Instantaneous Torque as a Predictive Maintenance Tool for Variable Frequency Drives and Line Operated Motors

Abstract

Technological advances in on-line testing of motors, diagnostics and motor monitoring have increased substantially over the past few years. Voltage and current signature analyses have improved the quality of predictive maintenance (PdM) compared to what RMS current and voltage measurements or power-factor readings have been able to achieve. Signature analysis has emerged from the laboratory stage to become the foundation for modern instrumentation in mainstream industrial maintenance programs. The most advanced method of current signature analysis is torque signal analysis due to the fact it offers multiple advantages. One is the instantaneous torque signature, gained from current and voltage signatures. It is inherently demodulated, and delivers a very clear signal independent of the line frequency (either 60Hz, or variable in VFD applications). In addition to demodulation, it delivers the clearest mechanical information available on the motor system, since torque production is the primary if not sole reason for the motor's existence. Both motor and load failures can result in costly outages or reduced production for weeks at a time in a plant environment. The cost of such failures can easily run into millions of dollars. This paper presents three case studies where modern instrumentation averted downtime or reduced output and failure. One case study is based on findings of a coal-fired power plant, the second case study presents findings of a Lignite powered plant, and the third case study involves troubleshooting a VFD application in a sawmill.

Introduction

Improvement of reliability, output and efficiency are the core responsibilities of plant management, operation and maintenance. The use of the latest technologies in electrical on-line testing is proving that additional monitoring capabilities are crucial for cost-saving operations.

This paper presents three case studies on how plant maintenance and operation benefit from monitoring plant operation with modern instrumentation, particularly with instantaneous torque monitoring capabilities. The first case presented is of a medium-voltage 500 horsepower pulverizing machine motor. The second application is of a medium-voltage motor that drives a circulating 1,250 horsepower water pump (this pump was fixed right before a pump running in parallel broke in operation, which reduced output to the plant over a five-week period; an economic evaluation of this case in particular will be presented). The third and last case study is an example of how a motor coupled with a variable-frequency drive (VFD) was monitored, and how its operation was corrected using instantaneous torque signature analysis.

In all three cases, measurement and analysis was performed using the **Baker EXP4000 dynamic motor analyzer** from Megger.

Basics of modern on-line monitoring

Connectivity

On-line monitoring tools designed for field use must be safe and easy to use if they are to be used frequently and reliably. Connections to medium- or high-voltage applications can be achieved safely by hookups to existing current transformers (CTs) and potential transformers (PTs). A general rule of thumb in predictive maintenance says that the quality of a PdM program is about equal to the quality of the tools used times the frequency with which they are applied. In other words, only top-of-the-line tools and frequent monitoring are likely to yield effective plant reliability program results.

On-line monitoring is too often performed with unsafe procedures, usually for the sake of getting a job done as quickly as possible. Responsible plant operation, however, allows for only the following two methods for safe performance of on-line testing:

a) Lockout procedures using protective gear
b) Dedicated hardware in critical motor control cabinets

The crucial need for plant reliability requires frequent monitoring, and that can't be achieved with the first option if cost-effective long-term measures and ease of operation are desired. Only additional hardware installed in critical motor control cabinets (MCCs) will yield reliable plant operation in an easy, safe, and cost-effective manner.

Voltage quality and load level

As stated previously, on-line monitoring has evolved considerably from the times when state-of-the art electrical monitoring was confined to current and voltage levels. Power analyzers introduced the capability of monitoring power quality several years ago, and they are now capable of identifying and logging voltage unbalances, distortions and transients.

Poor voltage conditions are a main cause of overheating in motors that are not running over-loaded [1-5]. Comparisons of the severity of sub-optimal voltage quality with its effect on the motor, however, are not possible with power analyzers. Evaluations of the influence that real-world poor voltage conditions exert on motors at different load levels allows a maintenance professional to ensure that the motor is running at the proper NEMA derating [2-4]. Only the addition of very accurate load estimations [5,7-8] to power quality analysis will offer very useable results from a motor PdM standpoint.

The concern in the field is this: is a given motor operating under too much load under the particular voltage conditions it encounters? This can only be answered reliably if accurate load estimations and power quality measurements are put together with the use of the applicable professional standards and guidelines [1-4].

Voltage levels and estimation errors

A frequent circumstance in the field is that voltage busses are operated at an over-voltage exceeding five percent. The reasons for this practice are twofold: on one hand, a higher voltage level on the voltage bus can ensure that the voltage that reaches the motor terminals is sufficient after subtraction of the voltage drop in the lead resistance. On the other hand, over-voltage will induce lower currents, which are frequently preferred in the field. The reasons behind this preference are more for comfort than of necessity. Stator currents are frequently used for rough load estimation. Additionally, stator currents are known as the source of I^2R losses in the motor. Increased voltage levels are frequently used to artificially drop the current level.

This promotes a feeling of reduced losses to the motor as well as a cooler and healthier operation of it. This condition, however, only marginally improves operational efficiencies of motors while causing severe deterioration of the operating power factor [1]. Only substantial efficiency increases will reduce the operating temperature of the motor, and in turn, lengthen its life. A higher voltage level raises the efficiency of the motor only marginally, and does not strongly change the operating temperature or expected life. However, artificially lower stator currents lead to erroneous conclusions if current levels are used as a measure of load.

In addition to nameplate inaccuracies, this method also depends upon voltage level. As mentioned above, over-voltages are very common in the industry. Load estimation based upon current level can incur severe errors, prompting a false sense of security in the case a motor is running with an over voltage and rated stator currents. In reality, motors under these conditions are operating into their service factor, introducing conditions of overheating and rapid deterioration.

Case study #1: A 500 HP pulverizing machine in South Korea

Nameplate and setup

A 500-horsepower 6.6kV motor was monitored in a unit of a major power generation facility in South Korea. The nameplate displayed 54A, 882 rpm as shown in Figure 1.

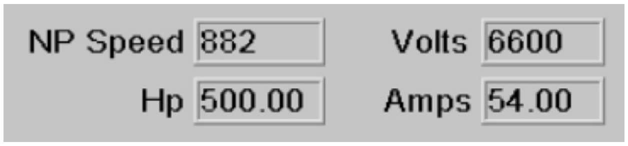

Figure 1 – Motor nameplate information

The nameplate speed displayed is low when compared to common eight-pole motors. The potential reasons for this could be that it is an older design, a conservative nameplate, or an inaccurate nameplate. Eight-pole motors of this rating have typical nameplate speeds of 885 rpm or 890 rpm. Slip is proportional to rotor copper losses. This high nameplate slip opens the expectation for a either a motor of lesser efficiency than modern design, or an inaccurate nameplate.

Results

The application in question was tested from the secondaries of the PTs and CTs. All data shown in Table I was obtained at the motor control cabinet (MCC).

Voltage level	105.8 %
Voltage balance	0.74 %
Voltage distortion	1.0 % THD
Current level	80.7 %
Power factor	0.77
Input power	406.6 kW / 544 hp
Speed	886.2 rpm
Percent load	100.3 %
Percent efficiency	92.0 %

Table I – Test results

These results show clearly how misleading a focus on pure RMS values can be. With careful consideration of the load placed on the motor by the current level, one would reasonably expect loading of less than 80 percent (accommodating to a power factor lesser than one).

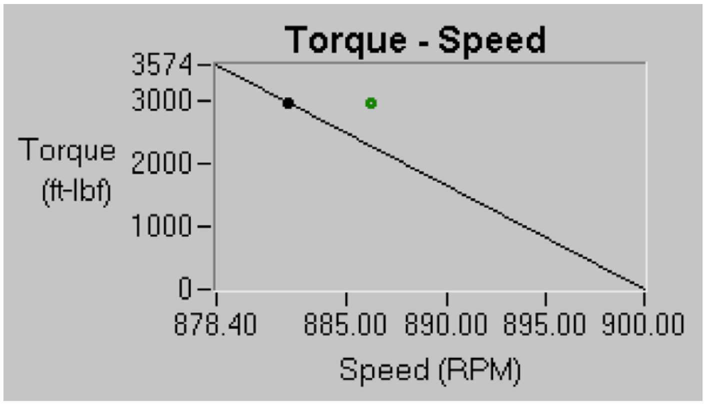

Figure 2 – Slip line and operating point

The load of 100.3 percent, however, is far superior to this forecast. If the load forecast had focused on the slip with respect to the nameplate, the result would have been 76.7 percent. This is the result of the division of actual operating slip by rated slip.

The motor monitored revealed a much lower slip than the nameplate slipline, as shown in Figure 2. The black line is the slip line. It runs from the synchronous point to the lower right, 900 rpm and 0 nm to the rated point, which is shown by the black point. The operational point (green dot) is to the right of the line. This shows that the motor is operating under a clearly higher speed than the nameplate would lead one to expect.

A look at the input power to the application shows there is 8.8 percent more power pushed to the motor than the rated output of the motor. This begs the question: is the motor running at five percent over load with a very high 97 percent efficiency, or is it running at 100 percent load at a very low 91.2 percent efficiency? Standard instrumentation could not clarify these circumstances.

A calculation of the mechanical output power of the motor is performed by the multiplication of shaft torque times the operating speed; this delivers the desired results. Operational torque is calculated with the use of Park's vector, also called the two-axis theory [6-8]. The rotor speed is calculated with current signature analysis as described in [5,7-8]. A division of mechanical output power by electrical input power provides an operational efficiency result. As mentioned, neither of the three conventional approaches of speed-centered load estimation, stator current load estimation, or input power estimation could have given clarity with respect to the requested load and the operating efficiency of the motor.

In order to operate a motor truly at 100 percent load, it is necessary to have a very good power quality. In this case, it is provided by virtue of a low voltage unbalance and low voltage distortion. The voltage level is noticeably high, yet not to a level that would warrant cautionary measures.

The application investigated here specifically involved a motor for a coal pulverizing machine. This application is notorious for abrupt changes in torque, which change depending upon the sizes of coal pieces fed into it. Figure 3 shows the instantaneous torque against the motor's rated torque.

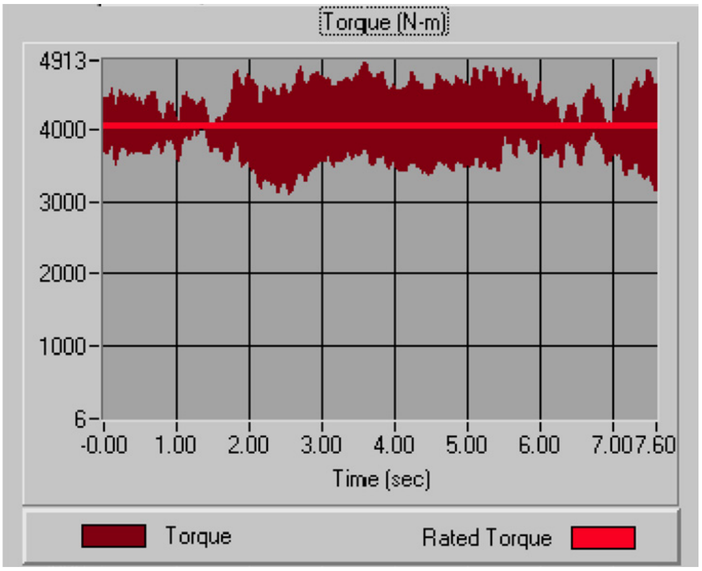

Figure 3 – Instantaneous torque

The rated torque is calculated for nameplate speed and hp. The brown trace shows the level of the actual instantaneous torque as calculated according to [5]. It is clear the average torque coincides with the rated torque; this is to be expected with the load at 100.3 percent. The amount of torque ripple added to that steady state torque, however, causes the motor to periodically operate at over-torque conditions (higher than 115 percent rated torque). The interpretation of this torque signature is simple: the motor under test is operating above rated load for significant periods of time. This is a typical marginal application that stresses the motor during operation. A reduction of the amount of coal fed into the pulverizing machine will reduce the motor load back to a healthy operational level.

Case study #2: Detection of mechanical problem saves millions in $US

The next case study is based on data obtained from tests conducted at a coal-fired power plant in the USA. This motor falls into the category of "critical, high-duty cycle and severe service condition" according to EPRI [9] (see Table II).

Critical	Functionally important, e.g., risk significant, required for power production, safety related or other regulatory requirements
High-duty cycle	Continuous duty
Severe service condition	High or excessive humidity, excessive temperatures (high or low) or temperature variations, excessive environmental conditions (e.g. salt, corrosive, high radiation, spray, steam), high vibration. High speed motors (~3600 rpm or greater)

Table II

Motor application

The motor in this case study was one of three circulating water pumps at a power generation plant with a total output power of 732 megawatts (MW). The plant's total output is nearly proportional to the sum of the output of the three pumps. All three pumps fed into a single system, which had just one total flow meter. No independent flow meters monitored each single pump at the time of this study. The two other motors operated at slightly slower speeds, and at higher stator currents. The third motor operated at slightly higher rpm and lower stator currents. Due to the nature of the under-water load (a deep submerged pump), it was impossible to conduct vibration monitoring.

No conclusive evidence had been compiled with the use of standard motor test instrumentation. This lack of conclusive evidence, coupled with the critical nature and continuous duty of this application, prompted maintenance personnel to choose not to stop this pump for closer investigation. However, a modern on-line monitoring instrument was connected to the pump motor, which in turn yielded instantaneous torque measurements and an eventual diagnosis of the problem.

Results

The results that the on-line instrument provided confirmed some expectations. The third motor was, indeed, requesting lesser input power, leading to lower power factor and lesser stator currents linked to faster operating speed. What was more interesting was the comparison between the instantaneous torque signatures of the two motors operating in parallel to the signature of the motor in question. Figure 4 shows the instantaneous torque of the healthy pump.

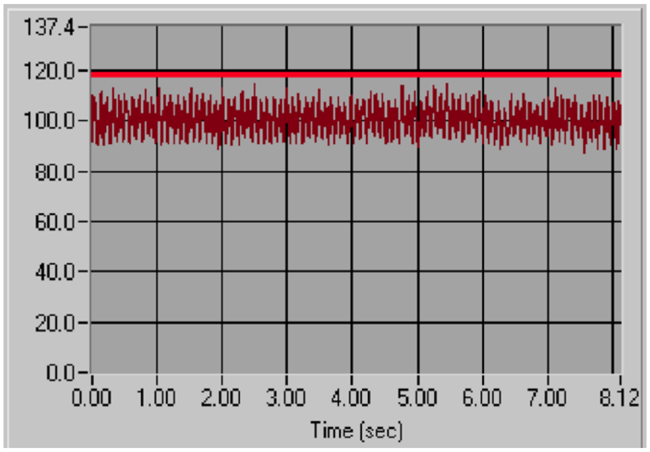

Figure 4 – Healthy torque signature of a circulating pump

The full red line, again, is the rated torque line. As can be seen, this pump operates at a high average torque level, yet healthily below the full rating. The torque ripple is small and of a constant nature. Pumps and fans without flow regulation are characteristic steady state loads with small torque bands surrounding a steady-state torque.

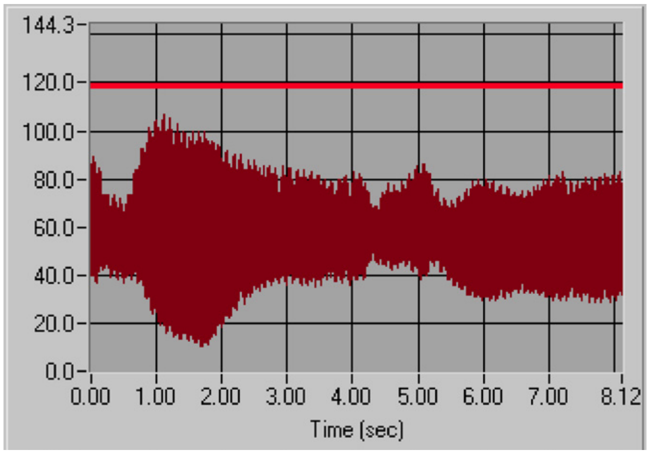

Figure 5 – Instantaneous torque of pump in question

The torque signature of the pump under question (Figure 5) differs considerably from the previous example. One main difference was that the steady-state torque was about 75 percent of the other two healthy identical applications. Secondly, the torque ripple of this application does not look like a healthy torque ripple for a large-sized pump. The torque band is too wide and does not have a steady envelope. These two differences are highly uncharacteristic of this type of application.

Figure 6 – Pump

Since torque is requested by the load, and the motor has to deliver the torque that the load is requesting, it was possible to state without the previous doubts that this pump had clear and severe problems. Up to this point it was not clear beyond a doubt that the load, and not the motor, was creating the different readings. This information was necessary to make the decision to stop the motor so that a diver could be sent down to examine the submerged pump. Upon visual inspection, the diver discovered the pump had lost its end bell. Figures 6 and 7 show the pump and its end bell, respectively.

The function of the end bell is to act similar to a funnel and let water flow into the pump with laminar flow. Without the end bell, the impeller of the pump is in close proximity to the opening of the pump. This causes the slow-turning impeller to only partially work as a pump. It effectively causes water to circulate within the pump instead of pushing the water down the pipe, which explains why the torque is so low (it takes less power to keep water circulating within the pump as it takes to actually pump the water). Additionally, when the blades are mounted closer to standing water, it creates turbulences and cavitation. This was the source of the additional torque ripple that had been found when on-line testing.

Repair

Upon discovery of the broken end bell, the pump was pulled for repair. At this point it was possible to take pictures shown in this paper of both, the pump and the end bell.

Figure 7 – Pump end bell

After repair, the pump was immediately placed back in operation, and subsequent on-line testing revealed that the torque level was back into a normal, higher range. The torque ripple of this and the other two pumps, however, decreased noticeably compared to previous results. The plant's maintenance personnel concluded that the fluctuating pressure introduced by the cavitation might have transported through the piping and actually influenced slightly the two parallel applications, adding torque ripple to the two healthy pumps.

Ramifications to a related failure

One week after the pump was repaired, one of the two adjacent pumps broke a shaft, which in turn damaged the pump in the process. Figure 8 shows the broken shaft at the impeller end of the shaft. This failure had to be repaired immediately; removal of the pump from operation, repair and reconditioning work and re-installation took five weeks.

The plant maintenance personnel concluded that this failure could have been linked to the additional torque ripple of both parallel pumps created by the broken endbell of the first pump in question. Until this point, no data or argument had arisen to prove or disprove this conclusion.

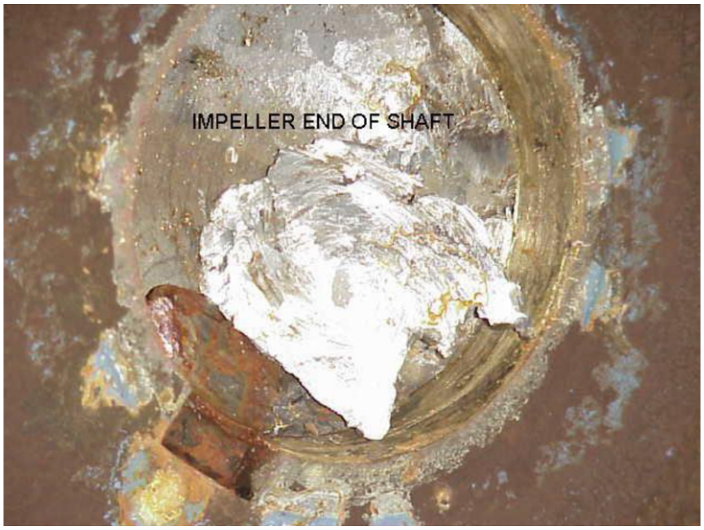

Figure 8 – Broken shaft at impeller end

Cost savings

Over the five weeks it took to remove, repair and reinstall the second pump, the plant was unable to produce the amounts of power it could have delivered at a price of US$80 per MWh. Over this period, however, the pump with the repaired endbell was able to deliver 25 percent additional output compared to pre-repair levels; this was linked to a proportional gain to the plant. This additional plant output would not have been available without the conclusive assessment of the instantaneous torque signature afforded by the online instrumentation.

A calculation of additional available output power was performed based upon the plant's rating of 732 MW, and the assumption that this power was attainable with all three pumps in full operation. Table III summarizes calculations of financial return (cost savings) as a direct result of the detection of the endbell problem.

MW per pump	244 MW
25 % of a single pump	61 MW
5 weeks x 7 days x 24 hours	870 hours
Total generation lost	51,240 MW hours
Cost per MW hour	$80 USD
Total additional revenu	$4.1 million USD
Repair costs	$180,000 USD
Monetary savings/gain	$3.92 million USD

Table III

Case study #3: A conveyor problem solved

The third case study of this paper involves a variable-frequency drive (VFD) application with a conveyor system at a pulp and paper mill in Canada. A 60-horsepower, 1,170 rpm 460 V motor is run by a variable frequency drive (VFD). This motor runs a conveyor belt at varying speeds. The conveyor belt feeds logs into a saw. When no log is in the saw, the conveyor belt runs at a higher speed; when a new log approaches the saw blade, the conveyor belt has to slow down to a speed tuned for cutting. Shortly after it detects that a log has left the saw, the conveyor returns to maximal speed again.

Figure 9 graphically depicts the described process with torque and frequency over time. Frequency is shown in red, and voltage in blue. Data was captured over a period of 7.5 seconds. The VFD runs the motor at 60 Hz, and then it slows down to 12 Hz for cutting. In this case, the cutting of a log takes less than 1.4 seconds, and the VFD ramps the frequency back up to 60Hz.

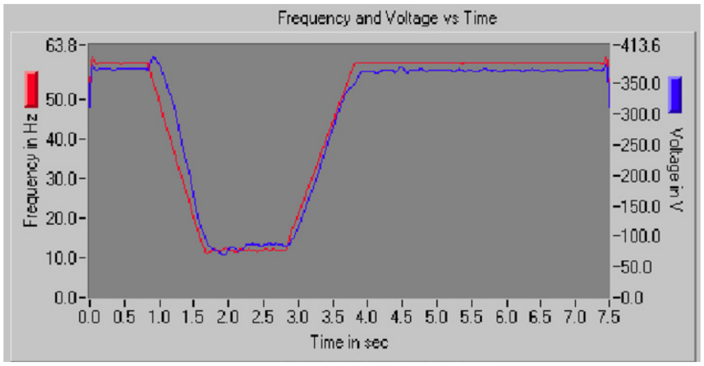

Figure 9 – VFD frequency and voltage level vs. time

The particular control of this VFD is of the V/f type. Voltage level is kept proportional to the operating frequency. This is a very common control type of control for low-cost implementations.

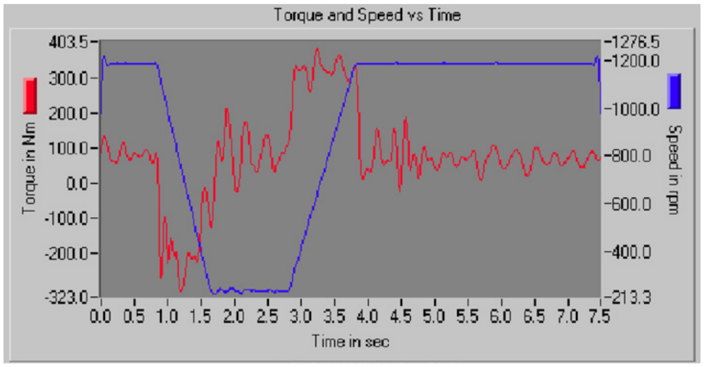

Figure 10 – Speed and torque vs. time

Figure 10 shows torque level (red) versus time, and the operational speed (blue) of the motor versus time. It reveals that the maximum speed of the motor is 1200 rpm, while the speed of the motor during the cutting of the log is of only 215 rpm. Torque level is constant when the conveyor operates at constant speed. During the time the VFD backs the voltages down, the motor speed slows down as well in response to reduced torque. As soon as the low speed is reached, the torque level normalizes to the steady-state level. During the following acceleration process, it is necessary to increase the torque level, which falls back to the steady state once acceleration is completed.

First, during deceleration, the torque drops severely. It even drops below the zero-torque line, which means the motor is employed as an electrical brake during this time. What this also means is that the log has actually slowed down rapidly (reducing speed of the motor to about 1,000 rpm in just one second). This information is telling because this ensures that the conveyor is designed not only for pulling, it can also withstand pushing.

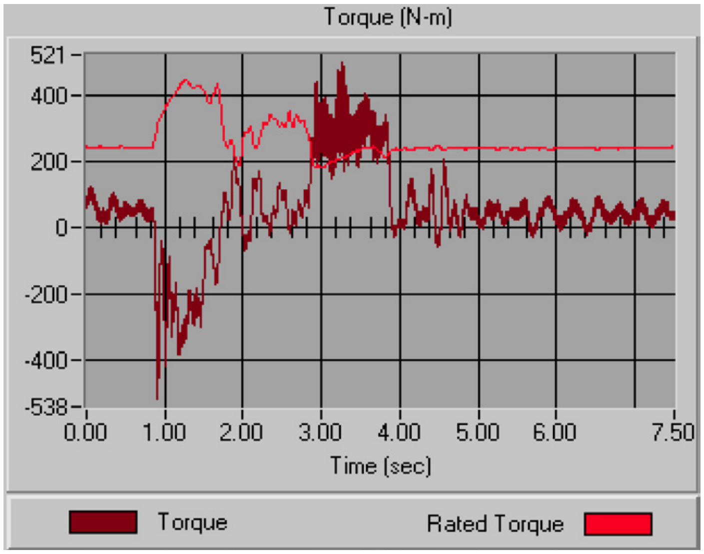

Figure 10 – Instantaneous torque vs. time

Secondly, it's noteworthy that over a period of about one second the operational torque rises above the rated torque. This means the motor is stressed during acceleration. The amount of torque required to accelerate the log to 1,200 rpm back from 215 rpm is too high, especially if it has to be achieved in less than one second. The solution to this dynamic over-torque problem is simple. The VFD is programmed with a constant, which is called Hz/sec. This constant sets the maximum acceleration and deceleration rates. In this case, the maximum acceleration rate is too high. A reduction of the Hz/sec setting of the VFD brings the acceleration torque down to healthy levels. A disadvantage of this, however, is that acceleration and deceleration processes take a bit longer (which can translate into reduction of production over time). In this case, the settings were changed such that both the acceleration and the deceleration took additional 0.2 sec, which has little to no effect on production.

Another notable issue can be identified upon inspection of the last three seconds of data. The operational torque over this period is oscillating, which is a typical symptom of an improperly tuned feedback loop. The application is 'chasing,' or is unable to maintain a steady state speed free of oscillations. This oscillation fatigues the conveyor system and often leads to premature wear and failure. This type of oscillation can be avoided with the installation of a PIO controller, and proper tuning. This can only be done, however, once such a problem was clearly identified.

The three issues determined by analysis of data on this graph have fairly straightforward solutions, yet they can't be identified with standard motor test and monitoring instrumentation. Only instrumentation that is capable of displaying dynamics of a VFD application can serve as a tool to ensure systems can be maintained and operated in a reliable way.

Conclusion

Case studies like the ones presented in this paper are the reason why more companies are adopting aggressive and high quality on-line monitoring predictive maintenance programs. The three presented cases are typical scenarios for on-line monitoring success.

The first scenario showed how it is possible to identify motor load operations that are running at levels that deteriorate the motor rapidly. This case showed why load estimation based on input power, input current or operating speed would have been insufficient to identify the necessary fix. Corrective action was taken on time to avoid unscheduled plant downtime.

The second scenario shows how it is possible to perform motor or load diagnostics to a new level. Knowing exactly what is happening on the shaft is frequently all that is needed to provide the difference between on-time corrective action, or crucial losses of production due to low plant efficiency and output. The third example shows that it actually is possible to monitor, correct and maintain the most dynamic applications in modern plants: variable frequency drives. There are tools available on the market now that allow that these newer applications be debugged and maintained so that they keep running tomorrow.

This paper stresses that on-line electrical monitoring and analysis is necessary to maximize plant reliability. To the best of the author's knowledge, it would not have been possible to diagnose any of the three cases presented here using different instrumentation than electrical on-line tools capable of displaying instantaneous torque.

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