Monitoring and Diagnosing Problems within Variable Frequency Drives in the Field

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Abstract: Predictive Maintenance professionals typically don't have the luxury of owning their variable frequency drive (VFD) vendor's software that identifies many of the motor-load fault mechanisms. The complexity of the symptoms exceeds the common RMS handheld instrumentation that is available. This paper presents three VFD applications and their diagnoses using modern field instrumentation.

I. Introduction

The focus of management is shifting from one of overall expenses, to expenses per product or value as the main measure to be optimized by management [1-3]. However, the prevailing working mode for plant operation is still "run to failure". This is augmented by a lack of following recommended guidelines in VFD installation resulting in future failures. These basic instructions, though time-consuming, cover fusing, wiring and motor lead length and provide a great deal of reduction in failure of the drive system [4].

With the change to asset management, predictive maintenance conferences are focusing on managerial education and the tactical steps required in following through with this approach [3,5,6]. This management shift from cutting expenses to increasing efficiency is changing the maintenance professional's perspective from a "replace the broken" to a more proactive root cause analysis that identifies problems prior to failure. Leading manufacturers have identified that electrical component replacement (motors and drives) is the third highest operational expense, behind wages and energy. Hence, they are investing in training and equipment to attach the problem.

The drive exposes the motor to millions of impulses, thus requiring effective maintenance and installation of both the motor and drive [7]. Line and load reactors, line traps and MOV Surge Arrestors [8] are protective devices that are needed even though their payback is not immediately apparent.

Tools available to field maintenance electricians are typically limited to RMS current and voltage meters, which are insufficient in diagnosing VFD's varying operation within the motor-load systems. Professionals can find some articles on debugging and root-cause analysis of VFD's; however, from a systems perspective there is a lack of authoritative and comprehensive technical fields guides for analyzing VFD related problems. The transient nature of VFD's, together with the motor and load system components interact dynamically, limiting the usefulness of standard RMS and waveform types of instrumentation [14]. The case studies present here, exemplify VFD motor load system diagnostics using modern instrumentation designed to bridge the gap of available field instrumentation.

II. Case Study 1 – Thermal Overload and Tuning the VFD

A plant in Washington State was concerned with high operating temperatures of a VFD operated motor. This motor is a 10-year old Design B – 460V 60hp – TEFC 6-pole. The common rule of thumb regarding insulation life is that for every 10^{o}C above rated temperature a winding operates at, the insulation's life drops by half. This is illustrated in Figure 1.

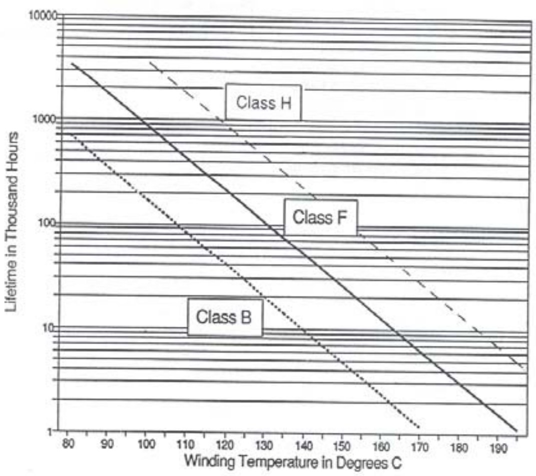

Fig 1: Winding Tempeature vs. Lifetime for Insulation Class B, F, & H.

To apply this concept, a motor operation 30°C above its insulations rated temperature reduces a potential life expectancy of 20 years to only 2.5 years.

The function of this motor is to drive a conveyor belt, which bring logs to a band saw. Its operation consists of three steps. While the log is not in close proximity to the saw, the motor operates at a faster pace. Upon nearing the saw the motor decelerates to cutting speed, and final once the log exits the saw it accelerates to the faster setting. Logs reach the saw every 15 seconds. The VFD's ability to dynamically change the speed of the belt is key for the efficient design of this band saw.

Standard debugging includes checking environmental conditions and ensuring windings are inverter rated and that HFV (Harmonic Voltage Factor) guidelines have been met. Ambient temperature was below 25°C and the motor's vents were not clogged with pulp.

Figure 2 show a partial cycle (in blue) of the motor's speed for 7.5 seconds. At the beginning of the cycle the motor is running at 1200 rpm. At 1 second deceleration starts and takes 0.7 seconds to reach cutting speed, where it remains constant for 2 seconds. At 2.7 seconds, acceleration starts and 1 second later it returns to 1200 rpm where it stays for the remainder of the cycle.

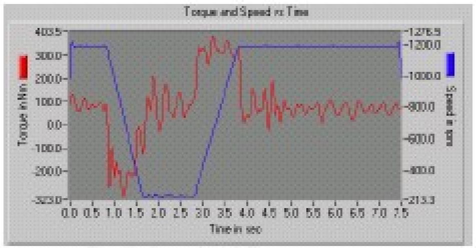

Fig. 2: Speed and Torque vs. time.

This application was first investigated with RMS and other types of waveform instrumentation [12-14], which did not identify any problems. The VFD output voltage level during the longest constant period was rated line to line – 460V, which is the desired voltage for the highest speed of operation, 60Hz. The voltage level during the second constant speed operation of 12Hz was 90V, which was also correct. The two continuous operation states agreed with the motor's nameplate voltage and current ratings agreed with the V/f control expectations. Handheld multi-meters, the tool choice for line-operating motor debugging, can not successfully check the two remaining operations modes of acceleration and deceleration.

The next debugging step was to connect a modern instrument capable of monitoring VFD applications. Figures 2-3 were captures from the Baker Instrument Company's Explorer II [16]. The red trace of Figure 2 displays torque versus time. Average torque during the first second of operation is 100Nm, which is approximately 1/3 of rated torque. The torque for the low speed operation averages similarly which is common for conveyor belt applications; along with during deceleration the torques seems roughly constant. This agrees with the application's programmed constant rate of deceleration; and negative, which shows that the motor operates as a generator when actively braking. Finally the acceleration shows a higher torque than the constant speed level torque, which is needed to accelerate the log. Overall deceleration takes 0.7 seconds, whereas, acceleration is 1 second.

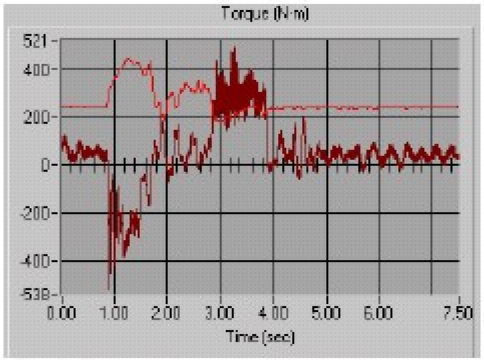

Fig. 3: Torque and equivalent rated torque vs. time.

Figure 3 shows instantaneous torque versus time and the red line within shows the equivalent rated torque. The Explorer calculates this with a motor model using voltage level, frequency, torque and nameplate information as its variables. The model's goal is to find the thermal equivalent stress to rated operation, but for other operating frequencies and voltages. The model implemented displays the torque so that the rotor's I^2R losses are the same as for full load operation. This estimation neglects the lesser cooling achieved by shaft-mounted fans when operating at lower RPM.

Between seconds three and four, the instantaneous torque is significantly higher (300Nm) than the equivalent rated torque (200Nm). This calculates to approximately 150% of full thermal loading happens every 15 seconds which overheats the motor. The solution is to reduce the required torque during acceleration by one third. The 1-second acceleration time was slowed to 1.5 seconds. This slowed production by 0.5 seconds for every 12 seconds or 2 minutes per hour. This was not a significant concern to operations. Also, the VFD could handle the high-speed setting changed from 60Hz to 66Hz without overburdening the motor thermally and staying within NEMA Part 31 guidelines for VFD operation of standard motors [15]. Introducing these changes increased productivity by half an hour per shift, while avoiding premature failure of the motor.

A second potential fault was recognized during the investigation. The VFD-motor-load system was consistently oscillating ("hunting"). Figure 3 shows the oscillation clearly in the last 1.5 seconds of the instantaneous torque where almost 5 cycles of this oscillation occurs. After identifying the frequency, it was noted that the repetitive load variation could be heard at the motor during period of continuous operation. This oscillation does not noticeably degrade the electrical system, but the mechanical system – from conveyor belt to motor bolts were under unnecessary stress. With help from the vendors field support the VFD's PID parameters were tuned and provided a much smoother running sound and a comfortable class F temperature range to the VFD-motor-load system.

III. Case Study II: VFD Control Board Malfunction

The second case study involves two 1hp VFD driven 4-pole motors in a South Korean flat screen TV tube manufacturer. Each motor operates a chain-gear reduction slowly spinning a stirrer, which keeps 2,000 gallons of molten glass in motion. One stirrer failure compromises the entire batch of high quality molten glass and disrupts production.

These critical 1hp motors are monitored 24/7 and warrant the installation of logging A-phase state current levels. Stirrer 2 showed an increase in the stators current over the previous two days. In order to avoid the unplanned downtime and the costly loss of production, the root cause of the problem needed to be found. Both stirrers were analyzed with the Baker Explorer. The most likely source of the problem is related to the load of stirrer 2. Figure 4 displays the load of stirrer 2, for 11 subsequent tests, showing a constant load level for all 11 testes between 22.5% and 23.2% load. Stirrer 1 was also checked and similar results were obtained.

This low load is advantageous to the operation because the VFD's are installed 20 feet above the open batch of molten glass. Ambient temperature exceeds 60^{o}C, which requires running both motors and the VFD under low load to avoid overheating.

Figure 5 compares other operational values for both VFD's. Figure 5a displays an expected constant frequency of 56Hz for stirrer 1along with a constant voltage level. Figure 5b shows stirrer 2 data. A negative frequency of roughly 56Hz is recorded. This negative sequence indicates that stirrer 2 is operating in the opposite direction of stirrer 1, which is needed to meet the best stirring practice of the molten glass. However, the voltage level varies between 470V and 300V. Since the load does not change, these abrupt voltage collapses cause the stators current to rise. The 1hp VFD's control board is not regulating the output voltage.

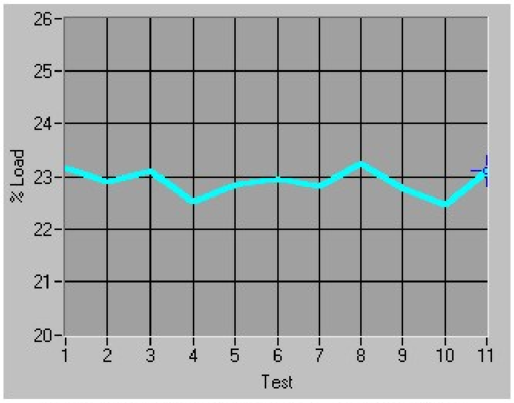

Figure 4: Estimated % load vs. number of test.

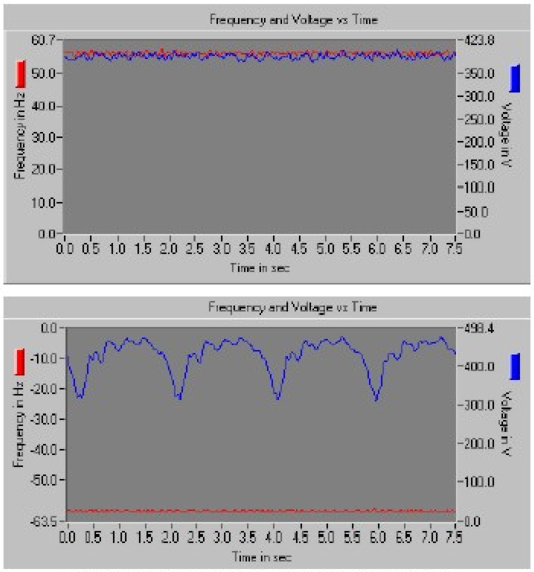

Fig. 5 a-b: Frequency and Voltage vs. time.
Stirrer 1 top figure, stirrer 2 bottom figure.

The root cause of this symptom is the faulty VFD, allowing the scheduling of maintenance to exchange the VFD when the batch is next empty. The flow of production is not influenced, and the cost of repair is minimal. The high temperature environment the

VFD operates under might have precipitated the failing control board. If a pattern of failure emerges for this critical application, then it might precipitate mounting the VFD's a larger distance from the molten glass.

IV. Case Study III: AC Servomotor Mechanical Failure

This final case study illustrates the wide range of information available along with the areas of future advancements that still need to be developed. A modern car manufacturing plant is highly automated, using hundreds of robots to meet the production requirement of more than a car a minute. These robots are operated with one or two AC servomotors in each joint. In order to achieve the fastest operation, the AC servomotors are linked to a mechanical brake to assist deceleration.

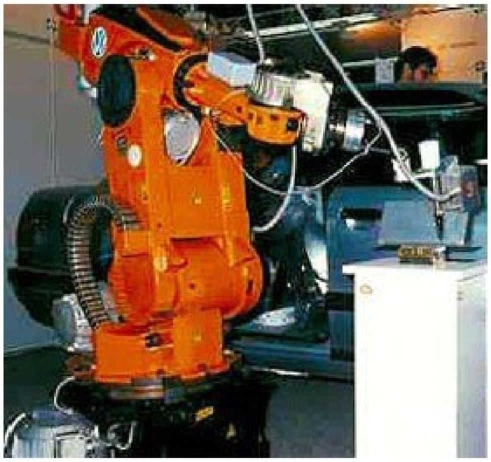

Fig. 6: Typical car manufacturing robot.

In order to exchange problem motors without stopping production, it is highly important to accurately predict motor failure. The manufacturer observed that many of the failed AC servomotors have a faulty mechanical brake. It seems that the additional deceleration stress on the servomotor is the root cause of the ensuing motor fault.

Test run raw data gathered was used to develop the streaming (continuous monitoring) functionality of the Explorer instrument. In this case 15 seconds of currents and voltages are measured, along with instantaneous frequency, torque, power factor, complex power, currents, voltages and impedances are calculated and stored. In red, Figure 7a shows the calculated frequency versus time for the first data acquisition and in green for the second, which was taken later.

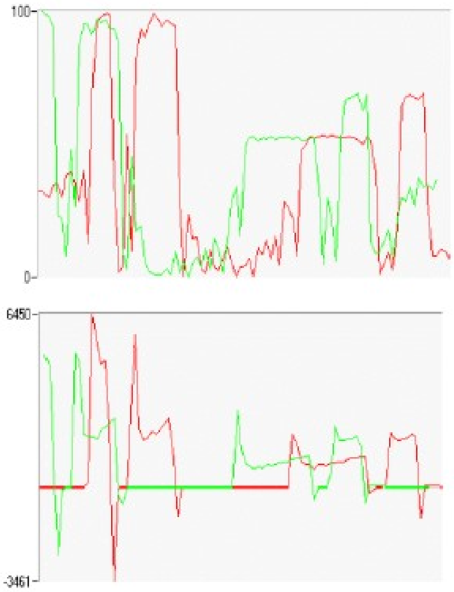

Fig. 7 a-b: Two runs. Top – Frequency vs. time. Bottom – Power vs. time.

The instrument is connected to the robots currents and voltages via the MCC (Motor Control Center). This leaves the robot out of sight, making synchronizing of data impossible. Figure 7b shows the instantaneous sum of powers for both data acquisitions. An algorithm allows super imposing of traces taken at different times. Figure 8 shows three superimposed acquisitions of input power. The red trace is a healthy servomotor, whereas, the blue and green traces display data with a malfunctioning brake.

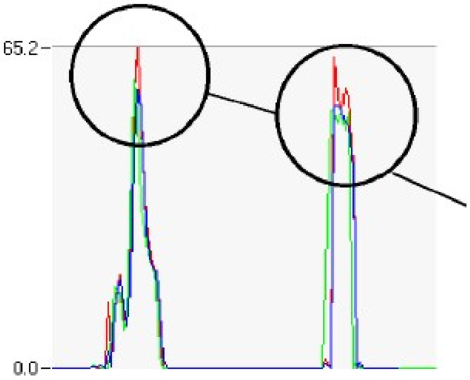

Fig. 8: Three runs, lined up.
Red – no fault. Blue, Green – fault.

The traces correlate well with each other, however, the peak input power is higher where the mechanical break assisting the motor has been deactivated. This visual proof verified the success of the first stage of the project.

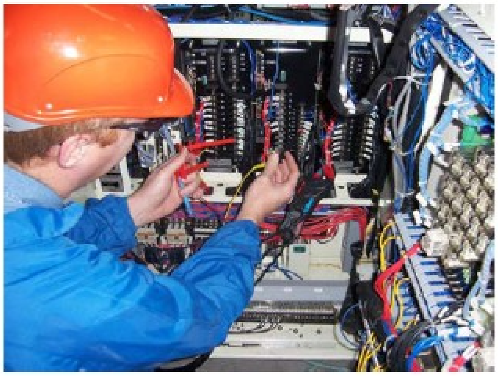

Fig. 9: Connecting in the MCC.

Stage 2: Hardware efforts are currently under way to integrate a safe low voltage connectivity package for data gathering for up to 8 servomotors via one connection without opening the MCC. Software efforts aim at automating the pattern recognition and alarm based assessment, enabling high volume testing with reduced acquisition and analysis. This is necessary for this type of operation since this manufacturer has in excess of 200 robots in just the paint shop with 6 servomotors in each robot. The connections, shown in Figure 9, data acquisition and analysis took approximately 10 minutes- per unit. With this time requirement and the need to identify faults quickly the estimated 5 weeks to complete one complete route is prohibitive. The estimated time to failure for a servomotor, once the brake fails, is only a few days and the cost of adding more staff is unlikely. The use of multi-acquisition points would cut the testing time drastically, making the equipment efficient and cost effective.

V. Conclusions and Future Work

Today's predictive maintenance professional has to solve problems involving VFD's and servo drive; however, the most common field instrumentation is not suited for this task. The three illustrations in this paper proved the RMS type or waveform display and harmonic analyzers are not realistic in finding these dynamic and often hidden problems. The variability of frequency and dynamic change in operating condition can also create other dynamic disturbances conducive to faults, which need to identified prior to unplanned downtime.

VFD's introduce many challenges that will continue until appropriate instrumentation is available. The variable nature of VFD's makes debugging with handheld digital multi-meters difficult along with the more refined capabilities of PID tuning to null resonant modes of the motor load system are commonly misunderstood and not used advantageously. However, the VFD is too attractive to ignore in terms of power savings, better control and report generation for industry. Currently, 28% of new motors are controlled by a drive, with growth potential substantial. By 2010, non-linear loads, such as VFD's and AC servo controllers will utilize 50% of the power produced [20]. Instrumentation and algorithms have been developed to offer some transparency in testing for maintenance professionals, however, much work still needs to be done.

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