector," or "field-oriented" control techniques are intended to provide a "DC-like" characteristic to AC variable-speed drives. By computation, the flux and torque components are "conceptually separated" and controlled in order to obtain DC-like performance.

Application Examples

Case 1

Fan application, 50 HP at 1750 RPM, variable torque load down to 900 RPM, environment requires totally enclosed motor, efficiency is a major concern.

DC: Frame size 320AT
Efficiency at 50 HP, 1750 RPM = 89%
Efficiency at 6.8 HP, 900 RPM = 76%

AC: Frame size 326T
Efficiency at 50 HP, 1750 RPM = 93%
Efficiency at 6.8 HP, 900 RPM = 82%

In this case, the AC motor is seen to hold a significant efficiency advantage over the DC option.

Case 2

Winder application, 50 HP at 500 RPM, field weakened (constant horsepower) to 1800 RPM, drip proof force ventilated enclosure, 150% overload required throughout the speed range.

DC: Frame size 360AT

AC: Frame size 440T

For this application, the DC option results in a much smaller motor than AC. The AC motor is also mismatched to the load at the low end of the speed range as a result of the peak torque needed to run constant power over a 5:1 speed range.

It may be a little bit of an overgeneralization, but if there are weaknesses in the capabilities of AC and DC motors, perhaps for AC it would be wide constant power speed ranges, and for DC motors, efficiency. Another "weakness" for AC might be the need for a feedback device (and field oriented control) to provide good control of torque down to zero RPM.

Conclusions

While the continued development of adjustable frequency power sources has increased the use of AC motors in variable speed applications, there are often specific application requirements which result in a preference of one technology over the other. Both AC and DC technologies are likely to continue as strong, viable means to control and convert electrical power into mechanical.

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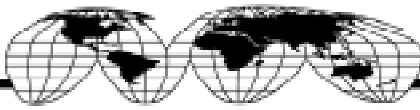

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