White Paper

Accelerated Optimization & Advanced Analysis For Electrical Machines & Drives

Boost Motor and Drive Testing Productivity, Capability and Data Analysis

by

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Introduction

Evaluating motor efficiency has become extremely important since significant efforts are focused on more efficient electrical machines and drives. The main issue is how to implement an accelerated procedure that obtains the motor or drive efficiency for all operating points safely, accurately and rapidly. Ordinary test methods using a typical power analyzer only offer inadequate numerical results. To get beyond numerical results, all electrical, mechanical and physical signals must be acquired simultaneously at high sample rates coupled with advanced real time custom analysis and fast data transfer to automation systems, making it possible to perform electric motor and drive efficiency mapping accurately and rapidly, as well as almost any type of advanced analysis.

Typical vs. New Testing Method

The Electrical Drive Train and Related Signals

Electrical drives are used in a wide variety of applications, including electric vehicles, ship motors, high speed trains, airplane electric wheel drives and actuators, forklifts, motorized appliances and wind energy, basically every electrical machine that is inverter driven or contains a variable speed drive. The key is to design and test for the maximum efficiency at all operating points in the entire drive train safely, accurately and rapidly. This includes optimizing the inverter, the motor or electrical machine, the matching between the inverter and the motor and the drive strategy, as seen in **Figure 1**. The better the inverter and motor are matched, the higher the efficiency. To improve inverter-motor matching, the motor needs to be carefully characterized with the inverter and sometimes the inverter may need improvements in the algorithm to drive the motor more efficiently. This can only be done by analyzing the raw data at all operating points along the drive train.

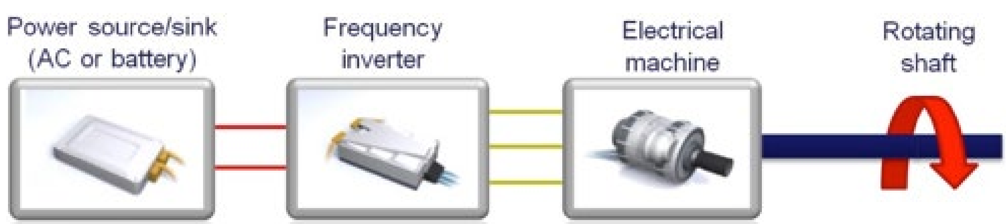

***Figure 1.** Simplified electrical drive train*

Electric drive trains contain many signals that need to be recorded in order to analyze and improve efficiency. Referring to **Figure 2**, signals include battery voltages up to 1000 Volts and currents up to a few hundred Amps. Inverters produce pulse width modulated voltages up to +/-1000 Volts, often in 3 phases, sometimes more and currents up to a few hundred Amps. A torque transducer can record a motor's torque and speed, as well as its position for advanced analysis. Measuring each of these voltages and currents enables calculations of the electrical power from the batteries, the electrical power from the inverter and the mechanical power from the motor. Calculating the ratios produces the efficiency of the frequency inverter, motor and the entire electric drive.

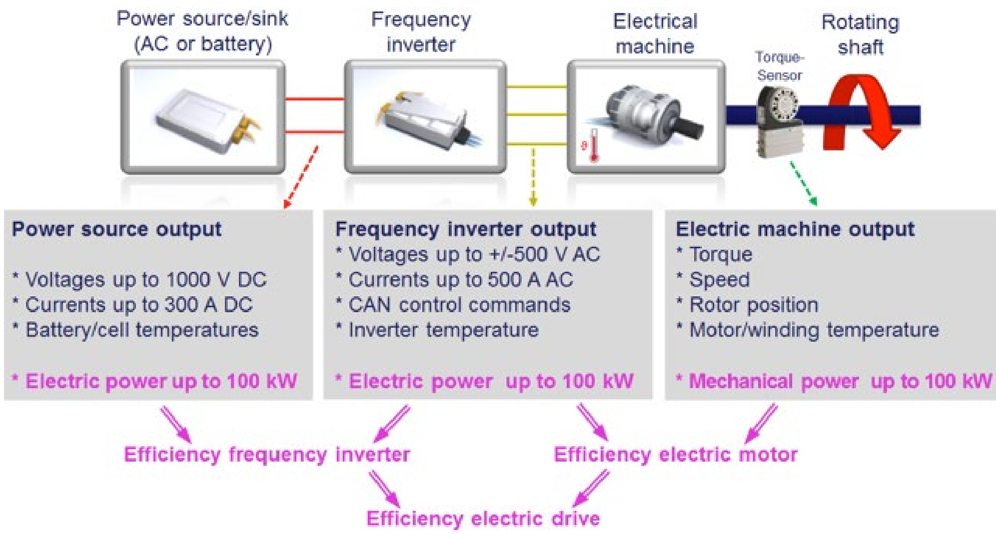

Figure 2. *Data acquisition requirements on an electric drive train*

Typical Testing Method

Traditionally, signals along the drive train are measured with the setup seen in **Figure 3**. Battery voltage and current are measured via a digital multimeter, the output of the inverter is often measured with a traditional power analyzer and to view the signals sometimes a scope is used. To measure machine output, a torque sensor and some type of data acquisition system is used. Unfortunately, there are several issues with this traditional setup:

1. There is no time synchronization between all the recording systems; therefore, it is difficult or nearly impossible to make comparisons between mechanical (torque/speed) and electrical (voltage/current) signals at the same point in time.
2. No raw data is available; therefore, no advanced analysis can be performed.
3. Typical power analyzers only offer a few calculations per second, not enough for feedback on automation/control systems.
4. Power meters are not reliable during dynamic load changes, an area that needs further testing and analysis.
5. Verification of results is not possible because no raw data is available, requiring retesting if anything is in question.

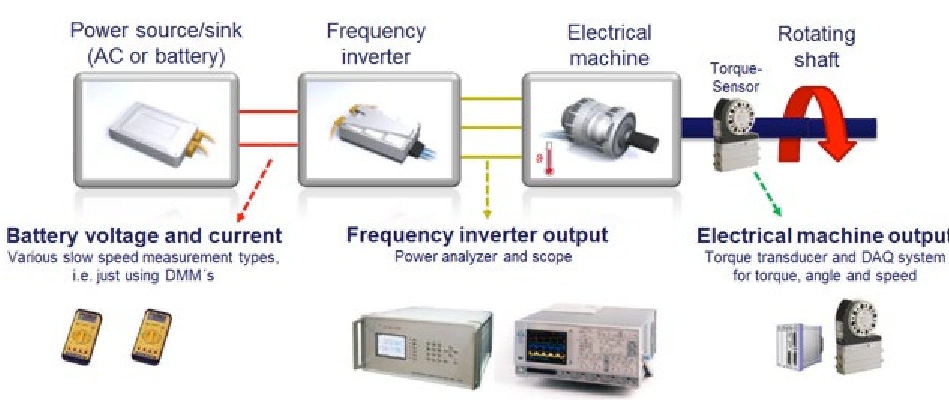

Figure 3. *Typical method for testing electrical drive trains*

As a result, one needs to make several assumptions about issues and errors; make changes based on those assumptions and then retest, which is time consuming and rather costly.

New Testing Method

Figure 4 outlines a revolutionary tool that overcomes the limitations of the typical test method using a high speed data acquisition power analyzer. Benefits include:

1. Synchronously record all drive train signals so mechanical and electrical traces can be compared accurately plus test 3, 6 or 12 phase machines and acquire more signals like CAN, temperature, vibration and strain
2. Real time advanced analysis like motor mapping enables immediate results rather than hours or days
3. Transfer real time calculated results to automation systems via EtherCAT at 1000 results per second
4. Perform real time power calculations per half cycle even during dynamic load changes, start up or slow down
5. Verification of results is possible any time because raw data is available, so no retesting is needed if anything is in question

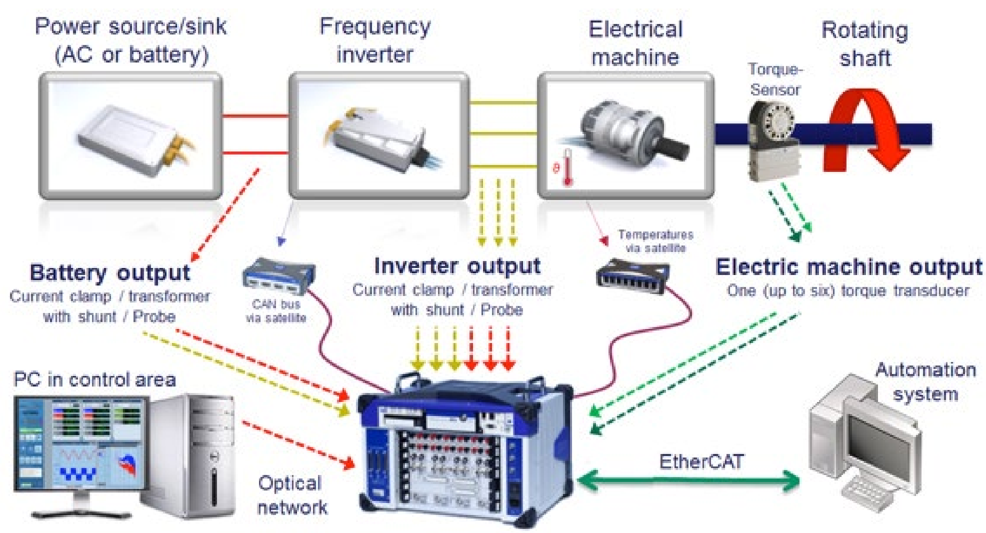

***Figure 4.** New method for testing electrical drive trains faster and more accurately*

Methods for Connecting Signals

Achieving the highest drive train efficiency requires the highest measurement accuracy. Let's identify the most desirable and accurate method for each type of signal.

Current Measurements

Most often the current measurement has the highest amount of error. Therefore, it is very important to invest in an accurate method for measuring current to obtain better efficiency calculations. Current clamps only offer low accuracy, often +/-1% at best. Current transformers offer higher accuracy, often +/-0.02% or better.

Figure 5. *Methods for measuring current*

Voltage Measurements

There are several methods for measuring high voltages; however, the most important factor should be safety followed by accuracy. Although an isolation amplifier often comes at a higher cost, it is the safest method for measuring high voltages for both the user and the equipment. Also, an isolation amplifier offers higher accuracy, typically +/-0.02%. Other methods only offer lower accuracy and sometimes compromise safety, including voltage transducers or transformers with about +/-1% accuracy or differential active probes with about +/-2% accuracy.

Figure 6. *Measuring high voltages*

Torque, Speed and Angle Measurements

To measure torque, speed and angle, a high accuracy and high dynamic range torque transducer should be used with at least 0.05% up to 0.01% accuracy. All signals from the torque transducer should be connected digitally to eliminate noise from the harsh test cell environment.

Figure 7. *Torque transducers*

Power Results and Rapid Advanced Analysis

Cycle Detection

To calculate any power result properly, the analyzer needs to identify the "cycles" of the incoming signal. Using advanced algorithms, the cycles can be easily detected and displayed as seen in **Figure 8**. Typical power analyzers use a PLL, which has issues during dynamic load changes. Digital cycle detection enables measurements during start up, slow down or any changes in load. **Figure 9** illustrates waveforms containing several dynamic load changes seen as humps. This is when a brake or load was applied to the drive train. Displaying these waveform results with the raw data enables further analysis of the inverter characteristics.

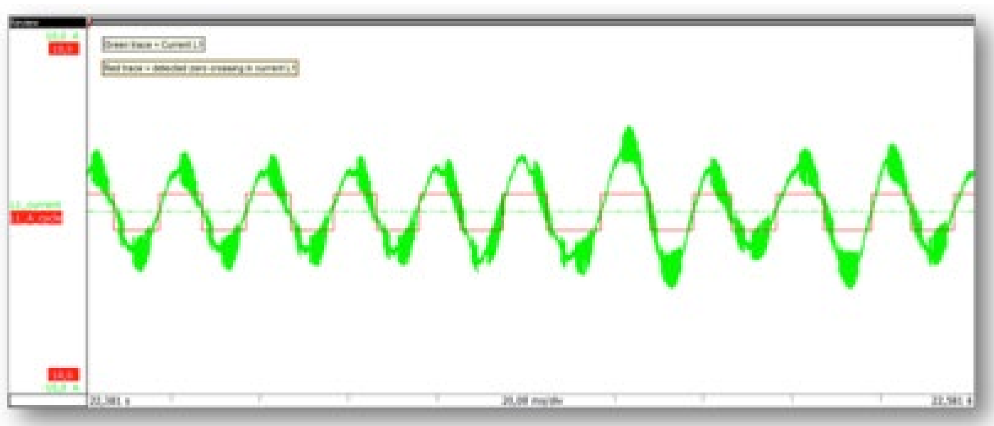

Figure 8. *Detecting cycles (red) on a phase of current (green)*

Advanced Analysis

Having all the raw data available enables the user to create any advanced custom formula, which can be calculated, displayed and streamed to an automation system in real time. The system can also be easily adapted to a wide variety of applications that a traditional analyzer is unable to solve, including; multi-phase motors, hybrid drives and multi-level inverters.

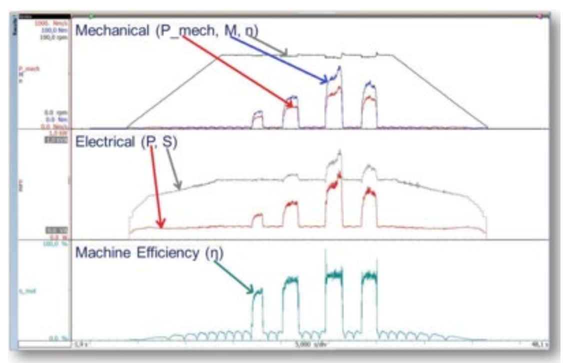

Figure 9. *Waveform results from formula calculations*

Accelerated Machine Efficiency Mapping

Machine efficiency mapping can be performed 100 times faster, in about 100 seconds using 1000 set points instead of nearly 3 hours on a traditional analyzer, a major time and cost savings as seen in **Figure 10**. Testing within 100 seconds also eliminates the motor temperature as a factor. A typical analyzer needs quite some time to settle on the changing fundamental frequency in order to deliver stable results; therefore, only one set point can be achieved about every 10 seconds. Using digital cycle detection enables the calculation to be performed every half cycle. Advanced motor maps can also be created using the machine angle and some advanced formulas to further understand the characteristics of the machine, including copper loss maps and iron-mechanical loss maps as a function of torque and speed, plus a trajectory map called MTPA (max torque per amp) where the machine's best working condition is drawn as a function of d- and q- currents.

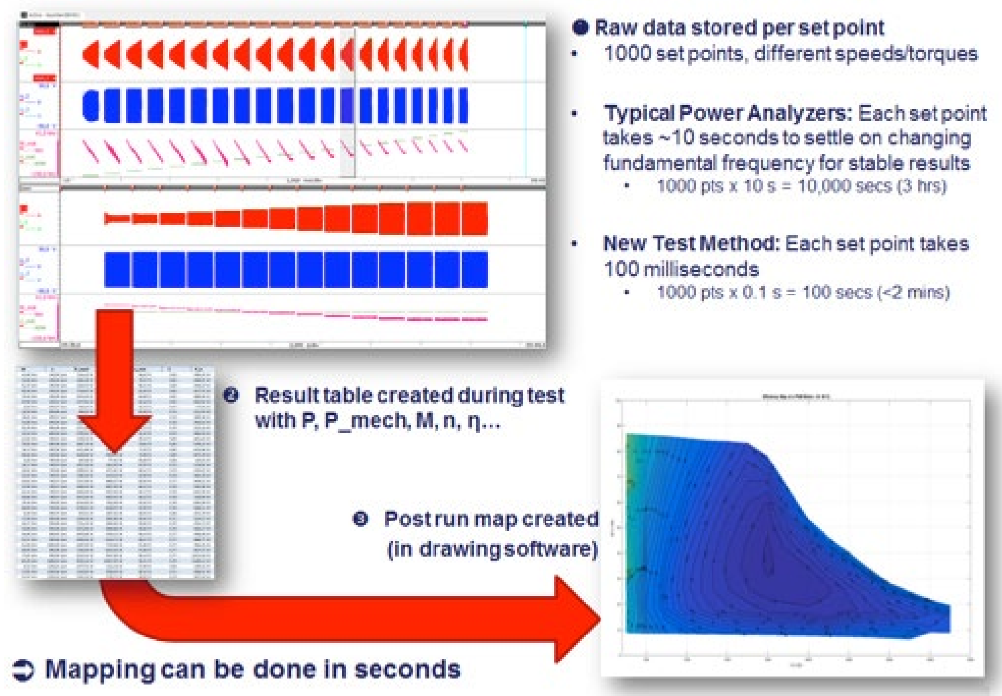

Figure 10. *Accelerated efficiency motor mapping performed 100 times faster*

Clarke (Space Vector) Transformation

Clarke or Space Vector transformation can also be accelerated. Space Vectors representing the three entities a, b, c of a three phase system can be converted into two linear independent entities α and β representing the generated torque and the magnetic flux. Displaying the two iα and iβ waveforms as an XY plot easily shows any system unbalance and the control behavior.

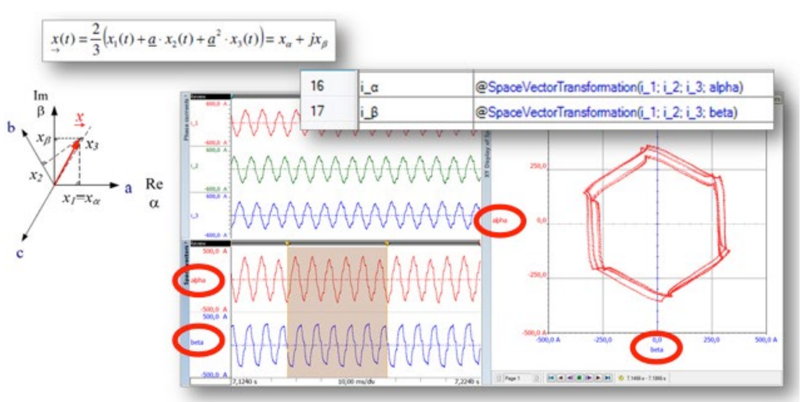

Figure 11. *Currents i1, i2, i3 converted to iα and iβ and displayed in a XY plot show system unbalance*

Park (dq0) Transformation

Park or dq0 transformation easily verifies control algorithms and often takes many hours and sometimes days to calculate using a typical analyzer. However, the new test method can calculate and display immediate results, offering a huge savings in both time and money. The resulting id and iq waveforms represent the current components for torque and flux. The 0 (zero) component is a measure of the symmetry and balancing of the system. If the motor is fully balanced, the 0 (zero) component is zero. This makes it easier to verify control algorithms because inverters make decisions based on the id and iq results and the inverter electronics converts these to voltages and currents sent to the motor that the test tool has measured. This helps inverter algorithm engineers understand what they have sent to the motor and what the motor actually did. They can now improve the algorithms trying to achieve better results, thus improving the efficiency.

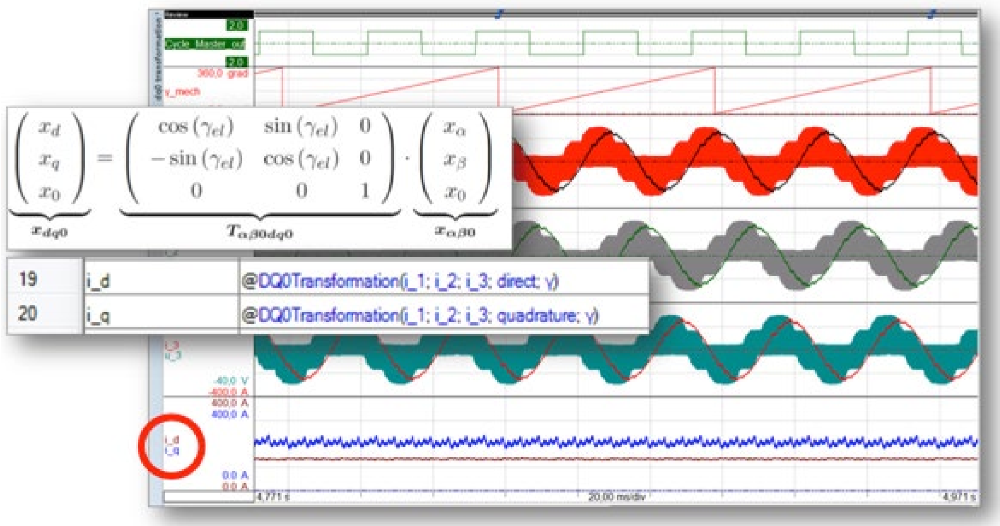

Figure 12. *Park or dq0 transformation can be done in real time instead of hours or days*

Conclusion

The previously described new efficiency testing method identifies a revolutionary tool offering significant savings in time and cost while greatly accelerating the ability to analyze electrical motors, inverters and drive trains with any type of rapid analysis in a matter of seconds rather than hours or days. As a result, this makes it possible to clear the way for even more efficient electric motors, inverters and drive trains at a rapid rate, thereby boosting productivity, capability and research and development in every application that incorporates an electrical machine that is inverter driven or contains a variable speed drive.

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