Implementing Motor Control with Predictive Maintenance Using the Lattice Automate Solution Stack

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Introduction

Many companies in the industrial equipment market are looking to leverage artificial intelligence (AI) and machine learning (ML) to help minimize the frequency of unplanned service outages that affect products, production lines, and services. The reason for this is readily apparent: reducing unplanned downtime increases operational efficiencies and helps maximize profitability. According to a 2016 research report from analyst firm Aberdeen, the average cost of one hour of downtime for businesses is $260,000[1]. By adding intelligence to industrial systems that can measure and analyze performance data, OEMs can help customers implement predictive maintenance (PDM) systems to help identify and replace faulty system components (like electric motors used in industrial robots) before they fail and interrupt production.

To help industrial equipment OEMs implement PDM capabilities in their products, Lattice Semiconductor developed the Lattice Automate™ solution stack for industrial automation. Lattice offers a variety of low power field programmable gate arrays (FPGAs), which are reprogrammable chips that can perform the data processing and/or co-processing needed to drive AI/ML inferencing models that inform PDM applications. To simplify and accelerate development of PDM systems based on Lattice FPGAs, the Automate stack includes software tools, industrial IP cores, modular hardware development boards, and software-programmable reference designs and demos to make it easier to design applications like scalable multi-channel motor control with PDM. Figure 1 is an example of a motor control system with predictive maintenance based on the Lattice Automate solution stack.

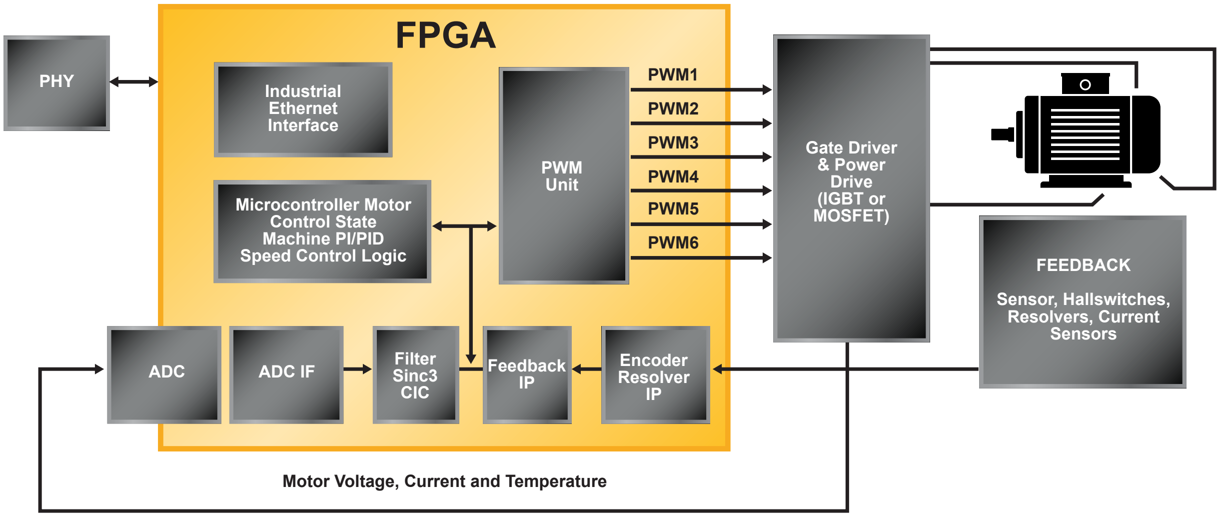

Figure 1: Motor control with predictive maintenance application based on the Lattice Automate solution stack for industrial automation applications

The Automate stack includes a multi-channel motor control with a PDM reference design that uses an industry-accepted technique of Motor Current Signal Analysis (MCSA). In Lattice's solution, the well-known Clarke transform converts the currents from a three-phase motor into two signals. The transformed currents become the alpha current and beta current. For a healthy motor operating normally, the alpha and beta currents are 90 degrees apart and when plotted onto the x-y plane, the locus of points constructs a circle. In the following sections, we will show various circle deformations that result from unbalanced currents or an unbalanced load.

A three-phase brushless DC (BLDC) motor is driven using a sensorless Space Vector Pulse Width Modulation (SV_PWM) technique implemented in the RTL of the FPGA. The SV_PWM control signals drive the Trenz TEP0002 motor driver board that implements Hall current sensors in line with the motor connections to sense the motor winding currents. The onboard ADCs digitize the output of the Hall current sensors so the reference design can read and control the ADCs for both motor control and PDM. Currents are sampled at the rate of 0.8 mega-samples-per-second (MSPS).

Using the Clarke transform (Eq. 1) the three (A, B, and C) phase currents (Figure 2) produce the alpha (α) current and beta (β) current as shown in Figure 3.

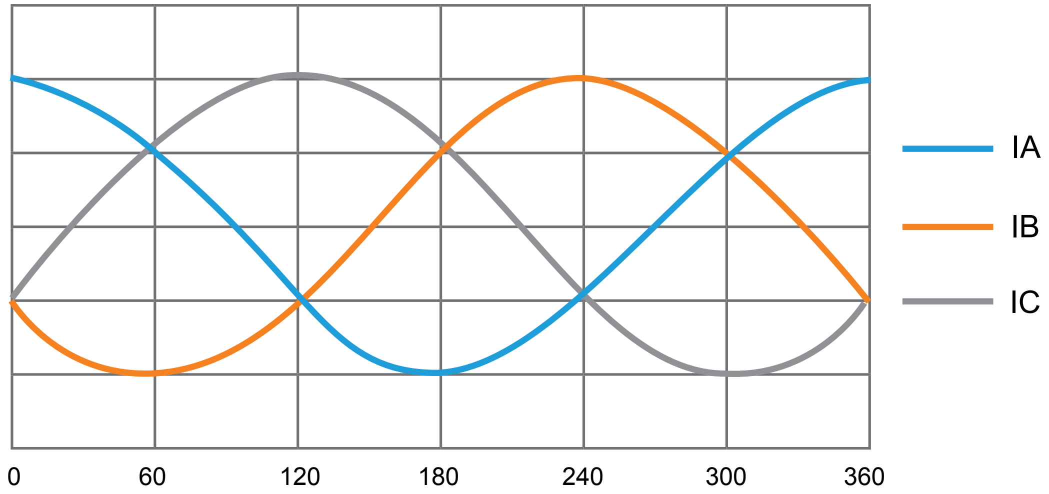

Figure 2: Three Phase Motor Currents (I_A, I_B, and I_C)

$$I_\alpha = \frac{3}{2} I_A \qquad \text{Eq. 1.a}$$

$$I_\beta = \frac{\sqrt{3}}{2} I_B - \frac{\sqrt{3}}{2} I_C \qquad \text{Eq. 1.b}$$

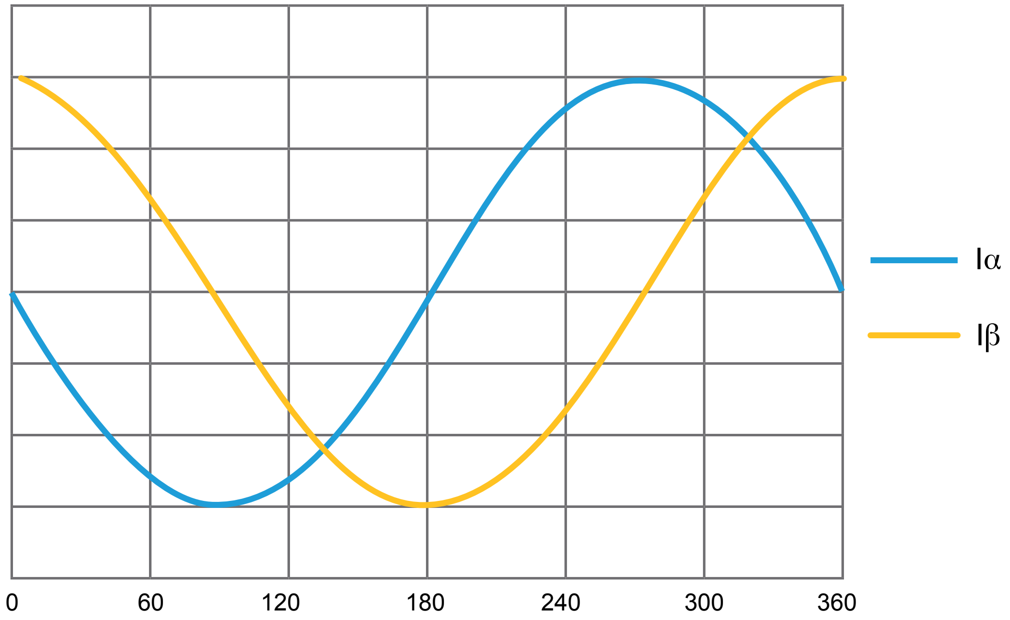

Figure 3: Clarke Transform Output I_α and I_β

Close examination of I_α and I_β shows they resemble the cos and sin functions. In fact, when they are plotted against each other on the x-y plane, the result is a circle (Figure 4).

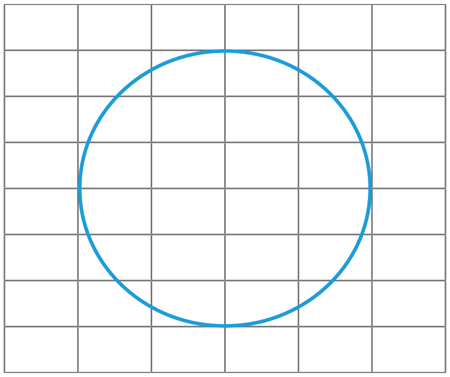

Figure 4: X-Y Plot of I_α and I_β

The reference design can capture a snapshot of the motor winding currents for a fixed number of shaft rotations (the default is a snapshot of 50 rotations) or for a much longer period of time based on user selections. The signal processing of the motor currents includes a peak-detect and normalization along with a moving average filter before applying the Clarke transform. This auto-scaling feature accommodates a wide range of motors and power levels for PDM.

The Lattice Automate stack's PDM solution includes a proprietary algorithm that folds the circular data (shown in Figure 6) into a smaller data set that has a higher concentration of features before processing it with the PDM AI engine. The PDM AI engine has been trained with over 10,000 models of both good and bad motor data.

Bad Motor Data Type 1 – High Current Winding

This data set represents early motor failure due to an overheated or burned out motor winding. Typically one winding will fail before the other two, either due to manufacturing tolerances or motor driver failure. This failure mode is easily simulated by placing resistors in series with the two "good" windings. Figure 5 shows the setup to simulate a motor with a "short" in winding A. Figure 6 shows both the folded and raw images that result from this scenario. The circle has deformed into an ellipse with the major axis along the x-axis. Table 1 summarizes the resulting deformations from high currents in any of the motor windings.

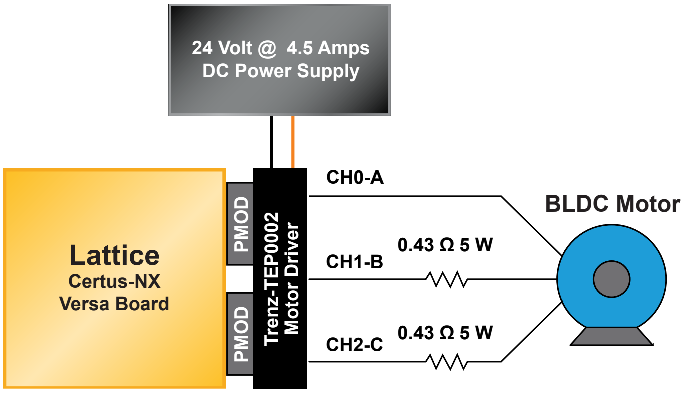

Figure 5: Motor High Current in Winding A

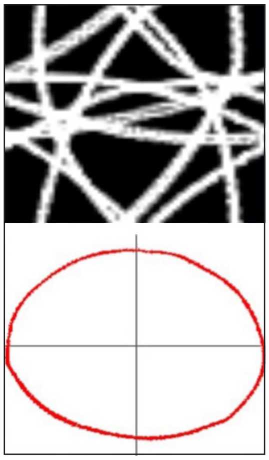

Figure 6: PDM Images of Motor with High Current in Winding A (Bad_Robot_D.jpg)

Winding with High Current	Resulting $I_\alpha - I_\beta$ Plot
A	Ellipse at 0°
B	Ellipse at 45°
C	Ellipse at 135°

Table 1: PDM Image Summary from Motor Winding Short

Bad Motor Data Type 2 – Low Current Winding

Several situations can cause a single winding to have low current. For example, the connections in a high powered motor could become corroded or loose resulting in an I-R voltage loss before the power reaches the motor winding. Also, two windings may start to fail before the third or the motor driver weakens during one of the phases. Again, we can simulate this type of failure by placing a resistor in series with the "bad" motor lead as shown in Figure 7. Figure 8 shows how the circle has deformed to an ellipse with the major axis at 135 degrees. Table 2 summarizes the resulting deformations from low currents in any of the motor windings.

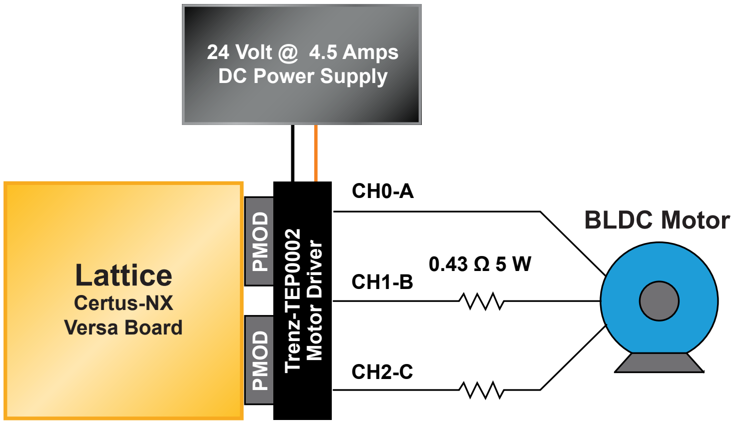

Figure 7: Motor High Impedance in Winding B

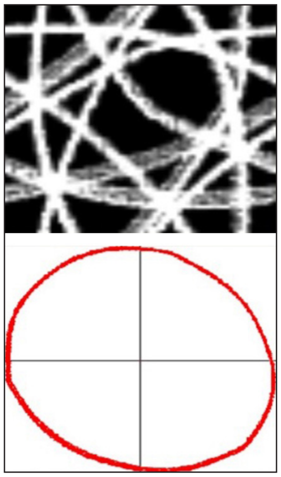

Figure 8: PDM Images of Motor with Low Current in Winding B (Bad_Robot_B.jpg)

Winding with Low Current	Resulting $I_\alpha - I_\beta$ Plot
A	Ellipse at 90°
B	Ellipse at 135°
C	Ellipse at 45°

Table 2: PDM Image Summary from Motor Winding Low Current

Bad Motor Data Type 3 – Unbalanced Load

This third type of failure also uses MCSA to detect an unbalanced mechanical load on the motor. With an unbalanced load, the rotational inertia is not aligned and wobbles around the rotor shaft (similar to a spinning top wobbling before falling down). As the moment of inertia wobbles around the motor shaft, the windings pull more or less current synchronous to the wobble and not the motor RPM. To simulate this condition, an unbalanced flywheel is secured to the motor shaft and data is collected after the motor has reached operational speed. Figure 9 shows the resulting PDM images from a motor with an unbalanced load. The same types of images can also result from a power supply with regulation issues.

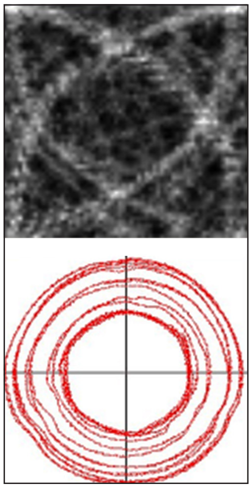

Figure 9: PDM Images of Motor with Unbalanced Flywheel

Good Motor Data - Balanced Load and Balanced Currents

So what constitutes a good motor signature? Figure 10 shows the PDM images obtained from a motor without any added resistors and a balanced flywheel. There are some slight deviations from a perfect circle around 60°, 170°, and 290° (roughly 120° apart). These are the result of the overlap of the SV_ PWM commutation from one phase to the next.

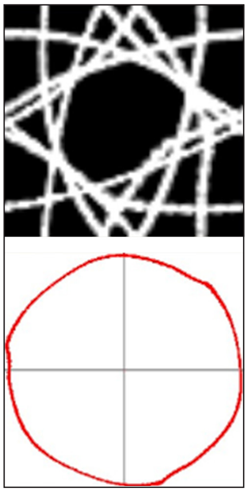

Figure 10: PDM Images of Motor with Balanced Currents and Load

Conclusion

Predictive maintenance for industrial motor control systems can provide significant savings by minimizing system downtime caused by unexpected failures. The Lattice Automate solution stack features the hardware and software components needed to quickly and easily implement PDM using an industry standard MCSA solution for the BLDC motors commonly used in many industrial applications, including robotics.

Reference

[1] https://www.stratus.com/assets/aberdeen-maintaining-virtual-systems-uptime.pdf

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