Transactions on Engineering Sciences vol 44, © 2003 WIT Press, www.witpress.com, ISSN 1743-3533

Investigating power quality solutions for computer numerical control machine tools

B. Damazo[1] A. Donmez[1], H. Soons[1], M. Stephen[2] & C. Thomas[2]
[1]*Manufacturing Metrology Division,*
National Institute of Standards and Technology, USA.
[2]*EPRI PEAC Corporation, USA.*

Abstract

Electric Power Research Institute (EPRI) research and testing, conducted over many years, has indicated that variations in electric power quality can negatively impact end-use equipment. This research and testing has helped to form the theory that the least costly and most effective measure for making end-use equipment more robust to power quality fluctuations is to embed effective mitigation solutions into the equipment itself. This work is best accomplished by the original equipment manufacturers (OEMs) themselves. Embedded solutions are equipment modifications that OEMs could make to substantially decrease the sensitivity of their product to various power quality phenomena (i.e., voltage sags). Recent voltage-sag tests performed at National Institute of Standards and Technology (NIST) on a Computer Numerical Control (CNC) machine tool has revealed that power quality problems such as voltage sags not only have an effect by interrupting production, but can also cause performance degradations that directly impact the quality of the machined product. This paper discusses the results of these tests and a variety of available power-conditioning technologies and methods of embedding solutions to improve the power quality performance of CNC machine tools.

1 Introduction

Voltage sags resulting from a thunderstorm can cause CNC machines to shut down or malfunction in a manufacturing plant. In each case, these machine tools must be re-homed, restarted, and, in some cases, re-programmed before production can resume. Furthermore, the quality of each part that was being machined at the point of the shutdown must be re-examined. Since a planned shutdown at the end of a machining cycle is more desirable than the chaos caused by unexpected shutdowns due to power failure, plant managers sometimes stop the production before an expected thunderstorm until the weather returns to normal. The resulting interruption to production and the possible remedies for faulty parts can be very costly to the manufacturing company. This scenario actually takes place at manufacturing plants today because the equipment is vulnerable to voltage sags. Specifically, sub-components such as relays, contactors, power supplies, drives, and sensors may be susceptible to voltage sags. These events are often caused by a phase-to-ground or phase-to-phase fault in the electrical system. Many of the problems associated with production and equipment downtime in the machining industry can be mitigated if the next generation of machining equipment is able to ride through common voltage sags.

In order to understand the magnitude of the problem and to develop methods for built-in voltage sag immunity in CNC machine tools, NIST and EPRI embarked on cooperative project. As a part of this effort, EPRI Power Electronics Application Centre (PEAC) and NIST conducted extensive on-site voltage sag testing to measure the effects of power quality on selected CNC machine tools and subsystems [1]. Based on test results and collective EPRI experience in other industries [2], it was demonstrated that there is an opportunity to embed solutions to voltage-sag problems into CNC machine tools without requiring large-scale mitigation solutions at the utility or plant-wide level. It is believed that new technologies such as advanced flywheels, super capacitors, and new power conditioning devices will allow the introduction of cost-effective *embedded solutions* into machine tool applications.

An "embedded" solution is the result of a product re-engineering effort to reduce the sensitivity of the equipment to variations in the quality of the supplied power. These measures can range from minor substitutions for the most sensitive components of a machine controller to major product revisions that incorporate new technologies. The embedded solution method differs from the ad hoc "black box" approach of enhancing voltage sag immunity by blindly adding power-conditioning equipment. Unlike the "black box" solution, the embedded solution is seamlessly integrated into the equipment design to function as a part of the overall control scheme of the equipment to enhance its performance.

One major goal of the current research is to determine what effect voltage sags might have on the machined product. Many previous voltage-sag tests on industrial equipment have shown two distinct effects of voltage sags on process equipment:

1. Process/Machine Shutdown. The equipment stops as a result of the voltage sag and inadvertently halts operations. The product and/or machine tool may be damaged by this interruption.
2. Process Fluctuation. The equipment stays on-line, but is affected as noted by inconsistencies in the product quality. In the machining operation, this could result in a part that is out of tolerance.

Transactions on Engineering Sciences vol 44, © 2003 WIT Press, www.witpress.com, ISSN 1743-3533

Furthermore, if power-conditioning strategies are used to enhance the voltage-sag immunity of typical "weak-link" components of the CNC machine tool, it must be determined if the machined product suffers further product degradation.

2 Voltage sag immunity tests of CNC machine tools

In order to evaluate the effects of power quality on the performance of machine tools, several tests were designed and carried out. There were two purposes for these tests. The first was to evaluate the ride-through characteristic, identify "weak" links, and implement and test a prototype embedded solution. The second objective was to identify hard-to-detect performance degradations of the machine tool. Performance degradations were investigated by measuring contouring accuracy of a machine tool, as well as minute deformations of machine components and output distortions of feedback systems resulting from the power sags. Over five hundred voltage sags were applied over a two-week period.

2.1 Diamond turning machine

A diamond turning machine (Figure 1) was chosen for this pilot project because the machine's ultra-high precision is easily susceptible to external environmental conditions. This machine is a three-axis turning machine that is used to produce complex contoured optical components with very high dimensional and surface finish tolerances. It uses an air-bearing spindle with less than 0.1 μm axial and radial error and near-gem-quality single-crystal diamond tools to produce such parts as infrared ellipsoidal and parabolic optics, microwave optics, and apertures for radiometry measurements. Some of these parts take long periods of time to machine and any interruption of operation causes unacceptable marks on their surface.

Each linear axis of the machine has three feedback sensors: tachometer for velocity, laser interferometer and encoders for position. The machine is powered by a three-phase 208Vac source. The voltage is divided into two separate systems (Figure 2). Phase A and B supply power to a 208 V/120 V ac control transformer powered (3) single-phase axis servo drives, spindle servo drive, all position and velocity feedback sensors, CNC controller, coolant system and operator interface console. Phase B and C power a 208 V/120 V ac auxiliary transformer dedicated to the internal air conditioner system and auxiliary power receptacles.

2.2 Voltage sag test setups and performance measurements

The tests were carried out by injecting voltage sags into the input power of the machine. The response of the machine was measured through an on-board data-acquisition system. To identify the "weak link," susceptible components were selected and measurements were taken during voltage sags. The test waveforms

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were captured and recorded using the data-acquisition system of the voltage-sag generator.

At the same time, a series of performance measurements were carried out. These tests included the circular contouring test to measure the machine's contouring performance during power fluctuations. Since the air-bearing spindle is a critical component of the diamond turning machine, the voltage sag immunity of the air compressor supplying the constant pressure air to the bearing was also examined.

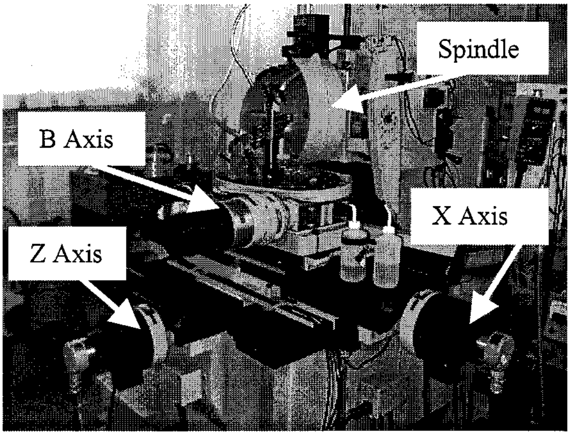

Figure 1: Diamond Turning Machine

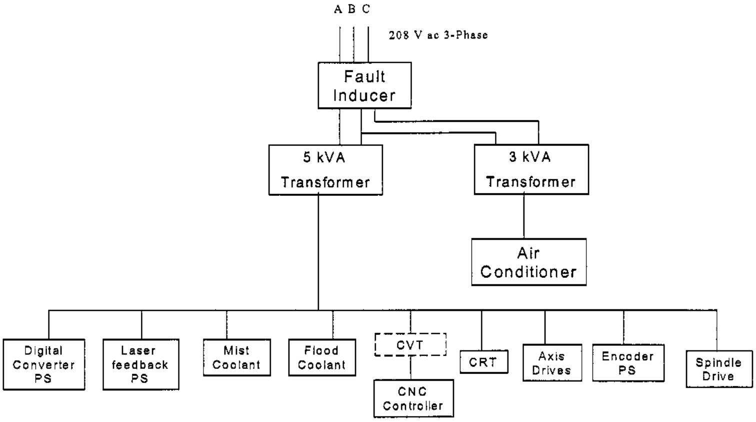

Figure 2:Power distribution of the diamond turning machine as tested (Constant Voltage Transformer (CVT) is used for testing only).

2.2.1 Circular contouring test

The circular contouring tests were carried out using a telescoping ball bar, an instrument used for measuring the changes in the distance between two spheres

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attached to the spindle and the machine table respectively through a telescoping mechanism. The machine was programmed so that the X-axis and Z-axis would generate a circular path using laser position feedback. Deviation from the ideal circle is measured as the output of the ball bar system. This system provides an indication of many machine errors including machine geometry errors, scale errors, the differences between axis servo gains and other servo-related machine tool errors.

2.2.2 Air compressor performance test

These tests were conducted to evaluate the effects of voltage sags on the air compressor that feeds the constant-pressure dry air to the spindle air bearing. Air-bearing spindles are sensitive to fluctuations in the supply air pressure that could cause axial and radial motion of the spindle face, which directly affects the accuracy of the machined part. The test setup uses two capacitance gages: one was located against the face of the spindle, the other against the periphery measuring the spindle error motion in axial and radial directions.

2.3 Equipment voltage sag test results

The machine had a very poor ability to ride through voltage sags. During single- and two-phase sags, it was faulted due to twelve-cycle voltage sags as minor as eighty-percent of the nominal voltage. This fault occurred because the CNC controller performed a self-initiated shutdown by design. Based on the existing literature [3], it would be possible that such a machine could experience from 20 to 140 voltage-sag-related shutdowns per year.

In order to continue the testing, a standard 750VA constant-voltage transformer (CVT) was used to condition the power to the CNC controller. With the CVT in place, the machine survived voltage sags down to 35 % of nominal. This increase in voltage sag immunity would make the entire machine tool much less likely to shutdown as a result of voltage sags. Under such conditions, the machine would be likely to shut down from zero to ten times per year. The voltage-sag susceptibility of the diamond-turning machine and the associated air compressor is shown in Figure 3 for ten-cycle voltage sags. One side effect of increasing voltage sag immunity of the machine tool is the possibility of allowing performance degradations during such ride-through periods. Therefore, embedded solutions need to be applied, not only to components that electrically change states but also to each critical process system that contributes to the quality of the final product.

2.4 Performance degradation test results

With a temporary CVT power conditioner placed on the CNC controller, it was discovered that at lower voltage sag levels, product degradation would indeed occur. Although air compressor performance tests did not indicate a significant motion of the spindle due to the existence of a large accumulator, the circular contouring tests were more illustrative. As shown in Figure 4, the test gave an

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indication that voltage sags created significant degradation of the machine's contouring performance to produce an adverse effect on the quality of the part machined during such periods. In summary, the performance test on the diamond turning machine demonstrated that 40-percent, five-cycle sags created performance degradations before the machine tool went into fault mode. This point is plotted on the single-phase ride-through curve of Figure 5.

3 Embedded solution strategies

Equipment that is designed with "built-in" power quality immunity is the best way to achieve system compatibility. This approach theoretically offers lower cost, lower complexity, and higher performance compared to the practice of retrofitting existing equipment with power-conditioning equipment. There are four levels of solutions that can be implemented with respect to power quality problems in machine tools. These levels are shown in Figure 6. In order to consider the embedded solution approach and capitalize on the lower cost of the built-in solution, one must have intimate knowledge of the machine tool design, as shown in Figure 6. Levels 1 and 2 are the equipment level and require cooperation between the machine tool / controller manufacturer and the power quality expert to determine the real weak links in the equipment. Level 3 is power feeder level that involves protecting the entire machine tool, which is more costly to implement. Level 4 is the most costly and logistically complex solution at the utility source stage.

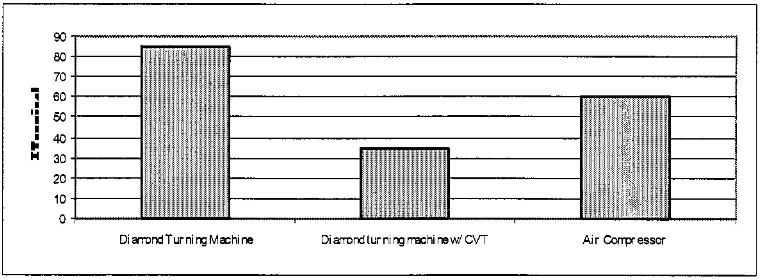

Figure 3: Percent drop in voltage resulting in fault (10-cycle sag).

In general, there are three types of embedded solutions used in industry:

1. Component Replacement. This involves replacing the typical "weak-link" components on the tool with more robust devices in order to improve the immunity of the entire machine.
2. Modified Designs. This involves designing the tool with power quality robustness in mind and employing simple strategies to make the machine more robust.
3. Supplemental Energy Storage. Embedding on-board energy storage to sustain weak components or subsystems of a machine tool during a voltage sag.

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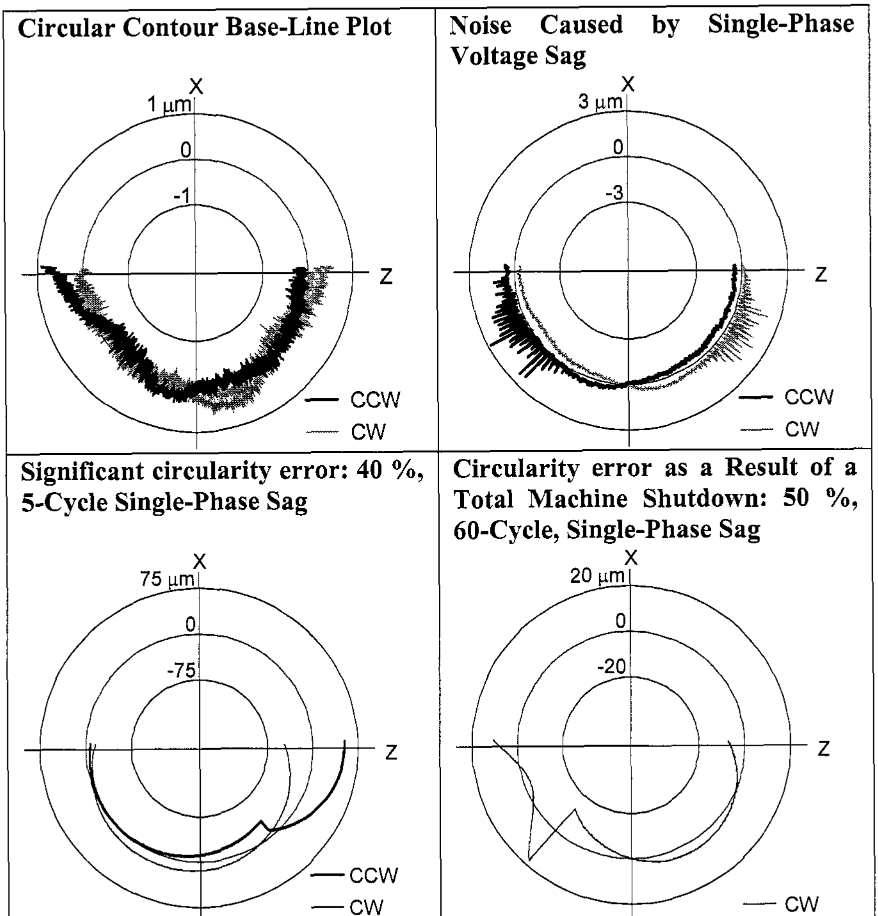

Figure 4: Sample circular contour plots for various voltage sags with CVT installed.

3.1 Some advanced embedded solutions for machine tools

It was already mentioned that the first solution introduced to the diamond turning machine during these tests was to introduce a CVT power conditioner on the CNC controller. A good method to improve the voltage sag ride-through of such a machine tool is through the use of supplemental energy-storage systems. A key to maintaining performance during voltage sags is to sustain the operation of the controller, drive system and the feedback devices. The potential applications of supercapacitors and advanced flywheels will be discussed.

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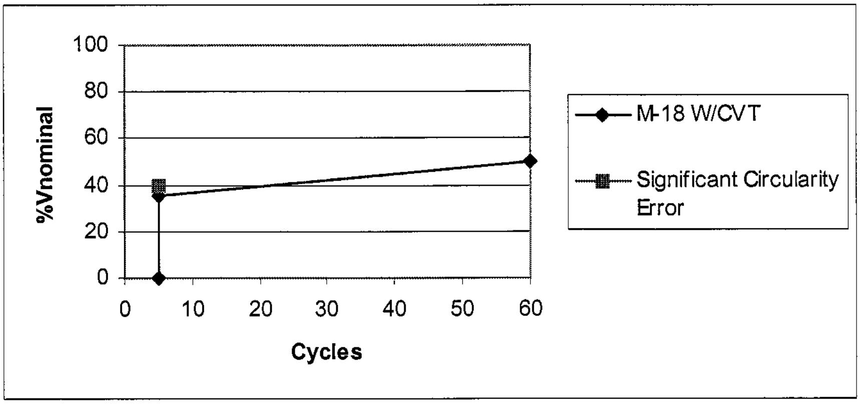

Figure 5: Significant circularity error occurrence plotted against the single-phase ride-through curve of the machine with the CVT power conditioner.

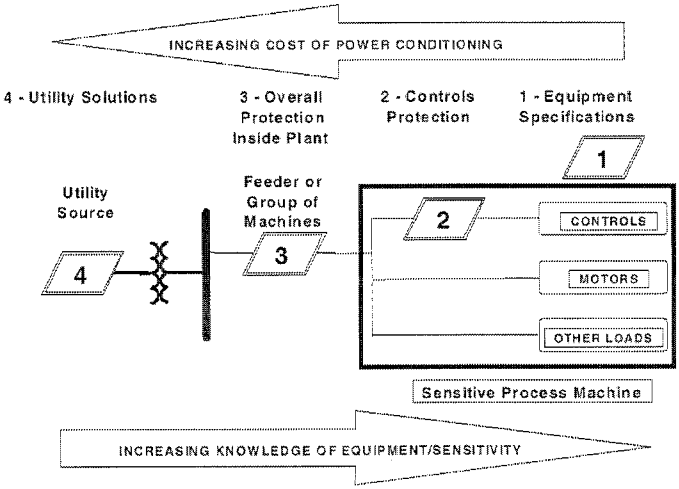

Figure 6: Four levels of applying embedded solutions for machine tools.

3.1.1 Supercapacitor applications

Supercapacitor is a supplemental energy source that could be connected to internal DC bus circuitry throughout the machine tool. One possible use of the supercapacitors would be to support the power supply system that is used to power the logic and control functions of the machine CNC. Supercapacitors offer extraordinarily high power density, compared with batteries, along with high cycle life and maintenance-free operation. Like batteries, they can be configured in various sizes of cells into arrays to meet power, energy, and voltage requirements of a wide range of applications.

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Medium-voltage supercapacitors can be embedded into future machine tool systems. This voltage range includes the voltage outputs of power supplies for CNC controllers as well as I/O power supply voltages for machine sensors and controls. For example, utilizing a 5.5 V supercapacitor with 7,000 J of energy to enhance the voltage sag ride-through characteristics of a standard 130 W CNC power supply could lead to protection from voltage sags and outages lasting up to 54 s. Furthermore, a standard 250 W, 24 W instrument I/O power supply could ride through complete outages as long as 83 min using a 26 V, 120,000 J supercapacitor. It is important to note that the integration of these technologies into standard power supply designs would require adequate charging circuitry.

Supercapacitor technology could also be employed in the drive systems. The capacitors could be used to hold up the DC bus voltage for the drives, which would definitely prolong the ability of the drive to survive voltage sags. Supercapacitors employed on drives that reverse direction frequently could also allow for energy storage.

It is important to note that these changes could be attempted with the existing supply by careful analysis and implementation on a prototype basis. However, the best solution may be to engage the CNC manufacturer to employ supercapacitor technology on current-generation systems.

3.1.2 Advanced flywheel applications

The use of CVT enabled the CNC controller to ride through events as low as 35 % of nominal. However, performance degradation was found to occur for voltage sags as low as 40 % of nominal. If the user would like to keep the entire machine tool on-line without any possibility of performance degradations, advanced flywheels could fit this application [4]. Unlike the supercapacitor approach, which is targeted to DC power, the flywheel would need to be employed on the entire machine tool and its auxiliary equipment and integrated into the control scheme.

Based on the load requirements of the air compressor and diamond-turning machine, the total load that would need to be supplied by the flywheel system is estimated at less than 100 kW. This power requirement falls into the range of advanced flywheel systems that are available on the market today. In order to make this a truly embedded solution, this option would have to be tightly integrated into the machine's CNC controller. For example, the CNC controller would need to communicate to the flywheel system and pass diagnostic information to the operator interface panel of the machine tool. If voltage sag is detected or the flywheel would require maintenance, this information would need to be conveyed to the operator through the single operator interface panel.

4 Summary and future work

The tests conducted revealed that common voltage sags not only stop production but can also affect the performance of CNC machine tools, which directly impacts the quality of the machined product. During the tests, the machine tool's ability to ride though sags ranging from 80 % down to 35 % of nominal was demonstrated by implementing a CVT on the controller. This solution, which could also have been accomplished by the supercapacitor technology, greatly decreased the probable number of times that the machine tool might be faulted by voltage sags, but also produced possible degradations in the performance of the machine tool during deep voltage sags. In CNC machine tools, the position control is a critical component that requires embedded solutions. Power quality considerations need to be incorporated into a CNC machine tool through engineering design and specification efforts and not as an afterthought. Embedded solutions offer the best way to protect such machine tools against common voltage sags.

The EPRI-NIST collaborative research effort has studied two other CNC machine tools with more modern CNC control units to characterize the susceptibility of CNC machine tools in a more general fashion and raise the awareness of power quality issues and solutions. One possible outcome of such efforts is to move the machine tool builders and users community toward the adoption of power quality standards.

Acknowledgements and notes

Authors would like to thank Mr. Scott Bunton of EPRI PEAC Corporation as well as Mr. Michael Kennedy and Mr. Robert Clary of NIST Manufacturing Engineering Laboratory for their support of this research effort. Authors would also like to thank Dr. Steve Fick of NIST Manufacturing Metrology Division for his extensive editorial and technical comments. Contributions of the National Institute of Standards and Technology, an agency of the United States Government, not subject to copyright. Commercial equipment, instruments, or materials are identified in this report in order to specify adequately certain procedures. In no case, does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

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