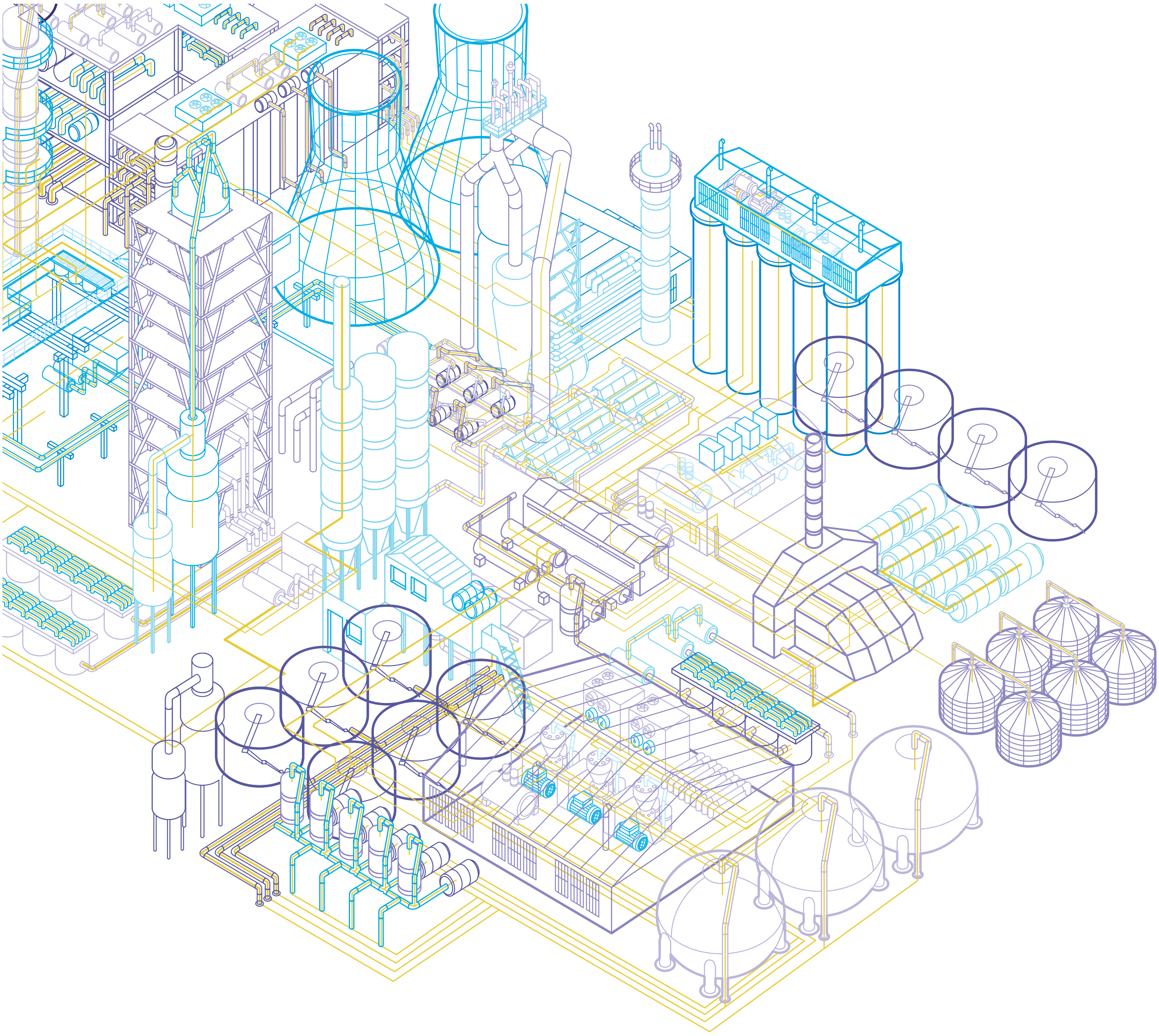


Hidden treasure

Drive data are a treasure trove of hidden information that can help industries solve problems before they even happen

MICHAL ORKISZ, MACIEJ WNEK, PIEDER JOERG – As processes become ever more complicated and margins thinner, minimizing downtime by ensuring that industrial machinery operates correctly is as important as ever. Proper condition monitoring of critical equipment can act as an early warning system against impending problems. However, condition monitoring is not used everywhere, often because of the expense of installing proper sensors and cabling, especially if the monitoring system needs to retrofitted to existing equipment. Another reason is that the task of selecting and interpreting the large quantities of data available in the most effective way seems daunting as well as costly. ABB has devised a way to easily access and process important data without the burden of additional equipment, costs and downtime. By extracting and processing data from existing devices traditionally used in process industries, such as drives, customers can prevent otherwise unforeseen problems from occurring and hence maximize the availability of their machines.

Industries are constantly under pressure to reduce costs while increasing service and productivity. The most effective way of fulfilling these aims is for managers to know the state of their equipment – in particular the critical components – at all times and to use this information to quickly identify and rectify faults before they spread to other parts of the process [1]. A good condition monitoring system helps predict the reliability of equipment and the risk of failure. With so much to gain, why is it that condition monitoring is not used everywhere? One reason is that existing equipment is often already retrofitted with a monitoring system and the installation of additional sensors and cabling could prove both complicated and expensive. Another reason concerns the interpretation of results. In many cases it may not be clear how to use a set of data that gives information about one aspect of a process to provide information about another. For example, determining the fractal dimension of a certain phenomenon may be fairly straightforward but relating it to the condition of a machine may not be so obvious.

Most processes use devices that are capable of collecting and producing relevant signals, which, if harvested and processed correctly, can also be used for diagnostic purposes. Among others, one such example is ABB's family of ACS variable-speed drives, which are often used to power critical equipment. The drives are based on powerful controllers that consume and provide tens, if not hundreds, of signals with sub-millisecond resolution.

To be useful for condition monitoring, data needs to be obtained from the drive inverter in one form or another. Internally the signals – which include measured and computed values such as speed, frequency, torque, flux, current, power and temperature, as well as parameters such as configurable drive settings – are stored in a regularly updated memory table. Data can be retrieved from this table as OPC [1] values or they can be loaded into hardware data loggers.

Data loggers are programmable buffers capable of storing values from several selected variables concurrently with a specified sampling rate, generally one that is high enough to make the data useful for spectral analysis. In normal operation, the newest data overwrites the oldest until the loggers are triggered by certain events, such as the occurrence of a fault or an alarm, a selected variable signal crossing a specified threshold or a software command. As the buffers are circular, some data prior to and after the trigger can be retained. ABB's DriveMonitor™ system → 1 can read the contents of a drive's hardware data logger. It consists of a hardware module in the form of an industrial PC and a software layer that automatically collects and analyzes drive signals and parameters [2].

Most processes use devices that are capable of collecting and producing relevant signals which can be used for diagnostic purposes.

Data enhancement

Because the resolution has already been determined and preprocessing has been performed, drive signals are generally available in a form not easily applicable to diagnostic evaluation. It is therefore necessary to employ a suite of "tricks" to transform the data so that it becomes useful for diagnostics.

True to their name, variable-speed drives dynamically change the frequency of the current supplied to the motor. The direct torque control (DTC) method employed in the drive produces a non-deterministic switching pattern, so there is no such thing as a constant switching frequency. This makes the straightforward application of spectral analysis methods somewhat challenging. Because individual spectra contain many hard-to-predict components collected one after another, the averaging of many spectra using point-by-point averaging, for example, is essential to obtain a "clean" spectrum.

In general, signals currently available from the ACS drive are used primarily for control purposes. Therefore some of the preprocessing needed for condition monitoring signals is missing. One such process is anti-aliasing filtering. Data points are sampled or computed at rates up to 40 kHz, but can only be accessed at lower rates (eg, by keeping every 40th data point). In signal processing it is typical that frequencies above the so-called Nyquist frequency – defined as half the sampling rate – should be filtered out prior to signal sampling. Skipping this step means the peaks from the higher frequencies will appear in the lower part of the spectrum, making it very hard to interpret. For example, signals containing frequencies of 400 Hz, 600 Hz,

1 ABB's DriveMonitor™

Footnote

1 OPC stands for object linking and embedding (OLE) for process control and represents an industry standard that specifies the communication of real-time data between devices from different manufacturers.

1.4 kHz and 1.6 kHz that are sampled at 1 kHz all produce the same aliased spectrum with a peak at 400 Hz.

When it comes to monitoring drive-induced changes in the output frequency, the high frequencies are important. Because they were not filtered out by the anti-aliasing filter combined with the fact that the drive's output frequency is rarely constant means they can be recovered.

This recovery process is illustrated in → 2. The individual true spectrum containing the original and aliased peaks, as computed from the measured data, is shown in → 2a. The x-axis is scaled so that the output frequency is 1. This spectrum is "unfolded" by appending copies of itself (alternating between reversed and straight) along multiples of the Nyquist frequency. A number of unfolded spectra for varying output frequencies are then averaged so that previously aliased peaks are returned to their original place → 2b.

Variable-speed drives are generally used in applications where a process parameter needs to be controlled. The drive changes the output frequency in response to an external request (eg, to pump more water) or because of process changes (eg, more load on a conveyor belt increases the slip of an asynchronous motor) or perhaps because of a combination of both. While traditional spectral analysis methods assume constant frequency, frequency variations can be handled using one of two approaches: selecting constant frequency moments or rescaling the time axis.

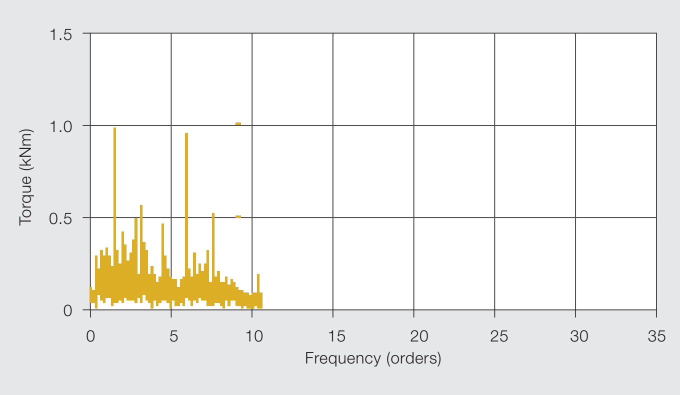
The first approach takes advantage of the fact that data is available in large quantities at any time. Most of it can actually be ignored in favor of keeping only a few "good" data sets. The trick, however, is knowing what to keep and what to throw away. A good criterion for selecting a suitable data set is that the output frequency should not change appreciably during the measurement, and only a set of conditions that occur regularly in the process should be considered for selection.

Sometimes the operating-point variations are so frequent that it is impossible to find such a stretch of data for any length of time. In such cases, the solution is to convert the data domain from time to another quantity, such as the electric field angle.[2] To aid in this transformation, various measurements can be collected from the drive inverter in parallel with the original signal. The instantaneous value of the output frequency[3] is one such measurement. This frequency is then integrated to yield the angle of the stator electric field, which then replaces the original x-value of each data point. Further normalization can be applied to the y-values.

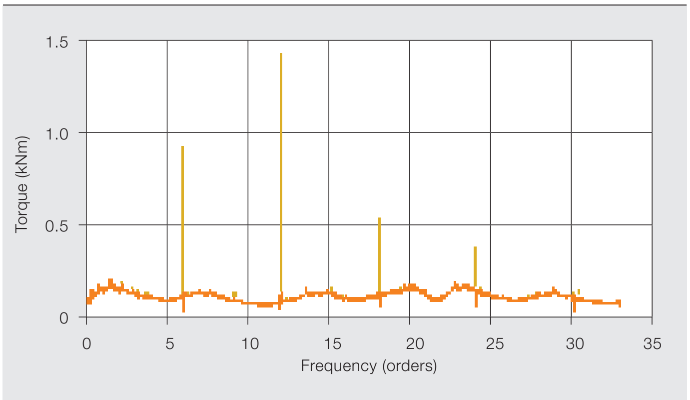
This transformation results in an x-axis that is no longer equispaced and therefore the fast fourier transform (FFT) spectral approach cannot be used. Instead, the Lomb periodogram method is employed [3]. This process, as applied to one of the phase currents of a hoist machine, is illustrated in → 3. The original signal with pronounced frequency and amplitude variability is shown in → 3a. The RMS current value reported by the inverter is given in → 3b and the measured instantaneous frequency is plotted in → 3c. The stator electric field angle is shown in → 3d and its shape follows the trend that the higher the frequency, the faster the rate the angle increases. The regular sinusoid shown by the solid mustard-colored waveform line in → 3e results when the original current signal is normalized (using point-by-point averaging) by the RMS current value and its x-axis respaced to reflect the angle. This in turn leads to a spectrum that is represented by a single-frequency peak (solid line in → 3f), while the raw data spectrum, shown by the dotted line, is not represented by a single-frequency peak.

Different transformations can be applied depending on the information required.

2 An individual electric-torque spectrum



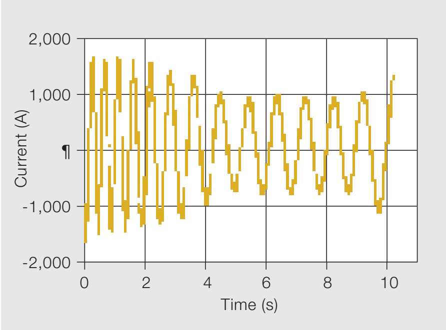
2a With aliased peaks



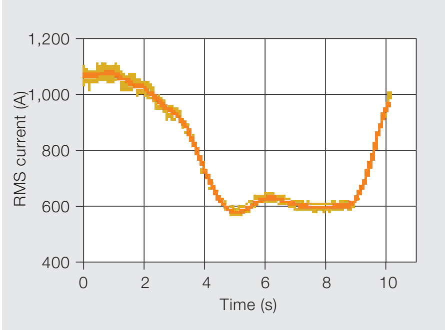
2b With an averaged "unfolded" spectrum

The frequency variations associated with variable-speed drives can be handled by either selecting constant frequency moments or rescaling the time axis.

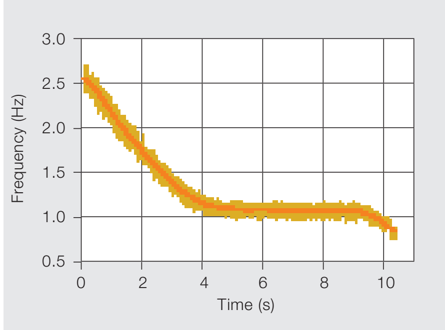
3 Normalization and transformation of variable frequency (and amplitude) current



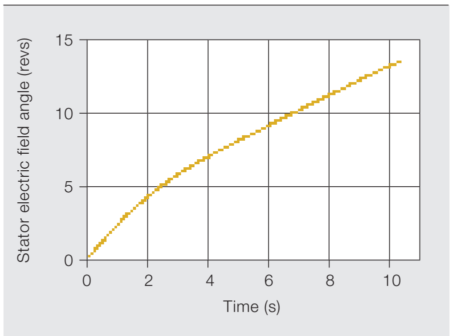
3a Original signal



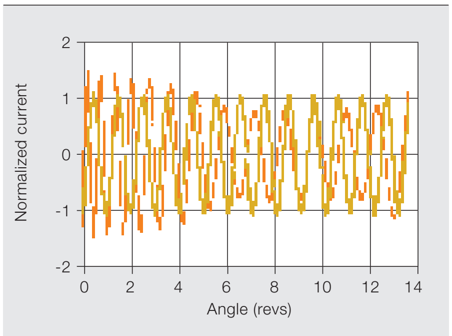
3b RMS current



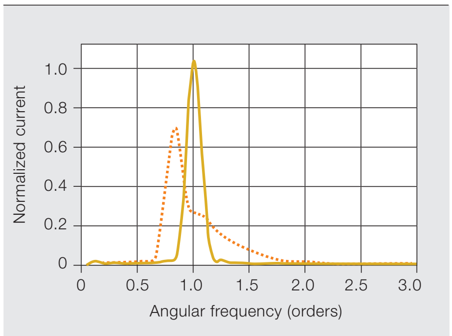
3c Instantaneous frequency



3d Integrated frequency (angle)



3e Transformed signal



3f Spectrum (raw signal is dotted; transformed is solid)

For example, suppose engineers want to know if certain motor defects such as imbalance, misalignment and bearing faults are present. Rather than measuring the instantaneous value of the output frequency, a motor speed signal may be acquired. After an analogous transformation, the x-axis represents the shaft angle, which in turn facilities the search for motor defects related to the rotating speed.

Diagnostic opportunities

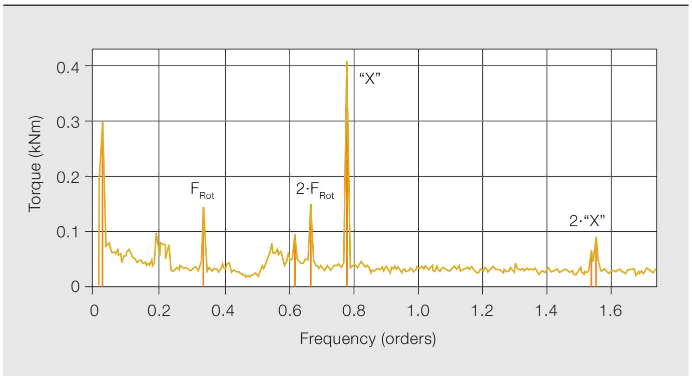
Converted drive data can be analyzed using two general methodologies that reveal different and important diagnostic information. These methodologies are:

- Point-to-point variability within one signal
- Signal-to-signal correlations

Point-to-point variability can be analyzed via spectral analysis in which periodic components are represented as peaks in the spectrum while various system defects or conditions can manifest themselves as spectral features with different frequencies. Signal-to-signal correlations, on the other hand, give information about the operating point and any associated anomalies.

Other methods use acquired knowledge about the normal behavior of a machine or process, and any observed deviations are immediately indicated. Irrespective of which method is used, their underlying purpose is more or less the same – to produce key performance indicators (KPIs) that give adequate information about, for example, the health of a machine, process robustness or supply quality. The conclusions can also be helpful in uncovering the root cause of a problem once it has been identified.

4 A fragment of the torque-signal spectrum from a rolling mill. On the horizontal axis, one equals the output frequency.



Spectral analysis

Drives equipped with an active rectifier unit can use the spectra of supply voltages and currents to yield valuable information about the quality of the power supply. Phase currents and voltages that are measured concurrently enable engineers to check for possible unbalances, phase shifts, harmonic distortions, etc. Similarly, looking at the harmonic content of the output current is a means of verifying the quality of the motor's power supply. The drive provides information relevant to the motor (such as frequency, torque, power, RMS current and flux) and to the inverter operation (such as internal DC voltage levels, speed error and switching frequency). In fact the spectral analysis of data supplied by a drive is capable of revealing more than is uncovered by the "classical" analysis of electrical or vibration signals.

An example of an averaged torque spectrum from a rolling mill is shown in → 4. The horizontal axis is scaled so that the output frequency equals 1. There are two peaks related to the rotating frequency, F_{Rot}. In addition, a family of peaks exists at an interharmonic frequency of "X" = 0.7742 (37.86 Hz) and 2"X" (1.5484), and

Footnotes

2 These domains are equivalent when the frequency is constant.

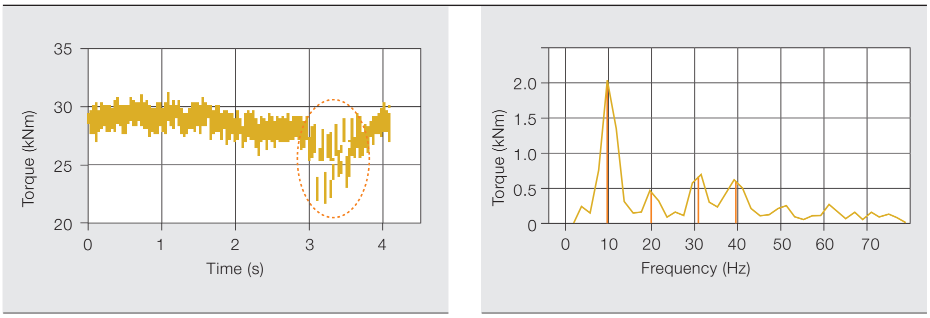
3 The frequency the drive establishes on the output current. The drive controls this frequency so it knows its exact value.

this likely corresponds to a resonance frequency in the driven equipment. This is an interesting piece of diagnostic information since such resonances accelerate equipment wear, which in turn could negatively impact certain process quality issues, such as the uniformity of rolled metal thickness.

Transient phenomena

Spectral analysis also helps to reveal the presence of transient phenomena in drive data. As well as stationary oscillatory components in the signals, other more temporary events may also be present that are indicators of potential problems. For example, the raw torque signal from a rolling mill, measured over the course of 4s is shown in → 5a. Some form of ringing, which lasts roughly half a second, is evident after approximately 3s. The spectrum of this ringing fragment is given in → 5b where a 10 Hz frequency component and its harmonics are obvious. The source of this oscillation is unknown but the spectrum has highlighted a potential problem that needs to be investigated.

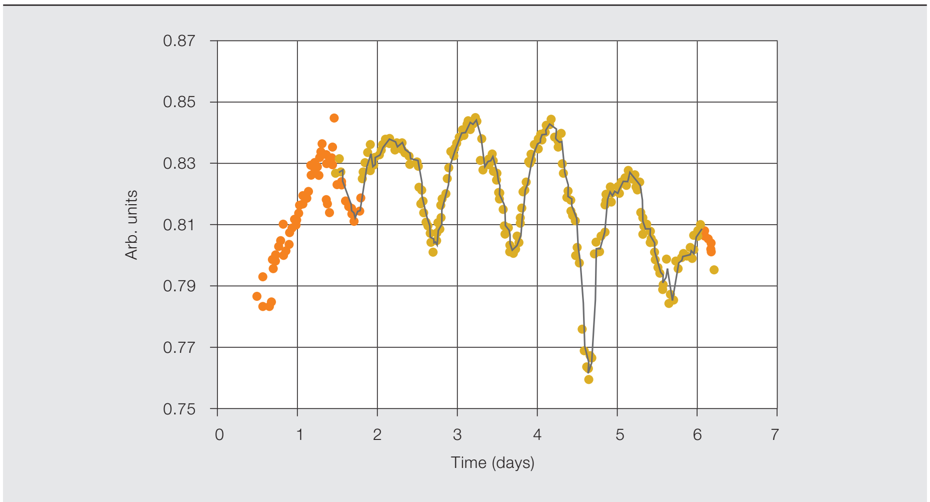
5 Transient phenomena in a torque signal.



5a The raw waveform with ringing

5b Spectrum of the ringing fragment

6 Time evolution of the torque/speed ratio (τ/n2) for a fan



The spectral analysis of data from a drive is capable of revealing more than is uncovered by the "classical" analysis of electrical or vibration signals.

While it is impractical to continuously collect high-frequency data, the periodic collection and examination of such signals significantly improves the chance of detecting unwanted temporary occurrences.

Operating-point tracking

Concurrently tracking operating-point quantities (such as current, torque, speed, power and frequency) in drive data is an example of the signal-to-signal correlation methodology mentioned previously. Analyzing the relationships between certain quantities can shed light on both the operation of the machine and the state of the process. The relationship between torque and speed, governed by the fan laws, is a good example of a process-dependent relationship.

The velocity pressure difference at the output Δp is proportional to the gas density ρ and the square of the output velocity V:
$\Delta p = \rho \cdot V2/2$

Power P is equal to the pressure difference times the volumetric flow rate Q:
$P = \Delta p \cdot Q$
but it can also be expressed as a product of torque τ and rotating speed n:
$P = \tau \cdot n$

In normal operation under constant geometry, both Q and V are proportional to n, thus:
$\tau = C \cdot \rho \cdot n2$
where the constant C depends on the fan's geometry.

It follows that the ratio $\tau/n2$ reflects the density of the gas and the fan's geometry, which rarely changes.

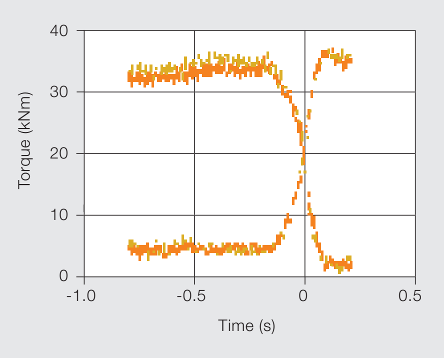
In → 6 this ratio for a drive-powered fan over a period of several days is plotted. The oscillations (with a period of one day) reflect the daily variations in temperature and thus the density of the pumped air. High density (cold temperature) occurs at night while low density (warmer temperature) is evident during the day. The drive data alone enables the evolution of process variables, such as inlet temperature, to be tracked. In addition, comparing this data with values from the control system (temperatures in this case) can lead to the detection of any unexpected discrepancies.

Tracking the operating point is possible without having to employ any additional hardware – the data is already available in the drive. The analyzed data can be presented directly or further analyzed by using the principal component analysis (PCA) technique described below.

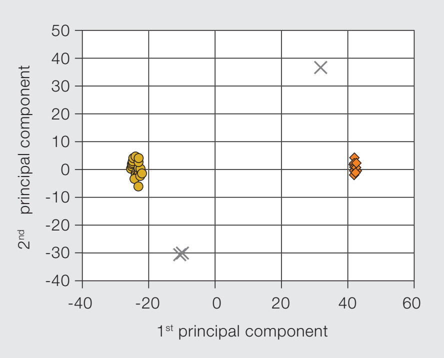
Cyclic process analysis

Some processes powered by a variable-speed drive are cyclic in nature. A rolling mill application is one such example where torque and current abruptly jump or increase as a slab is loaded onto the rolls and then suddenly decrease as the

7 A typical rolling mill torque profile



7a Examples of torque up and down profiles



7b The two clusters represent torque increases and decreases

ABB's medium-voltage AC drive ACS 1000

Drives are but one example of useful diagnostic data providers. Other examples include motor control centers, protection relays and intelligent fuses.

slab leaves. These jumps can be analyzed to detect any process instabilities or divergence from normal behavior that may be an indication of equipment wear or material variations.

In order to extract only the most essential information, high-resolution data gathered around torque jumps is processed using the PCA methodology [4]. This technique reduces multidimensional data sets to lower dimensions for analysis. These lower dimensions condense the set-to-set variability. Typical rolling mill torque profiles are shown in → 7. Each profile in → 7a, corresponding to one jump, is reduced to a single point as shown in → 7b. Jumps – or points – that tend to cluster within certain boundaries generally indicate the process is operating normally while those outside could signify a problem. The full data set can be saved for further examination at a later stage or, if the analysis takes place in real-time, more data can be collected.

Healthy machines, healthy processes

In today's competitive world, unplanned downtime can be disastrous for a company. That is why industries are constantly striving to maximize the availability of their machines. To do this effectively, some form of condition monitoring needs to be in place so that maintenance can be scheduled or actions taken to avoid the consequences of failure before it occurs. Condition monitoring is increasing in importance as engineering processes become more automated and manpower is reduced.

The benefits of condition monitoring need not come at the expense of having to install additional equipment. Often the data provided by devices for one purpose in a process can be used to satisfy another at no extra cost. As an important part of an industrial process, ABB drives have access to and generate large quantities of data, which, when properly processed, can be used for condition monitoring and diagnostics. Drives are but one example of useful diagnostic data providers. Other examples include motor control centers, protection relays and intelligent fuses. As well as being data providers, these devices are capable of using their onboard computational power for analyses.

Michal Orkisz
ABB Corporate Research
Krakow, Poland
michal.orkisz@pl.abb.com

Maciej Wnek
ABB Low Voltage Products
Turgi, Switzerland
maciej.wnek@ch.abb.com

Pieder Joerg
ABB Discrete Automation and Motion
Turgi, Switzerland
pieder.joerg@ch.abb.com

References

[1] Mitchell, J. S. (2002). Physical Asset Management Handbook (185). Clarion Technical Publishers, United States.
[2] Wnek, M., Nowak, J., Orkisz, M., Budyn, M., Legnani, S. (2006). Efficient use of process and diagnostic data for the lifecycle management. Proceedings of Euromaintenance and 3rd World Congress on Maintenance (73–78). Basel, Switzerland.
[3] Press, W.H., Flannery, B.P., Teukolsky, S.A., Vetterling, W.T. (1986). Numerical Recipes: The Art of Scientific Computing. Cambridge University Press.
[4] Jolliffe, I.T. (2002). Principal Component Analysis. Springer.