Variable Speed Drive for Wood Turning Lathe

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Abstract

Teknatool International lLtd - Auckland, New Zealand, wishes to incorporate an electronic variable speed motor drive unit into one of their series of wood turning lathes. Traditionally the lathe incorporates a constant speed motor with a pulley system to select one of several different speeds of operation. The development of an electronic variable speed drive will ultimately improve the value and marketability of the lathe. This was achieved and the product was introduced to the market as the first of its kind in the world market. This paper will outline all the stages involved from the initial concept to the final commercial product.

Key Words: *Variable Speed Drives Motors Comparison Applications.*

1. Introduction

The traditional lathe incorporates a constant speed motor with a pulley system to select one of several different speeds of operation (see Figure 1). The selection of the appropriate motor and drive unit is essential for the success of the product being designed. It is also essential to not only meet the required performance criteria in terms of torque and speed, but to achieve this without adding significantly to the cost, in order to remain competitive in the marketplace.

The traditional lathe is a successful product and is exported widely. However continued success and further market penetration is limited by a significant weakness – these lathes are all shipped unmotorised overseas. Some current issues are:

- The company is unable to control costs in the overall package presented to the customer.
- There are compatibility problems in the lathe/motor interface with each customer/market.
- There are performance quality problems in the lathe/motor interface which are difficult to resolve.
- It is difficult for customers to set up and use. Customers want a turnkey, 'plug and play' approach.
- Currently unable to competitively add motor drive features such as electronic variable speed.

The lathe was designed and has proved itself to be a machine of high desirability able to be sold in all the key markets. What is holding the machine back is the process of adapting to local motors and regulations in each market. With an integrated solution they could rapidly enter new markets. These are difficulties common to all our competitors, which leads to fragmented market penetration. Our ability to apply a generic but customisable solution would be a powerful market edge.

2. The Existing System

The existing drive system uses a 1 hp, constant speed, single-phase induction motor. The motor is rated at 1400 rpm and will run at or close to that speed shortly after being switched on. To change the speed of the lathe the belt must be manually shifted from one position to another [see Figure 1]. The existing system has eight such positions to give eight different speed settings. These speeds range from 190 rpm up to 3500 rpm. Teknatool International Ltd suggests that a range of speeds from 300 to 2500 rpm would be sufficient for a wood turning application.

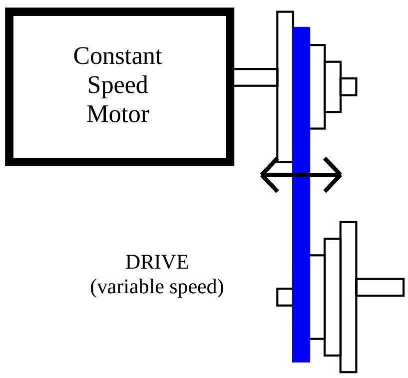

Figure 1: The existing manual variable speed drive

An Analysis of the belt system carried out by the V-Belt manufacturer, The Gates

Rubber Company, provides information on the speed and torque capabilities of the pulley transmission system as shown in Table 1 below. The torque / speed curve is shown in Figure 2.

Speed (rpm)	ω (rads^{-1})	Hp	Torque (Nm)
189	19.8	0.2	7.6
309	32.3	0.5	11.6
579	60.6	1.1	13.6
855	89.5	1.6	13.4
1251	131	2.1	12.1
2059	215.6	2.5	8.7
2793	292.5	2.5	6.4
3525	369	2.4	4.9

Table 1: Torque / speed data for the existing system

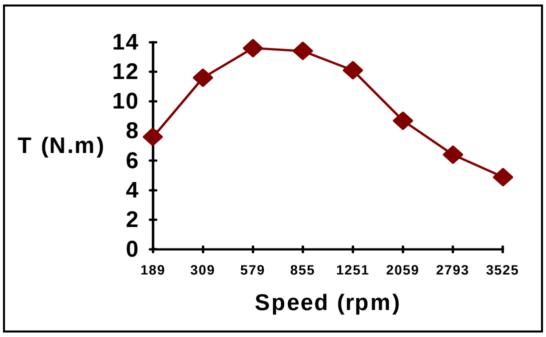

Figure 2: Torque v speed curve for the existing system

3. Electronic Variable Speed Drives

Many industrial applications require variable speed drive. Traditionally, DC motors have been used in such applications. However, recent advances in semiconductor power electronics and microelectronics have made it possible to use AC motors – see Mohan *et al* (1989) and Jacob (2002). Also, a new type of motor called the switched reluctance motor is coming into consideration for these applications.

A typical variable speed drive system has three major components: the control circuits, the power conversion circuits and the motor itself (See Figure 3). The control circuits consist of low power electronic components including microprocessors. For inputs they have a speed reference signal, and usually a signal giving a measure of the actual speed of the motor by either a tachometer or by analysing the motor's driving current. From this information they decide on the best course of action for the motor and then produce firing signals for the power switching devices found in the power conversion circuit.

The power conversion circuitry contains high power switching devices. These could be either Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFET), Bipolar Junction Transistors (BJT), Insulated Gate Bipolar Transistors (IGBT), Thyristors or Gate Turn-Off Thyristors (GTO). These are switched on and off by the firing signals produced by the control circuits, to produce an output power supply for the motor of the required form and magnitude. Rectifying, inverting and chopping circuits are used to produce variable voltage DC, variable frequency AC or pulses of varying duration and magnitude to feed their respective motors - see Bartelt (2002).

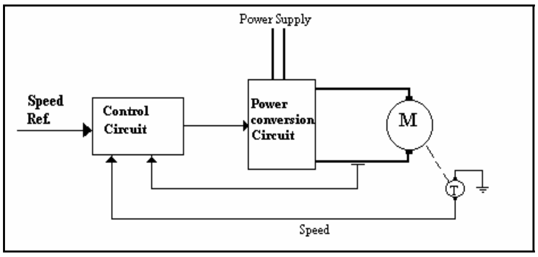

Figure 3: A typical variable speed drive system

4. Selected Variable Speed Motors / Drives for Investigation

There is significant overlap between the major types of motor and drive. This makes it difficult to lay down a set of hard and fast rules to guide Teknatool International Ltd directly to the best solution for the wood turning application. To make a successful selection of the motor / drive unit, the following points need to be carefully considered:

- Motor load: Wood turning lathes operate at "constant power". The power demanded by the load is constant within the speed range. The load requires high torque at low speeds and the torque will decrease as the speed increases [see Figure 2].
- Torque requirements: When selecting a drive it is important to consider both the starting torque and the running torque. The motor torque supplied must be greater than the required torque from start to full speed. The greater the excess torque, the more rapid the acceleration. The running torque

is the torque required to maintain the desired operating speed.

- Speed range: The minimum and maximum speeds of the wood turning machine application (300 rpm - 2500 rpm) will determine the base speed of the drive.
- Speed regulation: A speed variation of 3-5% would be tolerable in a wood turning application.
- Duty cycle: This is defined as the repetitive load pattern over a given period of time and is expressed as the ratio of on-time to the cycle period.
- Safety features: such as overload protection and over voltage protection.

An initial review of different types of electric motors and drive systems suggests that three types of variable speed drives can be made to meet the required performance criteria for this application, these being:

1. Variable speed drives for AC motors (Squirrel Cage Induction motor)
2. Variable speed drives for DC motors
3. Variable speed drives for switched reluctance motors.

5. Comparison Between AC and DC Drives

DC drive technology has dominated the market for many years, and any challenger must compete with it in terms of price and performance. The majority of inverter-fed (AC) drives are therefore marketed as a package consisting of an inverter and a standard induction motor, and priced so as to be competitive with the DC drive of the same rating and speed range. The higher cost of the AC inverter compared with the DC converter is offset by the much lower cost of the standard induction motor compared with the DC motor.

There is a clear implication in much of the promotional material that the inverter-fed system can perform at least as well, or even better, than the DC drive. This is true for some applications such as fans and pumps where high torque is only needed at high speeds. Whereas a DC drive will invariably be supplied with a motor which is provided with through ventilation to allow it to operate continuously at low speeds without overheating, the standard induction motor has no such provision, having been designed primarily for fixed-frequency full speed operation. Thus although the inverter may be capable of driving the induction motor with full torque at low speeds, continuous operation is unlikely to be possible because the motor will overheat. Manufacturers and suppliers of inverter drives are understandably not keen to emphasise this limitation, and no well established pattern has yet emerged. Users therefore need to raise the question with the supplier before committing themselves. The real problem lies in the use of a standard induction motor; when through-ventilated motors with integral blowers become the accepted standard, the inverter-fed system will be freed of most of its current limitations.

One recent trend designed to mitigate the danger of motor overheating at low speeds is for inverter suppliers to design their control circuits so that the flux and current limit are deliberately reduced at low speeds. The constant-torque facility is thus sacrificed in order to reduce copper and iron losses. As a result the drive is only suitable for fan or pump type loads which do not require high torque at low speed. These systems inevitably compare badly with DC drives. Over-sizing of the drive would be required to obtain the high torque needed for the wood turning lathe at low speeds.

To conclude; for the wood turning application the DC drive is more suited. The inverter-fed induction motor may not be capable of continuous operation at low speeds unless the motor is provided with forced cooling.

A third type of motor drive, called the switched reluctance motor drive, is of a simple construction and provides very good torque and speed performance. Initial investigations of a switched reluctance motor drive are reported below.

6. Switched Reluctance Motor Drives

In this type of motor, torque is produced on the rotor through simple magnetic attraction – see Miller (1989), Amin (2003). Figure 4 shows the basic construction of a switched reluctance machine. The stator consists of an even number of salient poles (8 in this case). The poles that are diametrically opposite other have their windings connected in series to form one “phase” of the machine (there are 4 in this case). The rotor is a simple cog like structure with no windings, magnets or brushes. For the same number of poles, the commutation frequency in the switched reluctance motor is double that of the AC motor. This means that the flux-density waveform is rich in harmonics and reaches high levels of saturation especially near the pole corners. The high frequency of the eddy-current component dominates the losses, making it desirable to use a thinner lamination (around .3 to .4 mm), preferably of silicon steel.

The stator phases are energised in sequence to produce torque on the rotor. The timing and duration of the energising pulses requires information supplied by a rotor position sensor. The rotor shape allows it to act as a fan for cooling the motor.

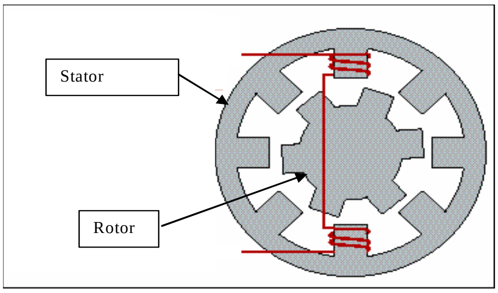

Figure 4: A 4-phase switched reluctance motor (the winding for one phase is shown).

The controller structure is similar to that of AC and DC drives. The biggest single difference is that the current magnitude and *wave shape* must be controlled. The current is not pure DC or pure AC and it varies with both speed and load.

6.1 Characteristics

The switched reluctance motor has outstanding performance characteristics in all areas of concern. These include:

- Very high specific torque and power outputs per frame - much higher than for other motors especially in smaller sizes.
- Very high electrical efficiency.
- A very wide speed range with excellent torque at low speeds.
- Mechanical and electrical durability - low maintenance.
- Excellent dynamic response.
- Operating characteristics are easily adjustable through re-programming.
- Ease of manufacture by existing means.
- Low cost (especially the motor itself).

Its low cost in particular places the switched reluctance motor in a very promising position for many future applications. It is envisaged that the cost of power electronics will continue to fall, and the overall cost of a motor and drive unit will weigh more heavily on the cost of the motor itself. The switched reluctance motor's simplicity, durability and power to weight ratio (less material is needed in the motor to produce the same amount of power) will place it in a commanding position.

For the word turning application, a manufacturer proposed a 2 hp (1.5 kW) SR motor rated at 1000 rpm with torque / speed characteristics as shown in Figure 5.

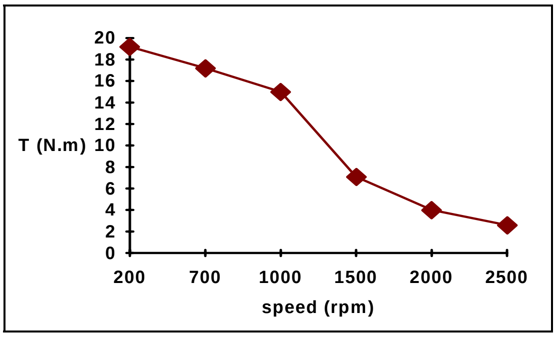

Figure 5: Torque / speed characteristics for proposed (2 hp) SR motor prototype

However, from the torque / speed curve the torque does not match the required loading torque as seen in Figure 2. A prototype of an SR motor would therefore need to be rated at a higher speed (1200-1300 rpm) rather than the 1000 rpm proposed. Although this would cause the output torque of the SR motor to drop at the lower range of speeds, it would still meet the torque required for the wood turning lathe application. A prototype mockup is shown in Figure 6.

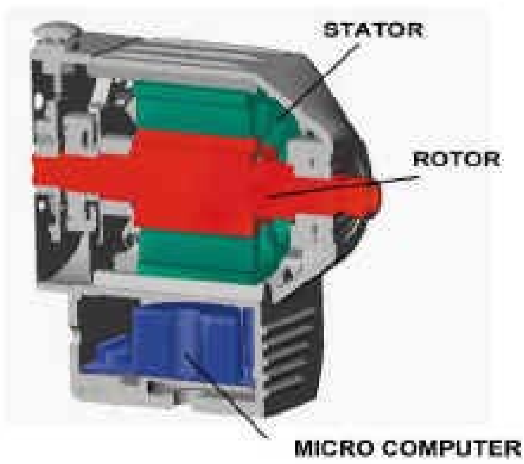

Figure 6: Mockup for the SR motor and its electronic drives.

7. Prototype Selection

DC variable speed control systems are simple, well-established and inexpensive. The cost of the DC motor itself, however, is greater than that of the induction motor due to the necessary brushes and commutator system. Hence based on cost comparison, the variable speed motor and drive units for the induction motor and DC motor appear equivalent. However, the DC motor has an edge over the induction motor with its speed range and torque performance. Based on performance therefore, it appears that the DC motor drive is more favorable than the AC drive for the wood turning lathe application.

However, switched reluctance motor drives deliver very high dynamic performance and with their wide speed range and wide constant power capability are well suited to the wood working machine applications. It therefore becomes a question of cost for the switched reluctance motor drive, particularly as it is a relatively new product.

In general it is safe to state that costs for SR drives compare at least favorably and frequently very advantageously with existing conventional drives (manufacturing cost estimates vary from one company to another). This is because SR control electronics are simpler and cheaper than induction motor control and as the motor is simpler and cheaper than the DC motor.

The authors' first choice for a variable speed drive prototype unit would therefore be an SR motor drive. This is assuming a manufacturer could be sourced to produce a prototype meeting the torque / speed requirements at a commercially viable cost. In this case, a manufacturer was successfully sourced.

8. Prototype Testing

After the prototype was manufactured according to the required specifications, the prototype went through intensive testing regarding the required performance and standards. Massey, in conjunction with Teknatool, carried out other tests in addition to the performance tests illustrated below to provide an indication as to whether the prototype would meet certification standards in the USA and Europe. The tests included the following:

- Speed-torque testing

A mechanical brake was used to load the motor. The output power dissipated in the mechanical brake. The torque was measured using both a torque arm and a digital scale. The speed was measured with a tachometer.

- Speed regulation tests

These tests were conducted with the motor hot, as resulting from continuous operation at rating conditions. Full load was applied and removed at different speeds. Then full load and no-load speeds recorded and speed regulation calculated. To comply, speed regulation needed to be within 3% as specified above.

- Noise level measurement

The noise-level was recorded at different speeds and different loading conditions. Noise-level must be below 80dB. This was one of the issues which concerned the authors about SR motor when proposing it as a prototype for this application. The concern was because of the inherited high torque ripple of the SR motor and the associated noise. However this did not cause any noticeable problem when the prototype was manufactured and tested. The nature of the woodworking machine application, as well as the increased number of silent poles for each motor phase, smoothed the ripple and the noise to an acceptable level as the results shows in Table 2.

- Temperature tests

Temperature tests were made to determine the temperature rise of certain parts of the machine above ambient temperature, when running under continuous loading conditions for different time durations. Thermocouples were used at stationary locations inside and outside the motor.

- Losses and efficiency measurement tests

Mechanical and magnetic losses of the motor were determined by measuring the electrical power required to drive the machine and the output mechanical power dissipated in the load. The efficiency of the motor / drive unit was then calculated.

- Compliance with IEC regulations and certification

The prototype manufacturer, designed and built the elements to comply with the certification standards. This is wiring of stator and control board elements to IEC standards.

- EMC emissions and flicker

A rough test was conducted to ensure that the prototype was reasonably in compliance before more formal certification testing.

Performance testing results of the first prototype for 110/120volt-input are shown in Table 2.

Speed (rpm) at no load	400	600	800	1000	1500	2000	3000
Speed (rpm) at full load	0	0	750	980	1500	2000	3000
Input voltage (volt)	117	115	110	109	110	109	108
Input current (Amp)	3.1	6.2	9.6	11	9.7	9	10.7
Power Factor	0.69	0.69	0.98	0.95	0.97	0.99	0.96
Input power (Watt)	250	492	1035	1140	1035	973	1109
Torque (Nm)	4.1	6.3	8.6	7.7	5.4	4.1	3.3
Output power (Watt)	172	396	720	806	848	859	1037
Efficiency (%)	69	80	70	71	82	88	93
Noise level (dB)	68	70	72	75	76	77	77

Table 2: Prototype testing results for version 1.

It is clear from the table that the prototype did not meet the required specification and did not delivered the high torque needed at the lower end of the speed range. The main reason is that initially we had differences in testing equipment between Massey University and the prototype manufacturer. Massey used a torque arm device that more closely simulated the actual conditions the machine would experience in use. The prototype supplier used an eddy current device which, while accurate, applied the load more slowly, so they were not testing for a suddenly applied load. The prototype supplier have since built a new test rig to match Massey's rig and a second version of the SR controller has been built. The controller was retuned to overcome the limitations faced by the first prototype. The test on the new prototype has shown that it meets the required specification and a commercial version was introduced to the market successfully [see Figure 7]. The commercial lathe is delivering the required torque over a 100-3500 rpm speed range.

Figure 7: The commercial version of the digital variable speed wood lathe

9. Conclusion

Traditionally the lathe incorporates a constant speed motor with a pulley system to select one of several different speeds of operation. The development of an electronic variable speed drive will ultimately improve the value and marketability of the lathe. The company are pleased to announce that the DVR lathe has been released in the USA and UK. Although the SR technology already exists, incorporating an SR drive in this type of application was new – making the SR drive lathe cutting edge technology (a world first) – putting it far ahead of any other wood lathe on the market. A provisional patent has been granted No 503922 for the digital variable speed lathe.

This paper outlined the stages involved from the initial concept to the final commercial product.

Acknowledgement

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