MOTOR DRIVES, DC

From the introduction of electric motors through the first three-quarters of the 20th century, the separately excited dc motor was the preeminent source of mechanical output power for electric drives, challenging ac motors, which had to wait for the threefold development of reliable inverters, digital controllers, and an effective control theory, *vector control.* Those factors must be equally reliable and available at a competitive cost. It attained this preeminent position because of the ease of speed variation and the linearity of the control algorithm. The apparent simplicity of the dc motor can be traced to the fact that the armature reaction magnetomotive force (mmf) in a dc machine is always directed along its quadrature axis, orthogonal to its main field mmf which is along its direct axis, whereas in ac machines the relative positions of the two mmfs varies with the operating conditions.

The basic relevant dc motor relationships are expressed by the electromotive force (emf) and torque equations,

$$e_{\mathrm{a}} = K_{\mathrm{e}}\phi_{\mathrm{f}}\omega_{\mathrm{m}} \tag{1}$$

and

$$T_{\mathrm{e}} = K_{\mathrm{t}}\phi_{\mathrm{f}} i_{\mathrm{a}} \tag{2}$$

where

ϕ_{f} is the value of the direct axis magnetic field,
ω_{m} is the speed of rotation,
e_{a} is the armature emf,
i_{a} is the armature current,
T_{e} is the electromagnetic torque (i.e., the torque produced by interaction of the armature current with the direct axis field),
K_{e} is the machine's emf constant,
K_{t} is the machine's torque constant.

The emf and torque constants depend on the size and construction of the machine and on the system of units employed in the equations, and are equal if meter kilogram second (MKS) units are employed (i.e., flux is in webers, speed is in radians per second, current is in amperes, emf is in volts, and torque is in newton-meters).

For the present purpose, it is convenient to rewrite the emf equation as the speed equation

$$\omega_{\mathrm{m}} = \frac{1}{K_{\mathrm{e}}}\frac{e_{\mathrm{a}}}{\phi_{\mathrm{f}}} \tag{3}$$

and the torque equation as the current equation

$$i_{\mathrm{a}} = \frac{1}{K_{\mathrm{t}}}\frac{T_{\mathrm{e}}}{\phi_{\mathrm{f}}} \tag{4}$$

The losses in an electric machine are small, and the armature emf is, in all but the most abnormal conditions, nearly equal to the armature voltage v_a so that the speed equation can be expressed as the approximate equation

$$\omega_m \approx \frac{1}{K_e}\frac{v_a}{\phi_f} \tag{5}$$

the error in this equation rarely amounting to more than 5%.

From Eq. (5), we see that the speed is approximately proportional to the armature voltage and inversely proportional to the direct axis flux, and from Eq. (4), we see that the armature current is proportional to the torque and inversely proportional to the direct axis flux. Thus, doubling the armature voltage will approximately double the speed, doubling the torque will double the armature current, and doubling the flux will halve both the speed and current.

CONSTANT TORQUE AND CONSTANT POWER MODES

The armature voltage and main flux are deployed separately. The flux is at its rated value when the machine is under armature voltage control, and the armature voltage is at its rated value when under flux control.

As the torque Eq. (2) shows, when the machine is operating at rated flux, its torque capability for a given current is at its maximum, and the electromagnetic capability of the machine is exploited to the full. This condition is referred to as the *constant torque mode,* a rather loose designation more accurately expressed as the *maximum torque per ampere mode.*

When the machine is operating at rated armature voltage and variable flux, its torque per ampere capability is reduced as the flux is reduced to increase the speed. Because the reduction in torque per ampere capability is proportional to the increase in speed, the power capability remains constant, and this condition is referred to as the *constant power mode* although one must be ever alert to the fact that this expression really means *constant power capability mode.*

These distinct operating modes are frequently expressed graphically by diagrams such as those shown in Fig. 1. Figure 1(a) shows how the rated armature current and flux vary with speed. Assuming that adequate cooling is maintained at low speed, the rated armature current is constant independent of speed. The main flux is held at its rated value as the speed is increased from zero under armature voltage control. Eventually, the armature voltage reaches its maximum value, the speed at this point being known as the *base speed.* Further increase in speed requires that the main flux be reduced proportionally with the desired increase in speed.

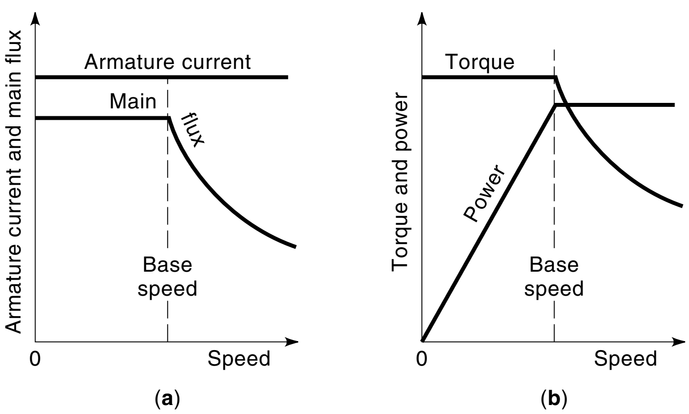

Figure 1. The torque and power capabilities of a dc machine operating with armature voltage control and field control.

Figure 1(b) shows the corresponding effect on the torque and power capabilities. Up to the base speed, the torque capability is constant, and the power capability increases proportionally with the speed. Above the base speed, the torque capability varies inversely with the speed, and the power capability is constant.

Operation above base speed in the *constant power mode* sacrifices some of the output capability of the machine, but the characteristics shown in Fig. 1 correspond well with the demands of many industrial loads and are therefore frequently encountered in drives.

BASIC DRIVE CONFIGURATION

The foregoing principles are incorporated in the basic drive structure shown in Fig. 2. Starting from the left, the speed reference ω_r is compared with the actual speed ω_m, and the resulting speed error ω_ϵ is passed on to the controlled voltage sources CVS1, which feeds the armature of the drive motor, and CVS2, which feeds its field. The drive speed is measured by the speed transducer ST.

The drawing employs the convention that the dc machine's direct axis coincides with the axis of its field winding, and its quadrature axis coincides with the line joining the two brushes so that the diagram incorporates the fact that the field and armature reaction mmfs are orthogonal.

The controlled voltage source CVS1 of Fig. 2 must be capable of supplying the motor-rated armature current plus a substantial (e.g., 100%) additional margin so that the load can be overdriven in order to achieve fast response. Until the late 1920s, the only such source available was a dc generator. The combination of a dc generator, driven at more or less constant speed by either an ac motor or a prime mover, supplying power to a dc motor armature at a voltage controlled by the generator's field current, has a solid place in the history of electrical engineering as the *Ward–Leonard* system, which is named after its inventors. Although rare today, this system has significant merits. Its dynamics are straightforward, and it is easy to control because the power flow to the motor is easily reversible. The substantial inertia of the rotating masses—the motor, the generator, and the machine driving the generator—constitute a low-pass filter shielding the power supply from fluctuations in the drive load, which can be considerable in many industrial drives. As an example, a dragline excavator operates on a cycle of about one minute duration during which its power demand ranges between its positive and negative limits.

The drive can perform the power filtering function only if the machine driving the generator has a drooping speed characteristic (e.g., it is an induction rather than a synchronous motor). The ability of a drive to perform load power filtering can be augmented by adding a flywheel to the generator, the drive then being known as a *Ward–Leonard–Ilgner* system.

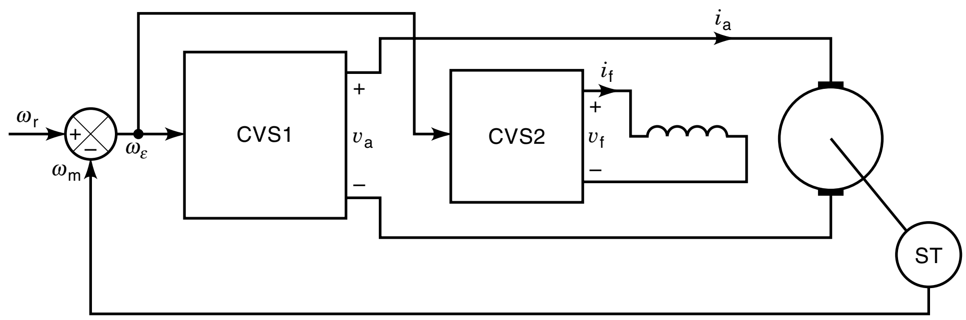

Figure 2. The basic dc drive configuration.

The development of the grid-controlled mercury arc rectifier in the late 1920s provided drive designers with a controllable power source capable of handling the dc motor armature power, which had much faster response than the dc generator, required less maintenance, was smaller and lighter, and was quieter. Against these virtues can be set the difficulties in handling reverse power flow, which is discussed later; the inability to filter power, all fluctuations in load power being felt directly by the supply: and the absence of an overload capability, the rectifier having to be rated for peak load power rather than the average value. In general, the advantages predominated and the majority of dc drives became rectifier fed.

A major factor limiting the penetration of the mercury arc rectifier into dc drive applications was the difficulty it had in handling reverse power flow, something highly desirable in a drive whose speed is best reduced by regenerating its kinetic energy back into the supply. Even though years of intensive development enormously improved this aspect of mercury arc rectifier operation, there always remained a significant possibility of a *backfire,* a loss of rectifying ability.

The development of the *thyristor* in the late 1950s heralded the demise of the mercury arc rectifier, and over the next decade dc drives using thyristor rectifiers as the source of power for both motor armature and field became the norm. Solid state rectifiers removed the major mercury arc rectifier problem, its tendency to backfire; additionally, they were smaller, lighter, and quieter. As the technology developed, they became more reliable, eventually becoming almost maintenance free. Some of the disadvantages of mercury arc rectifiers remained, including the inability to filter load power fluctuations and complexity of handling reverse power flow, but these did not stand in the way of the thyristor rectifier's absolute dominance of the dc drive market.

The problems associated with handling reverse power flow in a rectifier drive stem from a fundamental incompatibility between the rectifier and motor.

Rectifier–Motor Incompatibility

In contrast to the dc machine, which reverses power flow by reversing its armature current, the power flow though a rectifier is reversed by reversing the direction of its output voltage, its output current being unidirectional because of its unidirectional conductivity. This situation is often discussed in the context of a plane defined by orthogonal axes specifying the armature voltage and current, conventions regarding the axes varying with the situation. Here, the axis specifying the armature voltage is taken as the x axis and that specifying the armature current as the y axis. Furthermore, a machine whose field current is positive, whose armature is rotating in the positive direction, and whose armature is drawing power from the dc supply and converting it to mechanical output power defines the positive direction of the axes. Such a plane is shown in Fig. 3. The axes divide the plane into four quadrants, which are conventionally numbered 1 through 4 as indicated in the corners of the segments most remote from the origin so that point P1 is in the first quadrant, P2 is in the second, etc.

Assuming positive field current, when motoring with positive speed, a dc machine operates in the first quadrant with positive armature voltage and positive armature current. When generating with positive speed, it operates in the fourth quadrant with positive armature voltage and negative armature current. When rotating in the negative direction, the machine operates in quadrant 3 when motoring (negative voltage and negative current) and in quadrant 2 when generating (negative voltage and positive current). This behavior leads to a drive with unidirectional rotation capability, which is known as a *two-quadrant drive,* and another with bidirectional rotation capability, which is known as a *four-quadrant drive.*

In contrast to the dc machine, which it supplies, a rectifier can operate in only the first and second quadrants, its output current being limited by its unidirectional conductivity to the positive direction and the reversal of power flow being achieved by reversing voltage.

The basic incompatibility between a motor and a rectifier is resolved either by matching the motor to the rectifier or by matching the rectifier to the motor.

Matching the motor to the rectifier is achieved by reversing either its field or its armature. The power rating of the reversing mechanism is much smaller for field reversal than for armature reversal, but the inductive energy to be handled is

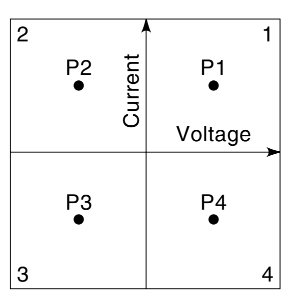

Figure 3. The four operating quadrants of a dc drive.

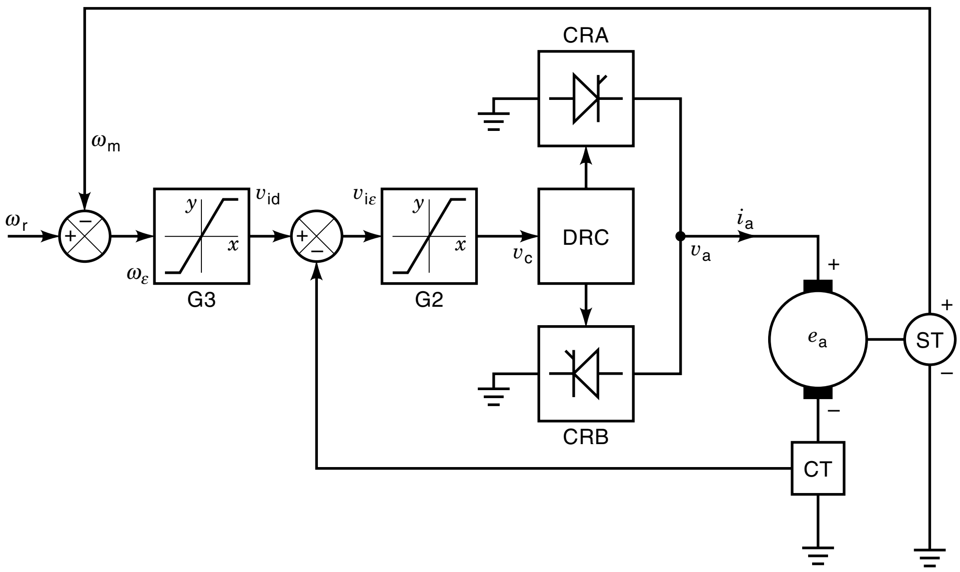

Figure 4. A dc drive with back-to-back rectifiers supplying the armature.

much greater so that field reversal takes considerably longer, seconds as compared to tenths of seconds. The rectifier output voltage must be reversed during the emf reversal period by increasing its delay angle beyond 90° to a point at which the machine will produce sufficient armature current to provide the required braking torque.

During the reversal period, control of the drive is lost, and avoiding this loss of control requires adapting the rectifier to the motor by providing two fully controlled rectifiers connected back to back, one handling positive armature current and the other negative current.

Back-to-Back Rectifiers

The two rectifiers of a back-to-back pair can be operated either with or without circulating current. When the delay angles of the two are adjusted so that in all instances current circulates between the two, power being drawn from the ac source by the one that is rectifying and returned by the one that is inverting, problems associated with discontinuous current flow, such as high current ripple and sluggish response, are avoided, and the machine is always under control. Set against this is the energy loss associated with the continuous circulation of power between the two rectifiers.

The circulating current-free system improves efficiency by having only one rectifier operational at a time. If the drive is motoring, the appropriate rectifier for the direction of rotation supplies power to the armature, and the delay angle of the other rectifier tracks it in the inverter mode but no gate pulses are sent to its thyristors so that it does not conduct. To switch to the generating mode, gate pulses for the conducting rectifier are blocked, and as soon as its thyristors have recovered their blocking capability, gate pulses are released to the second rectifier. Even though this procedure can require highly sophisticated control, this is done very rapidly at the very low power level of the control circuits so that the period of drive control loss is very short, a few milliseconds.

Generally, the circulating current mode is preferred for low-power applications such as supplying field current and the circulating current-free mode for higher power applications such as armature supply.

A drive with back-to-back rectifiers is illustrated schematically in Fig. 4. The speed reference signal ω_r is compared with the actual speed signal ω_m produced by the speed transducer ST to produce the speed error signal, ω_ϵ. This is amplified by G3, which has a limiting-type transfer function so that its output cannot exceed a preset level no matter how big the speed error signal may be.

As described later, it is essential that armature current limiting be incorporated in a dc drive. This is done in Fig. 4 by treating the amplified speed error signal v_{id} as an armature current demand signal. This is compared with the actual current signal v_{ia} produced by the current transducer CT, and the current error signal $v_{i\epsilon}$ is amplified by G2. Like G1, G2 has a limiting characteristic so that the amplified current error signal v_c cannot exceed a preset amount no matter how big the error.

The amplified current error signal is passed to the dual rectifier. The dual rectifier controller DRC creates the appropriate signals for the two controlled rectifiers, CRA for positive armature current and CRB for negative current. Controller DRC continuously generates gate signals for both rectifiers, but if circulating current is to be suppressed, the signals to the nonconducting rectifier are replaced by blocking signals.

Acceleration under this scheme is straightforward and is carried out at the armature current level set by the limiter in G3. A demand for deceleration in order to reduce or reverse speed changes the sign of the current demand signal v_{id} and of the amplified current error signal v_c. Controller DRC immediately replaces the gating pulses to the conduction rectifier by blocking pulses. The armature current is maintained for a brief period by the energy stored in the armature circuit inductance. Until this ceases and all the thyristors of the conducting rectifier have regained their blocking capability, gating signals cannot be released to the incoming rectifier.

Monitoring the blocking status of the outgoing rectifier is crucial to a fast response, and it is usually done not by looking at the armature current itself but by inspecting the status of the thyristor voltages. These provide a very sensitive indication of the thyristor states because a thyristor cannot support a positive voltage of more that a few volts until it has regained its blocking capability.

The delay angle at which gate signals are released to the incoming rectifier and the way in which they are advanced to reach the reverse current limit are crucial factors in drive performance. Once gate signal is applied to a thyristor, control is lost until the current falls to a level at which the thyristor can recover. This can result for a brief period when the rate of change of armature current is extremely large and there is the possibility of commutation failure in the dc motor because its interpole flux cannot keep up. The dc machine designer sets this limit as high as possible by using laminated interpoles and yokes, but the ultimate responsibility for safe operation lies within the rectifier controller.

Once conduction to the second rectifier is established, its gate pulses must be advanced so as to reach the armature current limit value as quickly as possible.

Discontinuous Conduction

A rectifier, as well as producing the desired dc output voltage, also produces substantial ripple voltage. For the majority of drives, which are supplied by three phase, fully controlled, bridge rectifiers, the ripple frequency is at six times the supply frequency. Larger drives, above a few megawatts output, can support more complex rectifiers and have a ripple frequency of twelve times the supply frequency.

The low intrinsic inductance of the armature allows the ripple voltage to create a significant amount of ripple current. Although this can be reduced by adding external inductance to the armature circuit, this adversely affects the drive's speed of response and is consequently limited in its application.

The ripple component of the armature current is independent of the drive load but increases substantially as the drive speed is lowered. As the load on the drive, and consequently the dc component of the armature current, decreases, there comes a point at which the ripple superimposed on the dc component tries to reverse the armature current during part of the ripple cycle. However, the unidirectional conductivity of the rectifiers prevents this from happening, and the drive enters the discontinuous conduction mode, armature current flow ceasing during part of the ripple cycle. This occurs only at low loads, below about 5% of rated; nevertheless, it has a profound effect on drive dynamics. In the discontinuous conduction mode, the speed of response is reduced and the accuracy is decreased to an extent which demands that the drive designer take steps to combat it. These take the form of some type of nonlinear control which effectively boosts the control loop gain.

OPTIMUM OPERATION

The low internal impedance of the armature circuit makes a dc drive very sensitive to changes in speed signal. Because of this, even minor speed changes of 1% or 2% are carried out in the current-limiting mode. In the sense that this is the maximum current that the armature can safely carry, such changes in speed are made under optimum conditions. The same cannot be said for very small speed changes such as are initiated by changes in load torque. Using a linear control algorithm under these conditions results in a decidedly less than optimum response especially if overshoot is to be avoided. The modern techniques of nonlinear control, such as sliding mode control, which are possible with digital controllers, can produce major improvements.

FORCE COMMUTATED RECTIFIERS

Despite their many merits, thyristor rectifiers have some disadvantages stemming from the fact that a thyristor once gated cannot regain its blocking capability until its current has fallen to zero and has been held at zero for a brief period. Because of this, the input power factor of a thyristor rectifier is somewhat less than the cosine of its delay angle, the fundamental power factor always being lagging. The increasing power handling capabilities of turn-off devices such as gate turnoff thyristors (GTOs) and power transistors and reductions in their cost provide an opportunity to overcome this difficulty by using them in *force-commutated* rectifiers that can operate at a fundamental power factor of unity or even leading. Once force commutation is available, it can be used to alleviate the rectifier change-over problems referred to earlier.

REGENERATION AND DYNAMIC BRAKING

If the machine is called upon the exert a braking torque on the load, the power that it generates must go somewhere. The obvious place is back into the dc supply from whence it originally came. This is called regenerative braking. Although this obviously improves energy utilization, the gain may be small and the technique may be inconvenient because of the basic incompatibility between the machine and its rectifier. It may then be appropriate to use *dynamic braking,* dissipating the regenerated power as heat in resistors. A control circuit senses the state of the drive and switches the power dissipation resistors into and out of circuit as required.

SPEED MEASUREMENT

Measurement of the speed of a high-performance drive has traditionally been done by generating a voltage proportional to speed using a dc *tacho-generator* which is a dc generator with a permanent magnet field. For high performance, such generators must be carefully designed and manufactured. The field magnets must be selected for stability so that the field does not change significantly either with temperature or over years of use. Noise and ripple on the output voltage signal must be kept to an absolute minimum because filtering introduces lag into the control loop, which may compromise the drive's performance. Ripple is minimized by using many armature coils and commutator segments. Noise is minimized by very careful construction: the use of silver-graphite brushes and sometimes silver commutators.

An ac tacho-generator producing polyphase ac output voltages can substitute for a dc generator. The permanent magnet excitation is on the rotor, and there are no sliding contacts to create electrical noise and wear.

If the output of an ac tachometer generator is to be used to create a voltage signal proportional to speed, it must be rectified, but as with any rectifier, this introduces ripple, which can be reduced, but not eliminated, by increasing the number of phases. Filtering of this signal must be done very carefully if the filter break frequency is not to affect the drive dynamics adversely.

Using simple rectification of the output of an ac tachogenerator results in a speed signal that is unidirectional, independent of the direction of rotation, unacceptable for a reversing drive. This problem can be overcome by using a phase-sensitive rectifier.

The output frequency of an ac tacho-generator is directly proportional to the drive speed, and it, rather than the magnitude, can be used as the speed signal. A frequency-to-voltage converter can be used to give the traditional system of Fig. 4, but the alternative of direct use becomes attractive. The tachometer frequency can be synchronized to the frequency of a control signal. This is effectively a position controller, the angular position of the motor being locked to the phase of the control signal, a *phased locked loop.* Stability problems can be encountered in making an object with considerable mechanical inertia, the drive, follow exactly an agile, electronically generated signal. This requires that the rate of change of reference frequency be limited and/or the drive be designed to recover from a loss of synchronism.

If drive speed measurement is to be based on frequency, the substitution of a pulse generator for the ac tachogenerator becomes attractive in that the frequency can be much higher and the cost lower.

A speed transducer must be solidly connected to the motor so that its speed is always identical to that of the drive. A flexible coupling can result in small transient speed differences, which are amplified by the controller to produce unacceptable behavior. If a flexible coupling must be employed, its torsional stiffness must be sufficient to place the frequency of torsional vibration between motor and tachometer outside the bandwidth of the drive.

ARMATURE CURRENT LIMITING

The armature current of a dc machine is produced by the difference between the armature voltage and emf acting on the armature impedance. Considerations of efficiency and speed of response require that the impedance be small so that the net driving voltage (i.e., $v_a - e_a$) is small, a few percent of the rated voltage at most. The emf is directly proportional to the speed and therefore changes at a rate depending on the mechanical time constant of the drive, whereas the armature voltage depends on the rectifier control circuits, which are enormously faster. There is, as a consequence, the ever-present possibility that the balance between voltage and emf will be severely disturbed, producing armature current levels well beyond the commutation capability of the machine. The drive controller must therefore incorporate a mechanism for limiting the current to a safe value. There are two basic ways of doing this—continuous control and interventionist control.

In continuous control, the drive controller has an inner armature current control loop within an outer speed control loop as is the case for the system shown in Fig. 4. The speed controller generates an armature current demand signal as the input to the current controller, which then produces the armature current to meet the speed demand. It is then a simple matter to limit the maximum value of the current demand signal to a level that the machine can tolerate.

In the interventionist system, under normal circumstance, only the speed is controlled. However, the armature current is continuously monitored, and if it becomes excessive, its controller intervenes to reduce the speed demand to a tolerable level.

With either system, substantial changes in speed are accomplished at maximum current (i.e., operation is optimum from the viewpoint of the mechanical components). Continuous control of current provides a smooth transition from the speed control mode to the current-limiting mode, but its dual loop design can be more restrictive than the single-loop design of the interventionist system. Continuous control tends to be preferred for the higher powered drives.

Thyristor rectifiers introduce a potential danger for the armature. Once gate signal has been applied to a thyristor, converting it from the blocking to the conducting mode, control of it is lost until the current through it has fallen to zero and has remained at zero for a brief period, typically a few tens of microseconds. There is therefore the possibility that a thyristor will be fired too early in its cycle for the prevailing conditions, resulting in a very large pulse of armature current, which can initiate commutation failure. It is essential that the design of the rectifier controller take this possibility into account.

DC DRIVE MOTORS

Even though standard dc motors can provide satisfactory motive power for many drives, the achievement of high performance requires machines specifically designed for this duty. A drive motor should have high overload capability so that the inherent slow response produced by the inertia of the rotating mass can be at least partially overcome by *overdriving,* the application of large torque for a brief period in order to get the system moving. The motor should also tolerate large rates of change of armature current, a related but separate requirement. Standard dc motors have limitations in these areas, which can be significantly improved by appropriate design.

The rated current of a dc motor, and indeed any motor, is determined by thermal considerations as the current that will limit the temperature of the conductor insulation to a level that guarantees adequate time before failure. This is the primary basis for the choice of motor for a drive. In making it, it is important not to build in overload capability by increasing the motor size because that adds to the total drive inertia and reduces the speed of response.

The power rating of a motor is proportional to the active volume of its armature, the volume of the cylinder just enclosing its armature laminations. This volume can be achieved in a variety of ways: by having a short machine of large diameter, by having a machine of average length and average diameter, or by having a machine of substantial length and small diameter. Because the rotating mass is proportional to the volume and therefore the power and because the radius of gyration is proportional to the diameter, low-inertia, fast-response motors tend to be long and of small diameter, inclining toward a pencil shape rather than a pancake shape. Other considerations may intervene. For example, space limitations may dictate a short, large-diameter motor, but, in general, drive motive power tends to be provided by long, small-diameter machines.

Even though the thermal limits of its insulation dictate the size of a motor, commutation considerations limit its transient overload capability, which is so important for fast response. Satisfactory commutation requires that the commutation flux in the interpolar zones be at all times directly proportional to the armature current. A variety of practical factors mitigate against this ideal.

Saturation of the ferromagnetic portions of the machine, notably the armature teeth and the interpole body, limit the extent to which the interpole flux can linearly follow the armature current. Machine designers linearize the magnetic characteristics of the path followed by the interpole flux as far as possible by using a long airgap separating the interpoles and the armature. However, there is a limit to this, and eventually, at some high level of armature current, the flux ceases to track the current adequately, sparking at the brushes occurs, and premature commutator failure results. The range of dc machine overload capability goes from about twice the rated armature current for run-of-the-mill machines to about six times the rated current for machines specially optimized for fast response, with good-quality drive machines having a transient overload capability of three to four times rated current. The rating of the machine also has an effect on this parameter, the transient overload capability decreasing with increase in size.

Commutation also limits the maximum size of a dc machine to the range of 5 MW to 10 MW. Above this size, either multiple dc machines or ac machines must be employed.

A machine may have adequate overload capability and yet still fail to commutate satisfactorily under transient conditions because the interpole flux cannot track the fast-changing armature current because of eddy currents in the interpole magnetic circuit. Full lamination is the answer to this problem. The ferromagnetic portion of the armature has always been adequately laminated. Interpoles have, for many decades, been laminated, although usually with a thicker grade of material than the armature. Transient commutation problems caused by eddy currents can usually be attributed to currents induced in the yoke, the exterior envelope that holds the poles in place and supports the armature bearings. The yoke of a standard dc machine is usually made of solid steel, and any attempt to rapidly change the interpole flux results in yoke eddy currents which slow the change. The dc machines intended for high-performance drives have fully laminated magnetic circuits, which effectively eliminate the eddy current problem.

Finally, there is the last weapon that the designer can deploy in the search for fast response, *compensation,* an expensive process used only on highly responsive or very large machines. Compensation means counterbalancing armature reaction by passing the armature current through a stator winding. Full compensation requires that the ampere-turns of the compensating winding be equal and opposite to those of the armature reaction, which dictates that it be of roughly the same size and weight as the armature winding. The winding is placed in slots in the pole faces, and making space for it increases the overall diameter by an amount approximately equal to twice the armature slot depth. This is offset to some extent by a reduction in excitation requirements because the cancellation of armature reaction permits the length of the airgap to be reduced close to its mechanical limit. The armature itself is not affected by compensation so that its inertia is unchanged but compensation does significantly increase the cost of the machine.

BRUSHLESS DC MOTORS

The commutator, brushes, and interpoles of a dc machine constitute a switching mechanism that reverses the current in each armature coil as it passes through the magnetic neutral zone between the main poles. This reversal process is controlled by the interpoles whose excitation windings are connected in series with the armature. The interpole mmfs have two functions: they counterbalance the armature reaction mmf in the neutral zones, and they provide enough magnetic flux to induce an emf in a commutating coil sufficient to overcome the delaying effects of its inductance.

Almost as soon as the thyristor became widely available, it was realized that the functions of the commutator could be performed by a solid state circuit, an attractive prospect because the commutator is a highly stressed device that is responsible for most of the maintenance cost of a dc machine and that adds considerably to its cost, length, and inertia. Solid state commutation requires that a position transducer that tells the switching circuit when an armature coil enters the neutral zone be added to the machine, but this can be a simple noncontact device that adds very little to the cost and detracts very little from the reliability of the machine.

Direct replacement of the commutator requires a large number of solid state switching elements, but there is no practical need for this. It is simply mechanically convenient to have many commutator segments. Generally it is sufficient to arrange the armature coils in from three to six series-connected groups and to provide a switch with a corresponding phase number.

Once the move to solid state commutation has been made, it becomes mechanically convenient to turn the machine inside out, with the field on the rotor and the main windings on the stator. The machine then becomes indistinguishable from a synchronous machine, the only special feature of the commutatorless dc drive being that commutation of a phase always occurs as the phase axis passes through the interpolar axis. Additionally, there is at least the implication that the frequency of the switch, or inverter as it is more generally called in this context, in a brushless dc drive is decided by the speed controller, whereas that of the synchronous drive may be directly set. The switching circuits have, of course, kept pace with developments in solid state switching devices which have seen thyristors replaced by power transistors of various kinds and, for the larger powers, gate turnoff thyristors.

The remaining sliding contacts of a brushless dc motor, those carrying the current to and from its field, can be eliminated by using a permanent magnet field. This produces an almost maintenance-free machine, which, except for the point at which its output shaft exits, can be completely sealed from its environment, thus permitting operation in hazardous situations impossible for a normal machine.

SINGLE-PHASE SYSTEMS

Single-phase systems in industry are limited to low power applications, below 1 kW or 2 kW. However, electric railways provide an exception to this in that single-phase systems are employed at megawatt power levels.

The majority of main line electric railways supply power to the locomotives via an overhead wire fed at about 25 kV at the supply frequency, those still using dc doing so because of investments in dc equipment decades ago. A single locomotive may consume several megawatts, and the fact that this is supplied as single phase is a consequence of the single overhead wire and ground return, triple feeds supplying three phase to the locomotives being impractical. Rectifying such large amounts of single-phase power has led to many innovations in rectifier design and application, but they remain specialized designs restricted to traction applications.

CHOPPERS

Electric railways devoted to commuter service, light rail transit, and street cars usually transmit power to the moving vehicles as direct current. Autonomous electric vehicles obtaining their power from batteries or fuel cells perforce operate with a primary dc supply. The requirement of the drive for variable dc voltage from these basically constant voltage systems is met by choppers, solid state devices closely related to pulse width modulated inverters but with a single-sided output, which is variable voltage dc with a high-frequency ripple.

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The dc drives are a mature product whose basic design was established during the 1939 to 1945 war when they played an important role on both sides in gun positioning. Much of the relevant literature dates back to that period. Most of the relevant books are out of print and can be obtained only from libraries. University Microfilms International used to supply copies of out of print books, but I could find nothing relevant on their web site, www.umi.com. A search of book sellers sites such as www.amazon.com can be productive.

The search for further information could well start with a review of other articles in this encyclopedia, particularly DC–DC POWER CONVERTERS; DIGITAL CONTROL; RECTIFYING CIRCUITS; and VARIABLE SPEED DRIVES.

T. H. Barton, *Rectifiers Cycloconverters and AC Controllers,* London: Oxford University Press, 1994, Chap. 10 provides a detailed quantitative description of the operation of a dual-rectifier dc motor drive.

There is an enormous world-wide literature on dc drives covering the last 100 years. This can be overwhelming but the Transactions of Institute of Electrical and Electronic Engineers (IEEE), New York, on Industry Applications and on Power Apparatus and Systems and the Proceedings of the Institute of Electrical Engineers (IEE), London, are good place to start because they are widely available. The search for current practice should start at the present and work backward in time, but a historical search should cover the whole period from 1890 on. The totality of the literature expands substantially with each major technical development. Thus, there is much on Ward–Leonard drives during the period 1900 to 1925, much on mercury arc rectifier drives from 1930 through 1950, and much on solid state drives from 1960 through 1980. The literature on the control aspects of drives expanded greatly during the decade from 1945 to 1955 as the wartime developments were described. The literature on the nonlinear control of drives similarly expanded as digital control became economically feasible after 1980.

Of the many books on dc machines, some excellent examples follow.

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MOTOR DRIVES, SWITCHED RELUCTANCE. See SWITCHED RELUCTANCE MOTOR DRIVES.

MOTOR PROTECTION, AC. See AC MOTOR PROTECTION.

MOTORS, APPLICATIONS. See VARIABLE SPEED DRIVES.

MOTORS, DC. See BANDPASS FILTERS; DC MACHINES.

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