FOREWORD

AC brushless servo drive systems, based on rare earth PM magnets, provide the highest level of dynamic performance and torque density available today. The trend to replace conventional hydraulic, DC, stepper or inverter driven AC drives with brushless drives yields to a new level of system performance, in terms of shorter cycle times, higher productivity, improved accuracy coupled with shorter settling times, increased reliability and longer life. In order to achieve the steep performance improvement which is feasible with the new motors, however, a good understanding of the characteristics of this technology is a prerequisite. In fact, just replacing a conventional motor with a new technology drive on a machine not designed for high speed control could result in unexpected problems and at times even in a deterioration of the machine operability.

These application guidelines were designed to provide a basic tool for the optimization of new applications without prior knowledge of these new drives. For applications where the performance or the motor stress is perceived to be critical, or where a full optimization could be beneficial, contact the Factory.

DRIVE AND MECHANICAL LINKAGE SELECTION

The success of all drive applications dictate a careful selection of the complete system parameters. This in turn is based on a good understanding of the capabilities, which are very high but often not fully understood, of modern brushless drive systems. In fact, brushless drives are not motors, but complete, and complex, control systems; this results in more degrees of design freedom, and more parameters to select, than a conventional drive.

From a conceptual viewpoint, a high performance brushless motor is more similar to the membrane of a loudspeaker than to a standard induction motor. Just as a loudspeaker, the motor has a very short response time, limited inertia, and therefore it faithfully copies the control signal, whatever it may be. Just like a loudspeaker, the quality of the result depends more on the system parameters and drive conditions than on the motor itself.

The design choices facing the system designer are thus at the same time mechanical, electric and electronic, and such choices are interwoven, requiring an interdisciplinary approach.

In particular, all systems require two fundamental selections:

- *mechanical level: choice of the mechanical linkage, of the transmission ratio, of the motion type conversion, of the couplings and clutches;*

- *electronic level: Feedback strategy, sensor type and number selection, sensor placement, amplifier type, synchronization and control bus.*

The next chapters outline a few guidelines to help with the selection as a function of the application characteristics.

THE BRUSHLESS DRIVE: OPERATIONAL PRINCIPLES, CHARACTERISTICS AND LIMITATIONS

All brushless servo systems consist of an electronic drive, a servo motor, and at least one feedback sensor. All these component operate in a control loop: the drive accepts a reference from the outside world, and feeds current to the motor. The motor is a torque transducer and applies torque to the load. The load reacts, or accelerates, according to its own characteristics. The sensor measures the load position, enabling the drive to compare the motion with the reference and to change the motor current to force the motion to copy the reference.

As an example, if constant speed is required, the drive would increase the current to the motor until the motor speed equals the reference. If the load is suddenly stepped up, the speed diminishes; the sensor detects the speed change and consequently the drive increases the motor torque to match the increased load and to return to the set speed. From this example, a few deductions are possible:

- *the speed accuracy is virtually independent of load and motor, but depends on the quality of the sensor signal and the speed and control algorithm of the drive;*

- *the time lag between load perturbation and speed correction depends critically on the speed and resolution of the sensor and on the parameters of the electronic drive.*

Modern brushless servo drives react to sensor signals with time lags in the order of a millisecond or less, providing for very high loop performance.

At this level, however, the propagation time through the mechanical linkages often becomes the prime limit to the system dynamics.

As an example, consider a system in which a servo motor drives a constant speed, large inertia load through a timing belt. The timing belt has a finite, and significant, elasticity. Analyzing a speed correction at the millisecond timescale, the following sequence is obtained:

1 *the drive sets a current level through the motor which applies a torque almost instantly;*

2 *initially, while the belt is being stretched, the load does not accelerate as fast as the motor;*

3 *consequently, the motor reaches the set speed before the load; the sensor, on the motor, cuts the current and consequently the torque;*

4 *the increased tension of the belt slows the motor down forcing the drive to increase the current again, and a new cycle is initiated.*

In this example, the system is oscillating; the motor torque pulsates and so does the load speed. The end result is noise, overheat and wear, none of which are clearly due to the motor. However, superficial users would claim that the motor is noisy; in practice, if this motor is replaced with an older generation, large and high inertia drive, the problem would likely disappear, increasing the feeling that the new drives are not adequate.

This simplistic understanding is erroneous. In fact, analyzing the above example:

1 *the instability is due to the mismatch between the system reaction speed (high) and the mechanical propagation or reaction time (long); the motor reacts quicker than the time required by the system to settle through the new torque configuration;*

2 *the possible solutions are:*
either to reduce the mechanical system reaction time, by stiffening the linkage and lowering the inertias, e.g. going direct drive or replacing the belt with a gearbox; or to lower the speed of the control system, giving up some control bandwidth which would have been achievable with the new technology.

The second solution, of course, sells away some quality, as it impairs the capability to react quickly to sudden load variations. In fact, older drives, which were anyway slower, compensated the lack of speed with a large motor inertia; on the other side, brushless motors, where inertia is minimized, need a good bandwidth to guarantee good rotation accuracy.

All this explains why brushless drives are relatively unforgiving of mechanical inaccuracies, backlash, keyways etc.; for this reason, the best motors are manufactured with round shaft without keyway, for interference coupling with conical fittings (e.g. Ring-feder) and their shafts and flanges are machined to a reduced tolerance to remove the need for flexible couplings. If a coupling is needed, it needs to be torsionally stiff, such as the metallic bellows type.

In conclusion:

while traditional drive systems (DC of PM DC, inverter driven AC) would limit themselves, with their own inertia and response time, the performance of the application, the high level of the new brushless drives move the performance threshold above the mechanical limits of most traditional applications. As a result, the design verification of the mechanical system, and its upgrade to the new requirements, is more important than it used to be up until now.

The success of a new application hinges critically on a good dynamical design of the whole system.

A few rules can also be derived from the simple examples above:

- *the speed accuracy does not depend on the motor but on the sensor;*

- *the following speed, and therefore the ability to compensate for sudden load variations, depends critically on the stiffness and quality of the mechanical linkage.*

The motor noise, which is often observed in poor or retrofit applications, is not due either to the motor or the drive but often enough to a "primeval" mechanical linkage. In fact, noise in due to the motor "hunting" for the correct torque; in this situation, the motor is likely to overheat irrespectively of loading.

The same system might have worked well with an older drive, where the large motor inertia "rolls over" all imperfections.

The dynamic study of the application is fundamental to the motor selection.

To this aim, this broad concept can be divided in two elements:

- *large signal bandwidth: this is the raw ability to deliver enough torque and speed, in sufficiently short time, to force the load on the desired trajectory. This depends exclusively on motor and load torque and inertia, and can be studied considering all components as infinitely stiff;*

- *small signal bandwidth or control bandwidth, which relates to the inverse of the settling time. This is necessarily lower than any mechanical resonance frequency in the system; its inverse expresses the settling time of the control loop, i.e. the time required at the end of a motion command to settle in the target position within a required accuracy. Typically, it will be impossible to achieve a settling time better than 2-3 times the damping time of all the oscillations or resonances in the load and linkage.*

As an example, consider the indexing axis of a high speed notching machine. The rate target is set at 10 strokes per second, i.e. the drive starts and stops the workpiece in a new position ten times per second. If the whole linkage (shaft, reducer, belts, ball screw etc) has a first resonance frequency of 50 Hz, the system will settle in about 50-60 msec, leaving only 40 msec for the move and the punch! This application is near impossible, as very high torque and accelerations would be needed. However, if the linkage is stiffened, by removing the belt, adopting a larger screw, etc. so that the resonance frequency of the linkage is increased to 100 Hz, the settling time is reduced to 25-30 msec, the time available for the move is doubled, the required torque is halved, and the application is feasible.

OPTIMAL DRIVE DESIGN: THE TRANSMISSION RATIO, THE TYPE OF CONVERSION, THE COUPLINGS.

Brushless motors, like all other motors, are sized on supplied torque and not on output power. In all applications, therefore, low motor speed yields to a low specific power and relatively low efficiency. On the other hand, brushless motors have no minimum speed (the speed depends only on the sensor used; there are applications whose axis speed is 1 revolution/year); as a consequence, a high gearing is advisable only to minimize the motor mass (e.g. with electric traction) or to maximize the efficiency; it is often not advisable from the viewpoint of cost or dynamic performance. Wherever the motor is applied directly on the load, the control bandwidth is maximized because maximum transmission stiffness is achieved; consequently, these applications provide the best position or following accuracy with the shortest settling time.

Before starting with the selection of the right drive for a specific system, it is necessary to know the type of mechanical transmission which can be used. The most common transmissions are the following:

ROTATION-ROTATION CONVERSION

- *timing belt;*
- *reducer with helical wheels and parallel axes;*
- *cycloid and epicyclic reducer;*
- *Harmonic Drive™;*
- *tangent screw reducer or Gleason gears.*

ROTATIONAL-LINEAR MOTION CONVERSION:

- *timing belts;*
- *pinion-rack;*
- *metallic band;*
- *ball screw.*

For any transmission system, the load parameters can be transferred to the motor axis as follows.

If n = transmission ratio (ratio between the motor and the load speed, rad/m in the case of a conversion from linear motion):

- *Motor torque = Torque (thrust) to the load/n*
- *Motor speed = Load speed x n*
- *Load inertia reduced to the motor axis = inertia (or mass) of load/n^2*

Among all the listed transmissions, the first ones, which are the least expensive, are also the slowest; they result in low control bandwidth (lower than 10 Hz, using a high stiffness belt); for the same reason, it is important to avoid the ratios which make the load inertia transferred to the motor axis too much higher than the motor one. The belt transmission should not be applied for positioning applications with cycle times a lot shorter than one second.

Gear reducers are a good solution, provided that their angular backlash is considerably lower than the accuracy required by the system; the best type of reducer (the most expensive too) is the epicyclic; there are special series of cycloid and epicycloid reducers purpose designed for servo controls, where the angular backlash at the output shaft is limited to 1-3 arc minutes. Such reducers are the only ones that can be specified for applications with control bandwidth higher than 10 Hz. The "servo series" reducers are designed to be coupled directly to the motor with a stiff coupling device, without keyway.

The Harmonic Drive™ gearbox was specifically designed for positioning. It has limited size, high ratio and low backlash. The angular stiffness is not very good and the achievable control bandwidth is in the 10-30 Hz range. Because of its limited efficiency, it should be used for positioning only.

Tangent screw reducers fit in a class apart. These gears, although common and inexpensive, are not suitable for position control. The tangent screw, whose efficiency is based on an effective lubrication, display a low efficiency which drops dramatically at low speed, because below a critical speed the oil film collapses, efficiency drops and a quick wear ensues.

Wherever a rotary to linear conversion is required, ball screws provide a quality solution up to about 4 m/s, especially if they are driven directly by the motor. Direct drive with a low inertia motor generally avoids the need of a torque limiting clutch. For very long movements it is necessary to check the flexure and torsional stiffness of the screw, which may limit the system bandwidth. Longer movements are carried out with rack and pinion, which have always a significant backlash which generally results in limit cycling and motor noise. The traditional backlash elimination methods add stick-slip non linearity instead, and so do friction wheels, typically with similar limit cycling results.

Fast and accurate movements can be obtained with metallic tapes replacing the timing belts with superior stiffness. This technique, while not well known and therefore not standardized, is able to reach excellent performances in the control of small loads (a few kilos).

In general, however, linear motors rest as the best solution for high accuracy control of a linear motion.

In order to select the most suitable reduction method and transmission ratio for a specific application, it is useful to classify first the applications into two broad families:

1 ***Power services**: the motor supplies power to a process (spindles, traction, winding, conveying etc.), where the dynamic performance is of marginal importance, the power controlled is significant, the motor cost is an important fraction of the system cost;*

2 ***Position control** or high rate cycling (electronic camshaft), in which most of the energy is used to accelerate, to brake and to position objects in a short time and with a more or less high accuracy.*

*Traditionally, the two above mentioned categories are referred to respectively **as spindle drives and axis drive.***

In the first case, the dynamic properties are often not important, therefore simple speed reducers are acceptable and, as the power is often relevant, a mechanical transmission with a reduction stage is normally useful. In order to choose the best transmission ratio, consider that up to ~ 4000 RPM, the cost and size of the motor decrease in a quasi linear way with the increase of the transmission ratio. On the contrary, the cost of the transmission increases step by step according to the number of gear stages or pulleys; from an application cost viewpoint, the minimum overall cost can only be found in a few points, precisely:

- *either with a direct drive;*
- *or at the speed corresponding to the maximum ratio which is possible with just one reduction stage;*
- *or at the speed corresponding to the maximum ratio which is possible with two reduction stages and so on.*

The economic optimization, in this case, is carried out checking these points and adding the costs of the motor to that of the reducer.

For all dynamic applications (axes) the situation is completely different. If the torque required in the drive cycle is dominated by the inertial torques both of the motor and of the load, for an increase in the reduction ratio there is a decrease in the impact of the load inertia and an increase of the impact of the motor inertia. Consequently, for an application where the required torque is exclusively inertial, the reduction ratio at which the load inertia, translated to the motor axis, equals the motor inertia (inertial match) is characterized by the minimum motor torque and therefore by the smallest motor.

For this reason, inertial matching was long considered the best gear ratio selection tool. Such rule, on the contrary, is just a useful indication. In fact, the minimum size motor, considering that the cost of a quality reducer can double the cost of the motor, does not correspond to the lowest cost application sizing. Furthermore, the level of quality and performance is determined a lot more by gear backlash and shaft elasticity than by the motor itself. Consequently, a ratio selection which accounts for the motor only is clearly flawed. A better set of rules is the following;

- *any transmission ratio higher than the inertial ratio is wrong;*
- *the best ratio is always lower or equal to the inertial one, and it is obtained considering the motor and reducer costs;*
- *high ratios always yield a narrower control bandwidth and a lower degree of accuracy (with a higher energetic consumption) than what can be obtained with lower ratios.*

These considerations explain the current attempt to replace step down gears with direct drives.

Wherever the load inertia transferred to the motor shaft is more than a few times the motor inertia, however, care must be taken, because the motor inertia is not there to carry out a stabilizing action on the possible mechanical resonances or load disturbance on the system. As a consequence, a high control bandwidth needs to be achieved, to compensate electronically what is not obtained by inertia alone; to do this, the mechanical linkage in these applications needs to be of high quality, stiff and without backlash (no keyways!).

From an analytical viewpoint, extreme direct drives mandate a check on the torsional stiffness of the system. The torsional stiffness of the motor shaft needs to be considered as well; this, although minimized in the ULTRACT II design by means of large shafts, is significant for the long and thin motors. In fact, the ULTRACT II range was purposefully overlapped, so that the same torque can be obtained either with a long and narrow motor or with a short and stocky one. For this reason:

- *long motors have a minimum moment of inertia; they are intended for high acceleration with low inertia loads;*
- *stocky motors have a maximum torsional stiffness; they are intended for high inertia loads, where the motor inertia is small compared to the load.*

As a reference, the torsional stiffness of a shaft whose diameter is D and whose length is L, made of steel, is:

$$S_m = \frac{\pi}{32} \bullet \frac{D^4}{L} \bullet 78.5 \bullet 10^9 \bullet \frac{N}{m^2}$$

while the frequency of torsional resonance of a load with inertia Jl connected to an axis with torsional stiffness Sm is:

$$F_1 = \frac{1}{(2 \bullet \pi)} \bullet \sqrt{\frac{S_m}{Jl}}$$

In all applications with large inertia and short settling time, a check on the first torsional resonance frequency is highly advisable.

CONTROL STRATEGY SELECTION

All drive system can be configured according to three main control strategies:

- *torque control (the speed depends on the load);*
- *speed control (the torque depends on the load);*
- *position control (the torque depends on the load)*

The first strategy is the easiest to implement and can be used when it is necessary to control a force or a pull (winders/unwinders, textile, tape/paper processing, etc.). Torque control is native, or intrinsic to the brushless motors, which are always current controlled. For this reason, torque control has minimum sensor requirement (just commutation or Hall sensor), is very fast (control bandwidth >300 Hz) and intrinsically stable and robust irrespective of load. Torque controlled drives are simple amplifiers which require no calibration or adjustment whatsoever and are therefore the simplest controllers. Accuracy is not too high due to motor friction, cogging, ripple, sensor drift; typically it can range in the 5-10% area.

In the multi-axes applications with very fast and modern NCs or controller boards, where multiple axes must be linked (multiple electric gears and cams), or with adaptive control or with variable parameters, a simple and effective strategy is to set the drives in torque control mode and to assign the other loops to the NC. In this way the encoders are fed to the NC, all drives are equal, intrinsically stable and need no programming; all the system and control parameters (offsets, PID values, etc) are lumped in the NC or control PC. The drives can be replaced without programming and no download of parameters is necessary. The control signal to the drives is a simple differential torque reference, offset insensitive. The encoders are fed directly to the NC; the drive only reads the commutation system. This simple and elegant approach provides very good performance in multiple systems without incurring the cost and complexity of high speed field buses, which are anyway rather limited in the number of axes and in the achievable speed. On the down side, it downloads on the NC or PC the processing of the encoders, which could be cumbersome where very high resolution is needed.

Speed control is the most traditional strategy. It usually embodies an integration term so that the speed error is limited to the system offsets. In the digital drives, the speed loop is derived from the space loop (see next).

Position or space control in servo amplifiers is carried out only by digital drives (AX-V). In this way, the steady state position and speed following error is limited to a few points of the sensor, that is in the case of an encoder with 4096 pulse/revolutions, 1/16,000 of a revolution. Position loop capability, inside or outside the drive, is necessary to synchronize several axes (electrical axis or electronic cam).

CHECK OF THE DRIVE AND MOTOR SIZING

After selecting the motor and the transmission, a check of the correct sizing of motor and drive is required. Such check is easy for applications where speed and load are quite steady or which vary on a timescale which is long with respect to the time constant of the motor (or of the electronics). In this case, it is only necessary to check for the maximum load to be within the specified limits of the motor and the electronics.

For the applications where the load varies on a fast cycle, verification should proceed as follows:

1 Trace the speed/time diagram of the cycle, considering that the acquisition of a precise position or speed requires, apart from the time determined by the limits on the speed and acceleration of the system, also a settling time equal to 2-3 times the inverse of the system control bandwidth;

2 Transfer the inertia and the loads of the system to the motor shaft;

3 Calculate the cycle of the accelerations and the inertial torques [acceleration x (motor inertia + load inertia transferred to the motor shaft)], checking also the inertia of couplings, clutches, transmission devices;

4 Add the load on the motor axis to the inertial torque and derive a torque/time diagram in the cycle;

5 By inspection of the torque vs. time diagram obtain the root mean square value of the torque: e.g. divide the cycle into time segments t1,t2....tn inside of which the torque is constant; if the torque values in each segment of the cycle are respectively C1,C2...Cn, the root mean square torque in the cycle is:

6

$$Ceff = \sqrt{\frac{(C_1^2 \bullet t_1 \bullet C_2^2 \bullet t_2 + \ldots\ldots\ldots \bullet C_n^2 \bullet t_n}{(t_1 + t_2 + \ldots\ldots\ldots\ t_n)}}$$

7 Calculate the root mean square or effective speed in the cycle ω_{eff} with the same formula;

8 Calculate the mean torque in the cycle Cave;

9 Calculate the maximum duration time of the maximum torque in the cycle tcmax;

10 Calculate the required torque at the maximum speed Cwmax;

11 Calculate the maximum torque Cpk.

The data thus obtained needs to be compared with the motor and electronic limits to validate the application.

MOTOR SIZE VERIFICATION

Brushless motors are excellent torque transducers, linear to a peak torque several times the nominal. As a consequence, the obtainable peak torque is usually determined only by the choice of the electronic drive. The correct sizing of the motor is thermal and electric; the optimally sized motor is the one which, on the worst load, settles at the correct temperature rise, usually 40-50°C above the room temperature.

The complete check of the selection of the proper motor is carried out in three steps:

- Control of the peak or demagnetizing torque;
- Thermal dimensioning;
- Electric, or winding, dimensioning.

1 Demagnetization current check

Compare the peak current , expressed by:

$$I_{pk} = \frac{C_{pk}}{K_t} \bullet \sqrt{2}$$

with the motor demagnetization current, considering that the motor demagnetization current increases as the temperature decreases. This check is usually meaningful for small motors only.

2 Temperature rise check

Preliminarily, check that the point C_{eff}, ω_{eff} is within in the continuous operation area (S1) of the chosen motor. More accurately, the temperature rise of the motor can be predicted by:

$$\Delta_{mot} = \frac{65}{L_n} \bullet \left[\left(\frac{C_{eff}}{T_n}\right)^2 \bullet L_n + \left(\frac{\omega_{eff}}{\omega_n}\right)^2 \bullet L_0 \right]$$

where Ln represents the nominal losses of the motor with temperature rise of 65°C.

If the predicted temperature rise is higher than the motor maximum or acceptable temperature rise, it is necessary to select a larger motor.

NOTE: the excessive temperature rise is generally the only good reason for the use of a larger motor.

3 Electric sizing check

At the maximum speed, the voltage required by the motor to supply the required torque must be lower or equal to what is available from the drive, for the minimum mains supply voltage which is specified for full specification operation (usually 90% of the nominal voltage).

If Emin is the voltage value which can be supplied by the electronic power supply at the minimum supply voltage, it is necessary to check that:

$$V_{max} = \sqrt{3} \bullet \sqrt{\left(K_e \bullet \frac{\omega_{pk}}{\sqrt{3}} \bullet \frac{R_w}{2} \bullet \frac{C_{wmax}}{K_t}\right)^2 + \left(\frac{C_{wmax}}{K_t} \bullet \frac{PN}{4} \bullet \omega_{pk} \bullet L_w\right)^2} \leq E_{min}$$

If this condition is not verified, it is necessary to choose a motor with a higher speed winding; this will of course also require a higher drive current.