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Product Identification: PCNC 1100 Mill

Overview:
The choice to power the spindle of the PCNC 1100 with an AC induction motor and VFD (Variable Speed Drive) was made in 2003. As time has progressed the cost of the VFD has increased and the technology has changed considerably, so a decision was made to investigate the state of the art of VFD technology and take another look at competing drive vendors.

Objectives:
A laundry list of improved operation was created prior to the drive search including;

- Faster stopping of the spindle for reduced downtime on tool changes
- Elimination of potentiometers for drive adjustments
- Higher output power for increased cutting capacity
- Wider speed range for more flexibility

Technology:
When the PCNC 1100 was designed the selection of a VFD driver was a relatively easy decision[1], but the choice of which brand VFD driver was rather limited a few years back. We selected an analog volts/Hz driver because, at that time, the advanced technology drivers were considerably more expensive than the basic models. In the case of reasonably priced VFD's, the changing of technology from analog control to digital control has brought increased performance and features. While VFD's have become more expensive, the difference in price between a basic model and an advanced technology model has narrowed.
For anyone unfamiliar with induction motor technology, the first question might be "what constitutes advanced technology in a VFD?" The answer to that question has its roots in the basic operating principles of a 3 phase induction motor. Any electric motor has a rotating magnetic field. Induction motors are referred to as an asynchronous design because the rotor turns at a lower speed than the rotating magnetic field. The difference between synchronous speed and actual speed is referred to as slip and it varies as the motor is loaded. Slip is characteristic of an induction motor because it does not have permanent magnets in the rotor, rather it has electric magnets. There are no brushes or slip rings to carry power the magnets of the rotor. The electrical current necessary to create the magnetic (flux) field of the rotor is generated by the difference in speed between the rotating magnetic field in the stator and the rotation of the rotor. Slip is what magnetizes the rotor. As the motor comes under load the magnetic field in the rotor needs to increase in strength, so the motor slows down, slip increases, and the generating effect of slip puts more current in the rotor. There are complex mathematical relationships between slip, torque, speed, current, and voltage. The variations among VFDs lie largely in their ability to manage the necessary calculations. It's a complex problem and the success of a VFD design is demonstrated by performance.

As various drive vendors were investigated, it became obvious that only digital drives would meet our needs. A number of digital drives were brought in house to test on the spindle. During this testing, it became clear that those drives with an enhanced operating algorithm outperformed the more standard drives.

[1] http://www.tormach.com/document_library/TD30204_DesignAnalysis.pdf

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There are 3 basic types of VFD's for Induction Motors:

- Volts / Hz
- Sensorless Vector
- Closed Loop Vector

Volts / Hz drives have the simplest operating algorithms and are typically used for non-demanding applications such as conveyors and fans. These drives provide an output whose frequency and voltage changes to vary the speed of the motor. The drives have little knowledge of the motor characteristics or of the connected load. As load variations occur, the speed regulation suffers. Slip is roughly approximated through motor current and adjusted by a Slip Compensation term. Volts/Hz drives have the limitation of not being able to deliver significant torque at low speeds.

Sensorless Vector drives have significant computing power and have more knowledge of the motor and load than do Volts / Hz drives. Motor parameters are entered into the drive memory during set-up and the drives have software that measures motor characteristics. With this background knowledge the drives can make reasonably good judgments on what is happening with the motor and load, and therefore react better to changes in load. These drives can produce significant torque at lower speeds that Volts / Hz drives.

Closed Loop Vector drives have all the features of Sensorless Vector drives and in addition use a feedback device on the motor so it knows exact motor speed. Because the drive controls the rotation of the magnetic field in the stator and knows the rotation of the rotor, slip is known precisely, not estimated as in a Sensorless Vector. Closed Loop Vector drives have excellent speed regulation due to the feedback device on the motor The Closed Loop Vector drive acts much like an AC servo drive and can even be used in some servo applications. The big difference is in the motor. Servo motors have much less inertia than comparably powered induction motors and can provide much better performance at low speeds. Vector Drives are more expensive than Sensorless Vector drives, yet when used with standard induction motors the performance difference is minimal. Vector drives really shine when they're used with a vector induction motor instead of a standard induction motor. The combination of a vector drive and a vector motor is nearly as expensive as an AC servo but can also provide acceleration and zero speed torque like an AC servo.

Sensorless Vector drives were found to provide all the features that Tormach desired for the spindle application. Low speed capability was increased sufficiently to be useful for the machine. The Closed Loop Vector drive could have allowed the spindle to be run even slower, however, that did not provide any significant capability to the machine. The speed regulation improvement with a Closed Loop Vector drive would not add value to the PCNC1100. It was therefore decided that the extra complexity and cost of a Closed Loop Vector drive was not in keeping with the Tormach philosophy of providing maximum utility at a reasonable price and Tormach's adherence to the KISS principal. Not only would the feedback device required on Closed Loop Vector drives make the spindle drive sub-system more complex, it is well known in the industrial world that sensors (the feedback device) are the most likely component to fail.

In an attempt to increase the high speed capability of the machine it was discovered that all drives in their standard configuration would fault if a speed was commanded that was higher than the motor could attain. Typically the motor would accelerate as fast as it could go and then the control would get confused and the speed would drop to 0. Interestingly, the drive would continue to pump out current to the motor which could result in motor burnout. This phenomenon occurs because of the way the drives must operate at the extended speeds we were demanding, over 2 times normal motor speed. All drives behave differently above the motor's base (normal) speed than they do below base speed. Below base speeds the motor provides constant torque but above base speed the motor acts as a constant power device. That means as the speed increased, the torque decreases proportionately. At twice base speed, the motor will only be able to provide half the torque it can at below base speed. Since the drag in the spindle and the drag in the motor increase as the speed increases, a point is reached where there is simply not enough torque to keep going faster. This is the point at which the drive gets confused.

One of the drives in the test group had some additional programmability beyond the typical parameter setting that is done on a digital drive. This additional capability is used to sense that the drive is having trouble attaining commanded speed and effectively backs off the speed to the level that can be attained. It is possible that more than normal friction in the spindle could prevent the

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top commanded speed. Now, the motor will just run at a speed as close as it can to the commanded speed and the drive will not fault through. We refer to this as the speed command fold-back logic. This is a significant enhancement to spindle performance and allows us to increase the top end speed of the machine. It was also the deciding factor in our choice of the Emerson Control Techniques drive.

One of our goals was to provide faster spindle stopping and deceleration. At high speed the spindle and motor contain considerable kinetic energy. During deceleration the motor acts as a generator and the problem of stopping is a question of what to do with the energy. The original PCNC 1100 drive used a technique known as DC injection braking. The kinetic energy is absorbed by the motor itself, through a slight heating. The deceleration rate is very limited, usually about 2X the normal coast down rate. As a part of the drive upgrade we incorporated a braking resistor. With this method the kinetic energy of the spindle is turned into heat in the braking resistor, thus allowing a high power deceleration.

Performance Increases on the PCNC1100 Drive Upgrade

1. The new drive provides much faster deceleration of the tooling. This is not the result of the advanced technology, but rather the incorporation of a braking resistor. It takes the standard PCNC1100 about 9 seconds to slow from its top speed of 4500 RPM to a stop. The upgraded machine will slow from 5000 RPM to a stop in less than 2 seconds. This is helpful for tool changes. Importantly it also makes the machine very suitable to tapping using a floating tapping head. At 500 RPM the tap will stop in less than one revolution.
2. The new drive is digital and has no potentiometers to adjust to calibrate the drive. There is no chance of bumping a pot or setting it incorrectly. The drive is programmed by Tormach with the specific configuration we developed for the PCNC 1100. The configuration includes the speed fold-back logic and programmed support for the optional load meter (see below).
3. Increased power output and speed range on the motor / drive improve its machining capability.
    a. Cutting
        i. 1.0" wide by 8.75" long mild steel bar was cut at a spindle speed 1200 RPM using high speed pulleys. Depth of cut/pass was 0.050". A TTS Multi Purpose Face Mill (30679) 1.5" Diameter with Octagon Face Mill Inserts (30682) cutter was used.
            1. X axis speed for standard PCNC1100: 21 ipm
            2. X axis speed for upgraded PCNC1100: 40 ipm
    b. Drilling
        i. A 1.0" diameter hole was drilled through mild steel 1.5" thick using a spindle speed of 200 RPM with the low speed pulleys. Maximum feed rate was 0.54 ipm (inches per minute).
        ii. Since the original series machine could not be run as slow as 200 RPM, comparable data does not exist.
4. Speed range has been extended

Machine	Low Speed Pulley	High Speed Pulley
PCNC1100 original	350-1750 RPM	900-4500 RPM
PCNC1100 upgraded	100-2000 RPM	250-5140 RPM

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5. Power capability has been extended:

Machine	Rating	Cont. Current	Peak Current
Original Drive	1.5 HP	5.0A	7.0A
Upgrade Drive	2.0 HP	7.0A	10.5A

New Available Option

Digital drives in general and the Emerson Control Techniques drives in particular, have programming options that allow several useful and important pieces of information to be made available to the user. Tormach has programmed the drive to provide the following information to be displayed on an optional Load Display Panel:

1. Drive Fault Pilot Light. This light illuminates when there is a condition that makes the drive shut down to protect the drive / motor system
2. Spindle On Pilot Light. This light illuminates when the spindle is on and is useful when monitoring the machine at a distance in noisy environments.
3. Analog Power Meter. This is a meter with a swinging needle that displays the power being output by the motor / drive. A primary use of the meter will be to indicate to the user that the tooling is in need of changing. It also gives some indication of how hard the spindle system is being pushed.

Project Summary

The project required approximately 2 months during the drive selection phase and another month for optimization and tuning of the selected drive. The drive upgrade design has met all goals for the project:

Faster stopping of the spindle

There is a 450% improvement in stopping time, moving from a maximum of 9 seconds down to less than 2 seconds for complete stop. This reduces tool change time as well as introducing the potential for using the tension/compression tapping method.

Elimination of potentiometers for drive adjustments

All potentiometers are gone. This eliminates the variability introduced by the setup technician at the factory and the variation over time that can be seen with analog electronics.

Higher output power for increased cutting capacity

The original drive had capability of 150% overload to cover peak current conditions. The upgraded drive has a 230% overload capability. This increase in peak current allows quicker starts and vastly improved carry through under tough cutting conditions.

Wider speed range for more flexibility

The increased torque at low speed and the improved frequency control at high speed combine to provide a much higher dynamic range. The original drive allowed a dynamic range of 5:1 between highest and lowest speed. The upgraded drive offers a dynamic range of 20:1. This is a 400% improvement in dynamic range.

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