Industrial Circuit Application Note

Stepper motor and driver selection

Stepper motors are used in many different types of applications this makes it difficult to recommend a general step-by-step design flow chart. The design process is more an iterative process, involving experience, calculation and experimentation. The purpose of this application note is to show how system performance is affected by motor and driver selection. Some popular motors and drivers are dealt with, as well as the importance of the gearing between the motor and the load.

Limits to system performance

Torque and output power

The output torque and power from a stepper motor are functions of the motor size, motor heat sinking, working duty cycle, motor winding, and the type of driver used. In applications with low damping, the usable torque from the stepper motor can be drastically reduced by resonances.

In data sheets for stepper motors, the pull-in and pull-out torque are given, as functions of stepping rate, for different types of motor and driver combinations. The pull-in torque curve shows the maximum friction torque with which, the motor can start, at different stepping rates, without losing any step. In an actual application, this curve has to be modified to account for the load inertia.

The pull-out curve is of more interest, because it shows the total available torque when the motor runs at constant speed at a given frequency. In an application, this torque is used for overcoming the load fiction torque and for accelerating the load and motor inertia.

One problem when selecting the right motor type and size is the big influence that the driver has on the output torque and power. The difference in output torque, power, and system efficiency for a 7.5-degree 57mm PM stepper is illustrated in figure 1. In both cases the winding and driver combination have been designed to drive the maximum current through the winding at stand still without exceeding the maximum 7-watt power dissipation for this type of motor.

From the chart, we see that the output power of the motor can be increased by a factor of six, through the use of a bipolar constant current driver, compared to the basic unipolar L/R-driver. The increased output power is a function of both the increased over-all pull-out torque and the increased stepping frequency range.

As we can see from the figure, the maximum output power is available at relatively high stepping rates, compared to the maximum pull-in frequency, for this type of motor (approximately 150 to 400Hz, for zero-load inertia, depending on driver circuit). This fact, which is true for

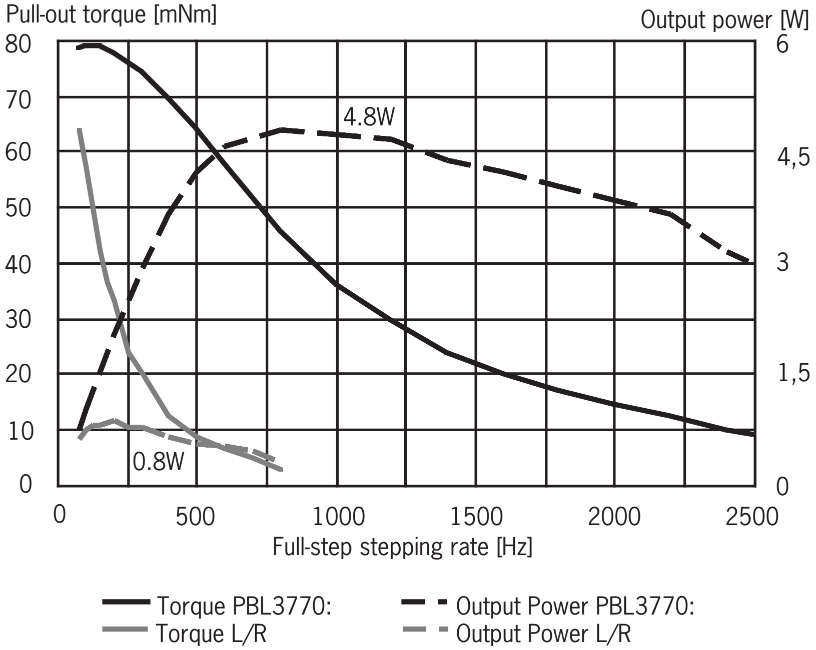

Figure 1. Pull-out torque and output power for a 57 mm PM stepper driven by a unipolar L/R-driver and a PBL 3770A bipolar constant current driver.

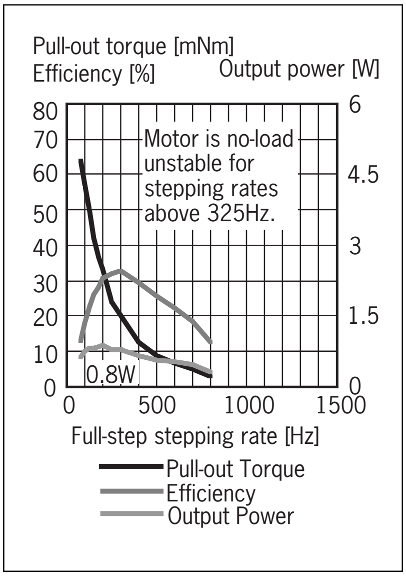

Figure 2. Performance curves for a 100 ohm unipolar 57 mm PM-motor driven by a 20V L/R constant voltage driver.

most stepper applications, shows that, to be able to get a high-performance stepper motor system, we have to use ramping up/down when we start and stop the motor and load. The use of ramping opens up stepper motors for power output applications, and does not limit the usage of steppers to low-performing low-output power system.

Damping and resonances

In applications with low system damping, the available output torque and power can be drastically reduced by resonance. Resonances in stepper motor systems can arise at low-, mid-, and high stepping rates. As a rule, *constant current drivers* have the most problems with resonances in the low-frequency region. These resonances can often be eliminated by using half-stepping or microstepping. *Constant voltage drivers* normally have problems with resonances at medium and/or high frequencies. At these frequencies, neither half- nor microstepping can reduce the resonances. This limits the usage of this type of drivers at medium and high frequencies to driving high-damping loads.

Damping also depends on the motor type—PM-motors have higher damping than hybrids, due to slide bearing friction and magnetic losses.

Some driver and motor combinations have such low damping, at certain stepping rates, that they do not run without a high-damping load. This condition is known as no-load instability.

Resolution and positioning accuracy

The resolution of a stepper motor system is affected by several factors—the stepper motor full-step length, the selected driver mode (full-step, half-step or microstepping), and the gear rate. This means that there are several different combinations which can be used to get the desired resolution. Because of this, the resolution problem of a stepper design can normally be dealt with after the motor size and driver type have been established.

Design time

Even though customization of step motors is possible, it requires both engineering time and time for manufacturing stepper motor samples. Using a more-flexible driver circuit, like the chopper constant current driver can make it possible to select a standard motor with no performance loss.

Table 1. Unipolar constant voltage driver attributes

Features

- Low electronic component cost.
- For small motors very low cost transistor arrays can be used.
- Low electrical noise level.

Drawbacks

- Lowest motor output power.
- Maximum power dissipation at stand still.
- Higher motor cost and larger size for the same output power as from other drives.
- Driver transistors have to withstand twice the maximum supply voltage.
- Windings must be designed for the used supply voltage.
- Regulated power supply normally required.
- Holding torque depends on supply voltage and motor temperature.
- Large torque ripple when driven in half-step mode.

Applications

- Low speed and low power applications were the motor mainly is used to produce a torque.
- Normally only used with small size motors.

Cost

In high-volume applications, the major cost is the hardware—including power supply, driver, wiring, motor, and gearing. In this case, the engineering cost is less important. In many applications, it is possible to lower the total system cost and increase the performance by using a more-complex driver (with a slightly higher cost) and less-costly motor and power supply.

In low- and medium-volume applications, the engineering cost becomes a larger part of the total cost. In this case the flexibility and high integration of a constant current driver can help save engineering time and cost.

Dynamic characteristics

In applications were the stepper must move from one position to another then stop in the shortest possible time, the settling time becomes a very important factor. If the system is designed properly, the settling time can be kept to a minimum—if not, the settling time can easily require several hundred milliseconds.

To get good dynamic behavior in an open loop system, it is important to have the correct gear rate and precise control of the motor running and holding torque. With well-designed gearing, it is possible to handle variations in both load inertia and friction.

Performance of drivers

In the following section, the performance of some commonly-used driver configurations are compared when they drive a 57mm 7.5-degree PM-stepper motor. Driving voltage/currents are selected so the stand-still motor losses are kept at maximum rated 7 W. The performance curves show the pull-out torque, output power (at the motor shaft), and the system efficiency. Efficiency is defined as the mechanical output power from the motor divided by the input power to the driver. For each driver, features and drawbacks are also listed.

Unipolar constant voltage

This is the classic low-end driver. It offers the lowest price for the driver electronics—only four transistors are used. To drive small-sized motors, a transistor array of ULN 2003 or similar type can be used. For mid-sized motors, power darlington transistors, or transistor arrays can be used. In figure 2, the performance of this type of driver is shown. A motor winding with 100 ohm phase resistance has been selected. This gives good control of winding current and low losses in power transistors. With this driver, the motor has problems with no-load instabilities at stepping rates above 325Hz.

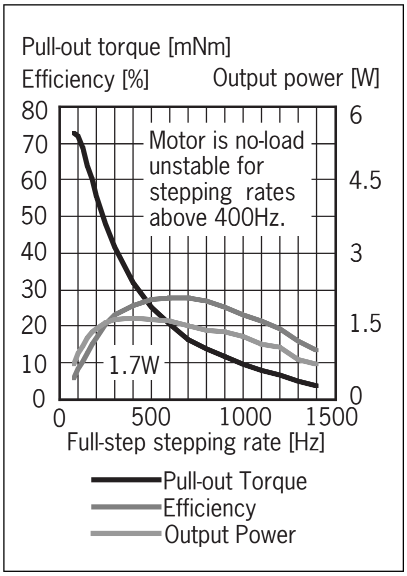

Figure 3. Performance curves for a 100 ohm unipolar 57mm PM-motor driven by a 40V L/2R constant-voltage driver (2 × 100ohm external series resistors).

Table 2. Unipolar L/NR constant voltage driver attributes

Features

- Low component cost
- Low electrical noise level.

Drawbacks

- Low or very low efficiency. Lower efficiency the higher R_{ext}/R ratio.
- Problems with heat dissipation from the series resistors.
- Maximum power dissipation at stand still increase by the L/nR ratio compared to the normal L/R driver.
- Large torque ripple in half step mode.
- Holding torque depends on supply voltage and winding temperature.

Applications

- Low and medium speed and low power applications.

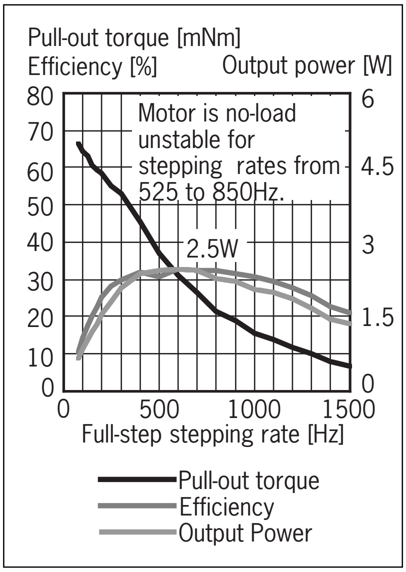

Figure 4. Performance curves for a 100 ohm unipolar 57mm PM-motor driven by a 40/20V Bi-level constant-voltage driver (High-voltage-on time = 4ms).

Unipolar L/nR constant voltage
This driver is similar to the unipolar constant voltage but has external series resistors in series with the motor windings. This driver can be configured with different L/R ratios. L/2R means that the total resistance is equal to two times the motor's internal resistance. A higher L/R-ratio increases high-stepping-rate output torque, but reduces the system efficiency. Figure 3 shows the performance of this driver in the L/2R-mode, driving the same 100 ohm unipolar motor.

Compared to the L/R-driver we now gain higher output torque and power. The maximum output power has doubled, but the peak system efficiency has decreased.

This drive also shows the no-load instability, here for stepping rates above 400Hz. This limits the applications, at high frequencies, to driving high-damping loads or to operating in ramp up/down applications, were the motor does not run at constant speed. It is possible to ramp through unstable frequencies, and use the full pull-out torque (with normal safety margin) if the motor only runs a limited number of steps in the unstable range.

Unipolar timed Bi-level
This driver uses two voltage levels to increase motor utilization. At every step taken, the voltage across the winding is raised, for a short time, to a higher level compared to the nominal voltage used at stand still. During the remaining time, the nominal voltage is used. This driver can also be configured in the "run/

Table 3. Unipolar timed bi-level driver attributes

Features

- Medium electronic component cost
- Medium electrical noice level.

Drawbacks

- Timing circuit or extra CPU overhead needed to control high voltage on time.
- 6 power transistors needed compared to 4 for the standard and L/nR unipolar drives.
- If large high to low driving voltage ratio is used the control off holding torque and step accuracy becomes difficult as a result of variations in winding currents.
- Holding torque depends on winding temperature and supply voltage.

Applications

- Low to medium speed and low to medium power applications.

Table 4. Unipolar constant current driver attributes

Features

- Nearly the same high speed torque as bipolar chopper drive
- Uses 6 power transistors compared to 8 for bipolar constant current.
- Half stepping without torque ripple possible.

Drawbacks

- Only 70% of holding and low speed torque compared to bipolar constant current.
- Power transistors have to withstand twice the maximum supply voltage.
- Winding leakage inductance have to be considered when snubbing circuit is designed.
- 6 lead wires add cost and space for motor connectors and flexible cables.

Applications

- High speed and medium power applications.

stop” bi-level mode, were the high voltage is used while the motor is stepped and the low voltage is used at stand still. This driver can also be combined with L/nR-series resistors to give higher flexibility in selecting stand-by holding torque. Ericsson’s PBD 3517 is a fully-integrated, bi-level driver intended for use with small-sized motors. In figure 4, the performance of the L/2R driver is shown while driving the same 100-ohm unipolar PM stepper. The torque curve for a given motor is a function of both the high-voltage level and the high-voltage-on time. In this example the high voltage is 40V (2 times the nominal voltage) and the high voltage on time is 4ms. Compared to the original L/R-driver, the maximum output power is three times higher. Compared to the L/nR-driver, the efficiency is higher—and is not decreased by losses in series resistors as the ratio U_{high}/U_{nom} is increased. This driver also has problems with no-load instability, but in this case only the mid frequencies are affected. If used in a ramp up/down application, this does not cause any problems, if the constant speed is selected in the stable area above 850Hz.

Unipolar constant current
This driver gives the best performance of the unipolar drives—but it is lower than for the bipolar chopper driver. The efficiency is reduced as a result of higher resistive losses caused by using only half of the windings at a time. At higher frequencies, power losses caused by leakage inductance and snubbing circuits also appear.

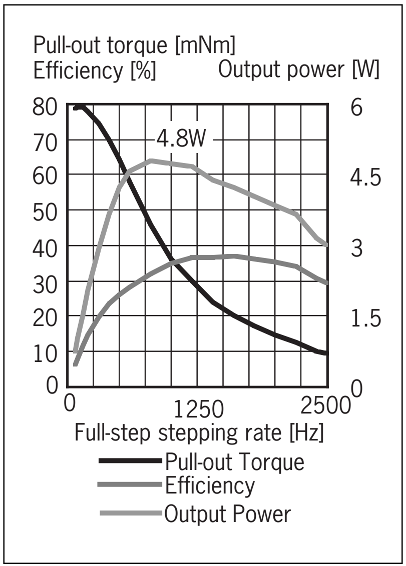

Figure 5. Performance curves for a 3.75 ohm bipolar 57mm PM-motor driven by PBL 3770A constant-current driver (Chopper voltage 20V, winding current 960mA).

Table 5. Bipolar constant current driver attributes

Features

- Maximum motor utilisation and high efficiency.
- Maximum torque at low and high stepping rates.
- Low losses stand bye mode possible.
- 8-lead motors can be configured for 3 different operating currents.
- No snubbing circuits required and current turn off can be selected for fast (return to power supply) or slow.
- Highly integrated drivers available, second sourced drives also available.

Drawbacks

- 8 power transistors needed to drive a motor.
- Problems with electrical noise and interference can occur.
- Power losses in current sensing resistors.

Applications

- For small and medium size motors highly integrated drivers are available.
- High speed and high power applications.

Table 6. Bipolar constant current microstepping driver attributes

Features

- Same as for the bipolar constant current, plus:
- Resonance free movement on low step rates.
- Increased stop position resolution.

Drawbacks

- Same as for the bipolar constant current, plus:
- Higher cost for the current control electronics than for normal bipolar drive.

Applications

- For small and medium size motors highly integrated drivers are available.
- High speed and high power applications.
- Applications were increased resolution is required.
- Applications were resonance free low speed characteristics is needed.

Bipolar constant current

The highest output power and motor utilization for a given motor is achieved with the bipolar constant current driver. DC-losses is kept at a minimum due to maximum utilization of the copper in the winding and no power losses from leakage inductance and snubbing circuits since every winding only consists of one part.

In figure 5, the performance for this type of driver is shown driving the same type 57mm PM-motor. Here a motor with a constant-current-adapted winding resistance of 3.75 ohms has been selected. The winding current is selected to give the same resistive losses in the winding at stand still as for the unipolar drives tested above. From the chart, we can see the increase of output power, maximum stepping rate, and system efficiency. Due to the better utilization of the winding, the holding torque is also raised.

The no-load instabilities in the mid- and high-stepping rate regions are no longer present. This increases the flexibility in selecting constant-speed running frequencies. However, a resonance at 100Hz is present. In a ramp up/down application, this does not cause any problems as long as this frequency is not used as constant speed frequency.

During the last 10 years, progress in IC-technology has made it possible to develop fully-integrated bipolar constant-current drivers, making this type of driver cost-effective for driving small- and medium-sized motors.

Bipolar constant current microstepping

This is an improved version of the basic full- and half- stepping bipolar constant-current driver. Here, the winding currents form a sine/cosine pair. This greatly improves low-frequency stepping by eliminating overshot movements, ringing, and resonances. Performance at medium- and high-stepping rates are close to that of full- and half-stepping.

This driver uses the same power stage as the bipolar constant-current driver, but extra electronics for setting the sine/cosine current levels are used. Microstepping can be used with different microstep lengths. A shorter step length than 1⁄32 of a full-step normally does not make any further improvement in the motor's motion. With most microstepping controllers, is it also possible to run the normal full- and half-step modes.

Microstepping can also increase motor resolution and step accuracy.

General driver aspects

Power supply design

For all drivers of constant-voltage type, regulated power supplies are normally required. This means that the over-all system efficiency will decrease further, compared to the values shown in the figures above, due to losses in the power supply. This will increase transformer cost and heating problems. If unregulated supplies are used, large variations of holding and running torques occurs, thus making stop-time minimizing more difficult or impossible. An unregulated power supply for a constant voltage driver also affects the motor power dissipation making good motor utilization impossible.

For a constant-current driver, it is normally possible to use an unregulated supply voltage. The motor current, and thereby also holding torque and power dissipation, is controlled by the driver itself. The pull-out torque at high stepping rates is affected by the supply voltage but at low step rates, its influence is small.

It is difficult to calculate the power consumption for a particular application. The best way to get this information is to make a prototype and measure the driver input current under different driving conditions. Remember that the power consumption depends on input voltage, current levels (if constant current mode), load, motor temperature, duty cycle and so on.

Snubbing and current turn off circuits

To assure trouble-free functioning of all unipolar drives, especially when larger size motors are used, the winding and current turn-off circuit has to be properly-designed.

It is important that a unipolar winding is bifilar wound—this means the two wires that build up the coil on each motor pole are wounded in parallel. This way, the leakage inductance is kept to a minimum, even though the energy stored in the winding has to be taken care of (or moved to the other winding half) when the current is turned off. This is done by a current-turn-off circuit or a snubbing circuit. If the current-turn-off circuit works on the principle of current commutation from one winding half to the other, the energy stored in the leakage inductance is handled by a snubbing circuit.

In the case of bipolar drive, separate snubbering circuits are never needed, since the windings only consist of one part each and no leakage inductance can occur. The current-turn-off circuit is of four diodes in opposition to the four power transistors in the H-bridge.

Hysteresis losses in motors

With some low-inductance motors, chopper-type drivers can generate increased iron losses, caused by the winding current ripple. To minimize this problem, use a high chopping frequency and do not use a lower inductance than needed to get maximum-required step rate—it is also possible to use a lower chopping voltage. In most applications, the hysteresis loss related to the chopping current ripple is low compared to the hysteresis loss related to the stepping current changes. If chopping current ripple is kept at or below 10% of the nominal current, this normally doesn't cause a problem.

Interference problems

For all chopper-type drives, the increased risk of different interference problems has to be considered. Separate and wide grounding lines, as well as physical separation from sensitive electronics on the PCB, can help to avoid interference. Stepper lead wires should also be separated from sensitive signal wires to reduce capacitive and inductive coupling. In a chopper application the capacitive coupling of the chopped voltage (this is a square wave signal with the amplitude equal to the supply voltage and the frequency equal to the chopping frequency) present at the motor lead wires can cause serious problems if not handled.

Performance of motors

The maximum output torque and power from a stepper motor is limited by the power losses of the motor. For low stepping rates, most of the losses are related to resistive losses in the motor winding. At higher stepping rates the hysteresis and eddy-current losses become the major ones. Especially for low-cost tin-can PM-steppers, these losses can be high—because of the absence of laminations and the use of low performing magnetic materials of the stator and rotor flow path.

From the above driver comparisons, we can see that the maximum torque, efficiency, and output power from a given motor is achieved with the bipolar chopper driver. We will now examine the performance of some commonly-used stepper motor types when they are driven with a bipolar chopper drive.

A drop in performance, similar that of the 57mm PM-motor used above, can be expected when other types of drivers are used.

57mm PM motor

PM-motors are a cost-effective alternative in many low- and medium-performing applications. The motors uses slide bearings and a simple mechanical design to keep cost low. Compared to hybrid motors, the life expectancy is shorter, step accuracy and efficiency is lower. The slide bearing can also cause problems if a belt drive is applied directly to the motor shaft.

The 57mm PM-motor is. for instance, suitable to use as paper feed and carriage drive motor in medium-performance matrix or daisy printers and in typewriters. Other applications are fax machines, sewing machines, valve controls, and plotters.

Other popular PM-motor sizes are 35mm and 42mm. 20mm, 25mm and 63mm motors are also common PM motor sizes. The 20mm motor is popular as a head driver in 3½" floppy-disk drive applications. Commonly-available full-step angles are 7.5 and 15 degrees but others are also available (9, 11.25, and 18 degrees, for examples).

In figure 6, the performance of this motor is shown again. The power loss is plotted as a function of the stepping frequency. This motor is rated at 7 watts maximum power dissipation. The chart shows the power dissipation of the motor and driver together. At low step rates about a 3W-loss in the two PBL 3770A circuits can be expected, as well as an additional 1W in the current sensing resistors and approximately 1W in the external diodes. At higher stepping rates, the driver losses decrease as the winding current decreases and the switching stops. At low step rates this gives a 7-watt loss in the motor. At higher step rates, the total loss decreases indicating the ability to get a higher output power without exceeding the maximum

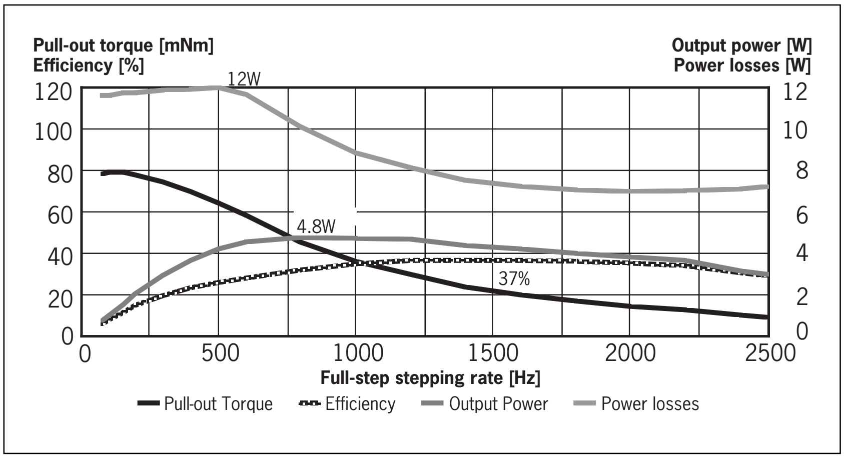

Figure 6. Performance curves for a 3.75 ohm bipolar 57 mm PM-motor driven by PBL 3770A constant-current driver. Power losses in motor and driver are also shown (Chopper voltage 20 V, winding current 960 mA).

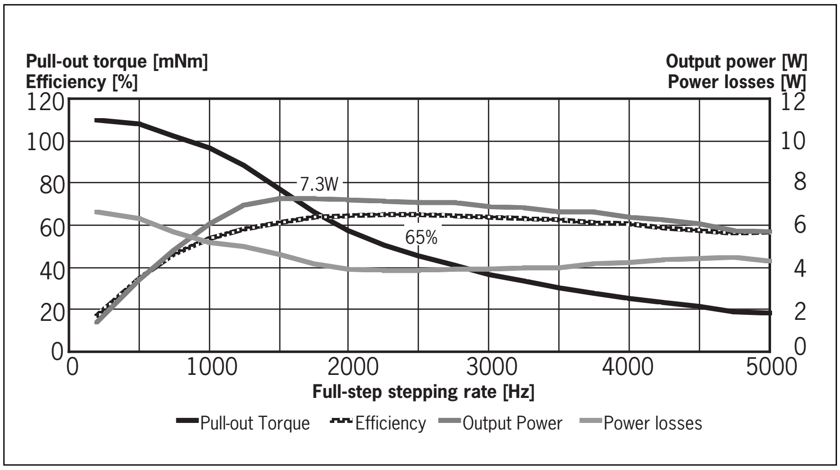

Figure 7. Performance curves for a 25 ohm bipolar 42 mm square hybrid stepper driven by PBL3770A constant-current driver (Chopper voltage 40V, winding current 280mA)

allowed motor losses of 7W. If a lower duty cycle or better heat sinking is applied to this motor a peak output power of at least 10W can be achieved.

PM-motors have one advantage over hybrid motors, they have a higher internal damping and offer, in some applications, a more-noise-free operation than the hybrid motors.

42mm square motor
This motor is normally manufactures with 3.6-, 1.8- and 0.9-degree step angle. Step accuracy is ±3% to ±7% of a full-step. The motor uses ball-bearings to maintain the very small air-gap required for high efficiency.

This type of stepper motor is available from many manufacturers at a reasonable price, but the price is higher than the PM-motors. The main feature of this type of motor, compared to the 57mm PM-motor, is higher efficiency and step accuracy. In many applications, the ball-bearings offer higher life expectancy and make the design of the gearing and mechanics easier. This type of stepper became very popular some years ago as head driver for 5¼" floppy and hard disk drives. It is suitable as a carriage driver for printers and plotters, and for driving the print wheel in typewriters and daisy wheel printers. It is also a competitor to the small-sized PM-motors, if the application requires higher efficiency or ball-bearings

Figure 7 shows the performance of a 25-ohm bipolar 3.6-degree 42mm square motor driven by a constant-current driver. The current level is selected to give 4W resistive losses at stand still. This motor type is rated for 4 to 6W losses depending on manufacturer. Compared to the 57mm PM motor in figure 6, nearly doubled system efficiency is the most interesting difference. From the power losses curve, we see that at higher stepping rates the losses decrease. This indicates that an even-higher high-frequency performance can be achieved with a higher chopping voltage or with a lower-inductance winding.

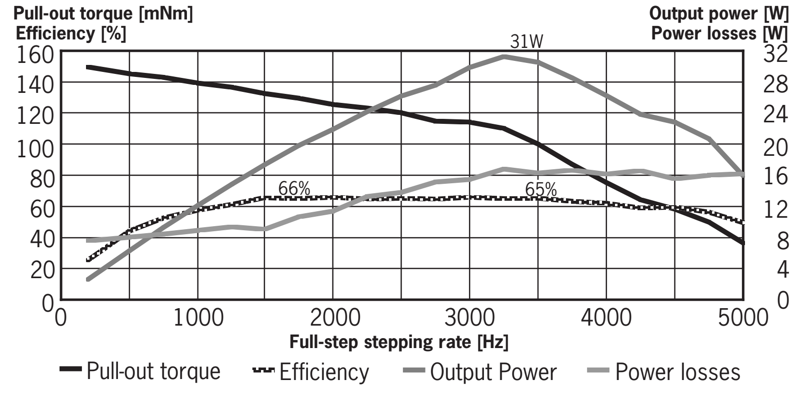

Figure 8. Performance curves for a 2.8 ohm bipolar 57 mm hybrid stepper (length 42mm) driven by PBL 3770A constant-current driver (Chopper voltage 40V, winding current 75mA).

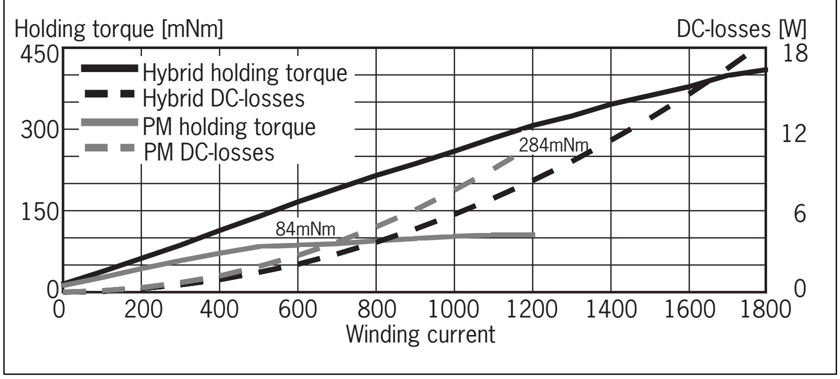

Figure 9. Holding torque and DC-loss as functions of winding currents for a 57mm PM motor and for a 57mm hybrid motor.

57mm (size 23) hybrid motor
This type of hybrid stepper motor is normally available with a 1.8- and 0.9-degree step angle and in a number of different lengths from 40mm to 100mm. This motor is more expensive than the two other types described above. On the other hand, a much higher torque and output power is available.

The performance of this motor type is plotted in figure 10. A motor with 5-degree step angle, 2.8-ohm bipolar winding and with 42mm length has been selected. This is the smallest motor size of this class. The 5-degrees step angle is interesting when high shaft speed is more important than high holding torque.

The diagram shows the same high-efficiency as for the 42mm square motor, but four-times-higher output power. A maximum of over 30W is achieved in the area of 3000 to 3500Hz. At high step rates, the power losses of the motor is approx. 12W (including driver 16W). This is acceptable with normal cooling of the motor and 100% duty cycle. At low step rates, the losses decrease and at standstill the losses are only 3W. This shows the ability to increase the motor current to get even higher output torque and power at low step rates. On the other hand, decreasing the low frequency torque can be a way of decreasing noise levels and vibrations in applications where the load friction torque consumes a larger part of the motor torque than the load inertia.

This motor is suitable for paper handling and carriage driving in high-performance printers and plotters, or industrial motion control. The 5-degree stepper, with per-formance shown in figure 8, is suit-able for driving the print mechanism of laser printers. PBL3770A is a suit-able driver for this size of stepper motor.

Power losses and holding torque
The limiting factor in high-performance stepper motor designs is the stepper power dissipation.

Stepper motor manufacturers often specify the stepper motor windings by the maximum-allowed power disipation at stand still. This gives the nominal winding voltage and current levels. In an application, the optimum performance often is achieved at different voltage and current levels. In figure 9, the holding torques of the 57mm PM and 57mm hybrid motors, described above, are plotted as functions of the the 2-phase-on current, as are the resistive power losses in the windings.

From the diagram, we can see that for the PM-motor, the holding torque curve shows a knee at 600mA—indicating that magnetic saturation starts to occur at this current level, even though the resistive losses in the winding is only 3W, compared to the specified 7W. This indicates that using the specified current level of 960mA does not give the optimum performance on low stepping rates.

Figure 10 shows the affect on motor and drivier performance when the winding current is decreased to 480mA. (50% of the value used in figure 6.) Comparing figure 6 and 10 shows the improved low-frequency performance. Low-speed losses are decreased to less than 50% and low-speed torque only dropps to 80%. In the high-stepping-rate region, only a small loss in torque apears. In figure 13 another combination of driving current and voltage is used to increase the output power to 5.5W with the same maximum losses as in figure 6. Now the losses occur where they are more motivated at the stepping rate where the maximum output power appears.

For the hybrid motor, we see that the winding currents can be increased beyond the maximum rating without causing too much saturation effect. In figure 8, the torque from this motor shows a relativly-flat torque characteristic for stepping rates below 3kHz. This is a result of the 750mA current level not using the full low-speed capabilities of this motor. Increased current will raise the output torque at low speeds and make the region with maximum output power wider (towards low frequencies), but it will only increase the peak output power marginally.

Designing a system

Analyzing the load
When designing a stepper motor system, the first question to ask is "What are the characteristics of the load?" Too often, this question is given too little consideration. To get the best performance, it is important to do an analysis before selecting motor and driver and before designing the transmission and mechanical system.

Friction or inertia loads
If the system will have high dynamic performance, (high acceleration/ retardation), then most of the output torque from the motor will be used to accelerate the system's inertia. To get the maximum performance from this type of system, the gear rate should normally be designed so that the load inertia seen by the motor is close to the motor internal inertia. The load inertia seen by the motor is:

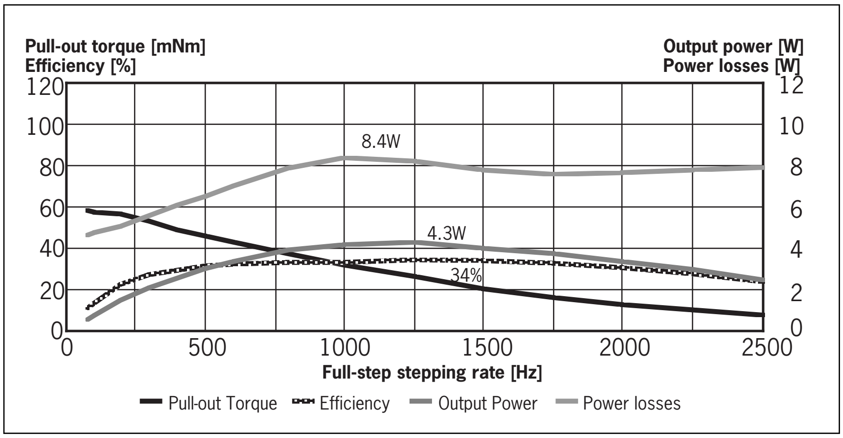

Figure 10. Performance curves for a 3.75ohm bipolar 57mm PM-motor driven by PBL3770A constant-current driver. (Chopper voltage 20V, winding current 480mA).

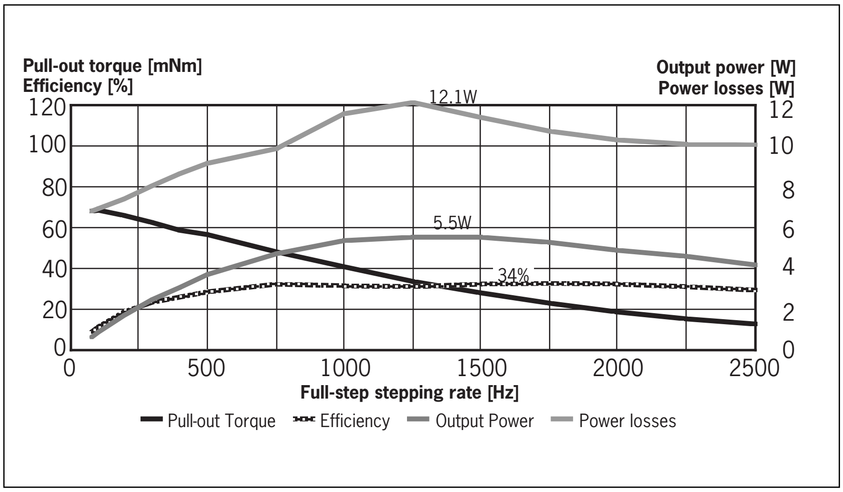

Figure 11. Performance curves for a 3.75ohm bipolar 57mm PM-motor driven by PBL3770A constant-current driver. (Chopper voltage 25V, winding current 600mA).

$J_{lm} = J_l \div G_r^2$ where:

J_l = load inertia without gearing

G_r = the gear rate.

A friction torque is reduced by the factor $^1/_{G_r}$ by a gear mechanism.

Friction torque/load power consumption
To select the right motor size and driver type, it is necessary to calculate or measure the load friction torque. For most type of loads, this is fairly constant at different speeds, which makes measuring easy. If the system involves a linear motion, a spring scale can be used—and for a rotating system, a torque watch can be used. From the measured force or torque, and information about the maximum speed of the motion, the maximum-needed load power can be calculated:

$P[W] = v[m/s] \times F[N]$
for linear systems and
$P[W] = \omega[radians/s] \times T[Nm]$
for rotating systems.

Another way of estimating the load power consumption is to replace the motor or motor and gearbox with a DC-motor with known current-to-torque function and drive the motor at the desired speed while measuring the current consumption. If this technique is used, it is possible to measure the power consumption at different speeds.

Damping
As noted earlier, the usable torque from a stepper motor can decrease at certain stepping rates due to resonances. At which step rates, and to what extent, this torque reduction appears depends on the application damping and inertia. The damping of the driver also influence the torque reduction.

Resonances at low stepping rates can normally be reduced by lowering driver current and voltage levels, or by selecting half- or microstepping mode drivers. At medium step rates the constant-current drivers normally have the least problems with resonances, but here the characteristics of the load have large impact.

Low system inertia normally creates fewer problems with resonances. However, in some applications, an increased inertia can be used to move a resonance to a lower frequency.

Selecting concept
After analyzing the load, we know the output power needed, the maximum and minimum stepping rates, and the resolution needed.

Depending on the importance of the different demands and the ability to fulfill them, the designer has a range of options in combining motor gearing and driver in a system.

The design is normally an iterative process, with calculation and experimentation. If highest-performance or lowest-cost for a given performance is essential, it is a good idea to compare a few different combinations of motor driver and gearing.

A higher-step-rate driver and a smaller motor, together with a suitable gearing, often gives better performance —in efficiency and output power—than a large motor driving the load directly.

Motor selection

Output power
This is the most important design criteria in getting the best price/performance of a stepper motor system. Compare the power requirements of the load with the data given above, or with the data in the manufacturer's data sheet. If the manufacturer's data sheet is used be aware of the big differences in performance of the stepper motors due to different drivers. Also remember that measuring stepper motor pull-out and pull-in torque is tricky. The measurement is easily influenced by inertia and resonances in the measuring system, and the inertia and damping of the application is normally different. As a result, the pull-out curves in the data sheet are not always valid for an actual application.

Mechanical aspects
The physical dimension and weight of the motor are important criteria when a motor is selected. Often the choice of a smaller motor can make a compact mechanical design easier. A smaller motor can also, if the motor is in a moving part of the mechanism, make the design of the motion system easier.

In applications where long life expectancy is needed, motors with ball bearings are required. Hybrid motors use ball-bearings as a standard (to maintain the narrow air-gap), but small-sized PM motors usually use slide bearings. PM motors, with ball bearing as an option, are supplied by some manufacturers—but the additional cost for this is rather high.

If the motor drives a belt gearing or a belt transmission directly, ball bearings are strongly recommended. This ensures proper lifetime and reduces torque loss due to bearing friction caused by the belt tension.

Cost
The motor cost depends on motor type and size. Winding type and resistance do not affect the cost. As a rule, hybrid motors are more expensive than PM-motors. The motor cost normally increases with motor size. Another factor that influences the motor cost is the production volumes of a certain motor and the number of manufacturers of that motor. This means that many times a "popular" type and size motor is the best choice even if the motor output power is a little higher than required.

Customizing the motor
In medium- and high-volume applications, it is possible to customize the motor. Most manufacturers offers customization on the following items.

Shaft	Single- or double-sided Length Pinions
Winding	Resistance Inductance
Rotor	Type of magnets hybrid air-gap distance
Lead wires	Length Connector

From some manufacturers, other parameters such as shaft diameter, bearing types, mounting flange can be customized but this is normally applicable only in high-volume applications.

Driver design

Selecting driver type

The performance curves at the beginning show the effect of the driver on the system. If only low stepping rates are used and the use of gearing is not a solution, the unipolar L/R-driver offers the lowest cost for the electronics for a given output torque.

As demand for output power from the stepper increases, more-effective drivers offer the best price performance ratio. The best motor utilization is achieved with the bipolar constant current driver and this driver is the obvious choice for all high-power applications.

For applications in the low- and medium-power range, several alternatives exists. If system efficiency is important, then the bipolar constant current driver is the best choice. This driver offers higher flexibility in selecting the motor winding, since both the chopper voltage and the current in the winding can be changed to get the desired pull-out torque curve from the motor. Power-supply design gets easier and power-supply losses decrease since regulated supply normally is not needed for constant current drivers.

If minimum cost for the driver electronics is the most important design criteria, rather than the over all system performance, then the different unipolar driver can be the best choice.

Selecting driver mode

FULL-STEP MODE: This is the basic stepper driving mode, it offers the simplest control electronics and it is recommended for high- and medium-frequency operation. At these frequencies, the inertia of the motor and the load smooth out the torque, resulting in less vibration and noise compared to low-speed operation.

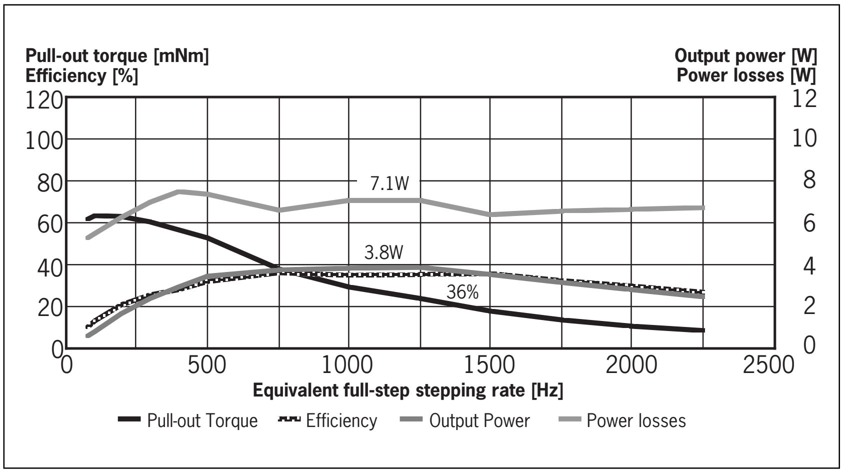

Figure 12. Performance curves for a 3.75ohm bipolar 57mm PM-motor driven by PBL3770A constant-current driver. (Half-step mode fast current decay. Chopper voltage 20V, 2-phase-on current 480mA).

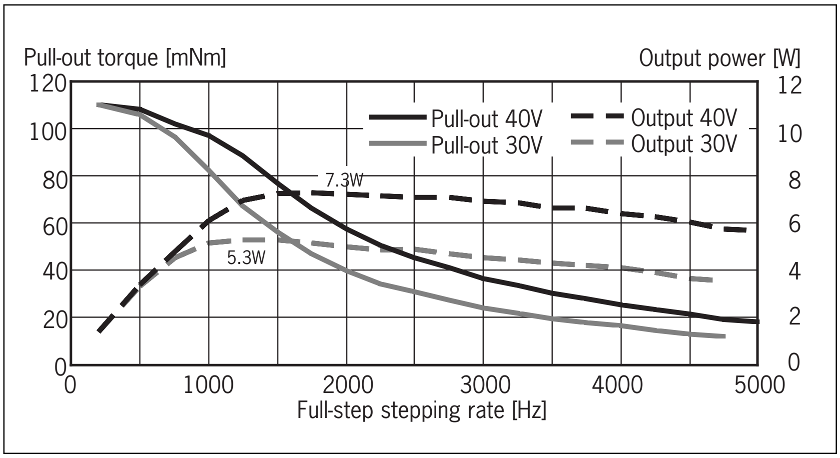

Figure 13. Performance as a function of chopper voltage for a 25ohm bipolar 42mm square hybrid stepper driven by PBL3770A constant-current driver (Chopper voltage 40/30V, winding current 280mA).

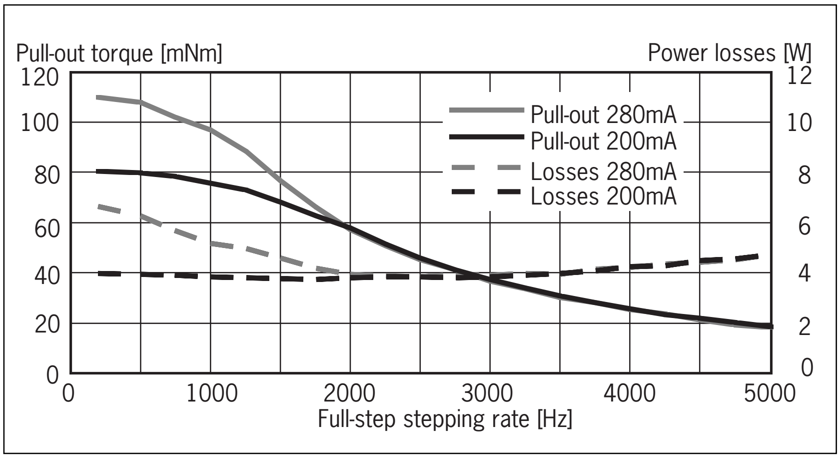

Figure 14. Performance as a function of winding current for a 25ohm bipolar 42mm square hybrid stepper driven by PBL3770A constant-current driver (Chopper voltage 40V, winding current 280/200mA).

HALF-STEP MODE: Half stepping with 140% 1-phase-on current gives smoother movement at low step rates compared to full stepping and can be used to lower resonances at low speeds. Half stepping also doubles the system resolution. Observe that for most steppers, the step accuracy specification only is valid for 2-phase-on positions. The accuracy is lower and the stop-position hysteresis is larger for 1-phase-on positions.

Figure 12 shows the effects on performance of the 57mm PM-motor when half stepping is applied to this motor. Compared to to full stepping (reffer to figure 10 for the same driving conditions), a slightly-higher torque at low speed and a small decrease at higher step rates. The main advantage is the lowered noise and vibrations at low stepping rates. If maximum performance at both low and high step rates is essential, a switch to full-step mode can be done at a suitable frequency. Change the stepping mode this way will also lowers CPU-time requirement (step rate reduced by 50% at high speeds) if the system use a microprocessor as control unit.

MICROSTEPPING: The smoothest movements at low frequencies is achieved with microstepping. Higher resolution is also offered. If resonance-free movement at low step rates is important, the microstepping driver is the best choice. Microstepping can also be used to increase stop position accuracy beyond the normal motor limits.

Designing the winding

For a constant current chopper type driver the winding design depends on the desired output power, maximum operation frequency, and chopper voltage. A simplified design method, which in most cases when high output power is important, gives a good results is described below.

EMF selection

A good design criteria for winding design is the EMF (electromotive force) of the winding The optimum motor performance efficiency and output power is achieved close to the step frequency where the EMF peak value is equal to the driving voltage (chopper voltage in the case of constant current drive). As an example, the 42mm square motor, with performance as shown in figure 7, has an EMF constant of 20mV/Hz (full-step frequency) With a 40-volt chopping voltage, this gives a optimum stepping rate of 2kHz. From figure 7, we see that at 2kHz both the efficiency and the output power are at their maximum values. To design a winding for 20 volts, with a maximum output at the same stepping rate, a winding with 10mV/Hz EMF constant should be used. This winding will have half the number of turns and thus ¼ of the resistance and inductance of the original winding. To get the same holding torque and low-frequency performance the winding current has to be raised to twice the original value.

It is not possible to increase the optimum stepping rate for a motor to very high values since then hysteris loss and rotor leakage inductance will decrease the efficiency.

The EMF constant for a motor is measured by conecting the motor winding to an osciloscope and rotating the rotor at a constant speed (by means of a DC-motor for instance) and measuring the peak value and the frequency of the generated signal. The generated frequency corresponds to a four-times-higher full-stepping rate. From this the EMF constant can be calculated.

Figure 13 shows the affect on the torque and output power of the 42mm hybrid motor when the chopping voltage is decreased. From the figure, we can see that the optimum operating frequency moves from approximatly 2kHz to 1.5kHz when the chopping voltage is decreased from 40 to 30 volts. Using the EMF-rule we get the same result:

20mV/Hz × 1.5kHz = 30 Volts.

Selecting the current level

In a constant-current driver the driver-current level mainly affects the torque at the low frequencies. Depending on the load torque demand (friction and inertia) as a function of stepping rate, it is often a good idea to reduce the current level to get a more-flat torque characteristics from the motor. This normally decrease resonances and power losses and allows a lower-rated driver circuit.

In Figure 14, the effect of decreased winding current is shown—from the curve we can see that only the low and medium frequencies are affected by the lower current. Power losses at low step rates have also decreased. The peak output power, however, is not affected as the torque at 2kHz is not decreased.

Summing up

The unipolar L/R-driver offers the lowest cost for the electronics for a given output torque, if the step rate is low.

As demand for output power from the stepper increases, more effective drivers offers the best price performance ratio. The best motor utilization is achieved with the bipolar constant current driver and this driver is the obvious choice for all high-power applications.