Oregon State University Solar Vehicle Team: Troubleshooting Three Phase Permanent Magnet AC Motor Using Tektronix MSO2024 Oscilloscope

by

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INTRODUCTION

The Oregon State University Solar Vehicle Team (OSUSVT: www.osusvt.org) is a group of Oregon State University students, staff, and faculty working together to design, build, and race solar-electric vehicles. To prove the viability of these vehicles, the team competes in two international races hosted by the Innovators Education Foundation: the Formula Sun Grand Prix and the biennial American Solar Challenge (www.americansolarchallenge.org). This paper will describe the specific electric motor problems experienced by the team while detailing the troubleshooting process. A description of each test will be included along with the purpose and results.

FIGURE 1: PREPPING THE PHOENIX TO RACE DURING THE 2013 FORMULA SUN GRAND PRIX

DESCRIPTION OF THE PROBLEM

The team's third solar vehicle, the Phoenix, uses an NGM SMC150 3-phase permanent magnet AC hub motor designed specifically for solar vehicle use. With this motor, the Phoenix is able to reach a top speed of 84mph and sustain speeds of around 35-45mph while consuming about the same power as a toaster. The motor is controlled by an NGM EVC402 motor controller. This motor controller is responsible for interpreting input from the pedals and controlling the power output to the motor. Hall-effect sensors inside the motor are used as a magnetic encoder to identify the rotor's current position.

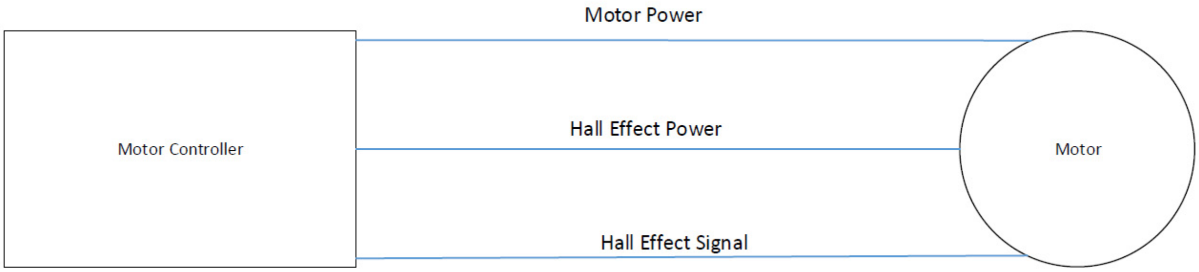


FIGURE 2: BLOCK DIAGRAM OF MOTOR SYSTEM

In 2013, the team's motor began having problems with commutation and torque production. When high torque was commanded by the accelerator the motor would have mechanical torque pulsations and highly audible vibrations described by the drivers as a loud "ka-chunka-chunka-chunka." This also happened when reverse torque was demanded during regenerative braking. The Tektronix MSO2024 oscilloscope was used to determine that the fault occurred during high motor current events when noise began to affect the hall-effect signals used for commutation.

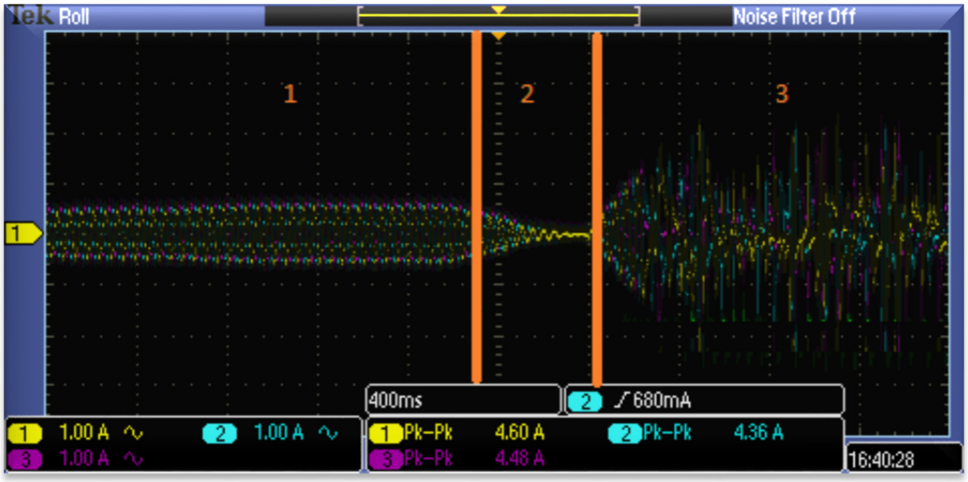


FIGURE 3: MOTOR BEHAVIOR DURING NORMAL OPERATION (1), NON-REGEN BRAKING (2), AND HIGH TORQUE DEMAND (3). CHANNELS 1-3 ARE MEASURING THE CURRENT IN THE POWER LINE OF EACH PHASE.

EXPERIMENTAL SETUP

To narrow down potential issues, the team's MSO2024 was set up to measure the hall-effects' voltages and the motor's current. The coupling was set to DC and the attenuation of the scope was set to 10X for voltage probes and 1X for current. The team had two test setups, one to check behavior under no load and another to test the behavior in normal driving conditions. For the first setup the vehicle was elevated so that the back wheel, with attached motor, was not touching the ground as it spun (Figure 4). During these tests the team looked at the hall-effect signals, examined our motor back EMF, and checked for shorts in our stator windings. The second setup utilized the scope during normal driving conditions (Figure 5). This setup focused on examining the behavior of the hall-effect signals. Auxiliary power packs were used to power the oscilloscope in order to eliminate a ground feedback loop that caused significant noise in our initial tests.

FIGURE 4: TESTING MOTOR BEHAVIOR UNDER NO LOAD

FIGURE 5: TESTING MOTOR BEHAVIOR UNDER NORMAL DRIVING CONDITIONS

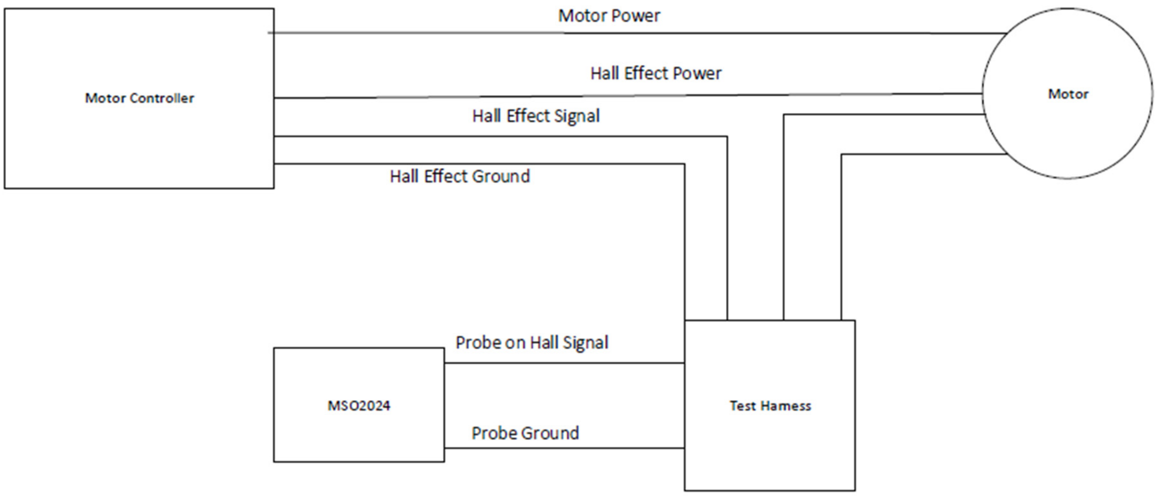


FIGURE 6: BLOCK DIAGRAM OF HALL-EFFECT SIGNAL TESTING SETUP

EXPERIMENTAL PROCEDURE

The first step was to identify situations that induce an event. During the first test setup, with the vehicle elevated, the team noticed that pushing the pedal past a certain point caused an event. However, if the pedal was compressed to just before this point the motor would accelerate normally up to maximum speed no matter how quickly the pedal position changed. This led the team to the conclusion that speed was not a factor, but perhaps torque was. To test this theory, the team reprogrammed the motor controller to request a flat 50% torque across all pedal compressions. At this point the motor would work perfectly. Further experimentation with the motor controller allowed the team to determine that anything above 78% torque would cause an event.

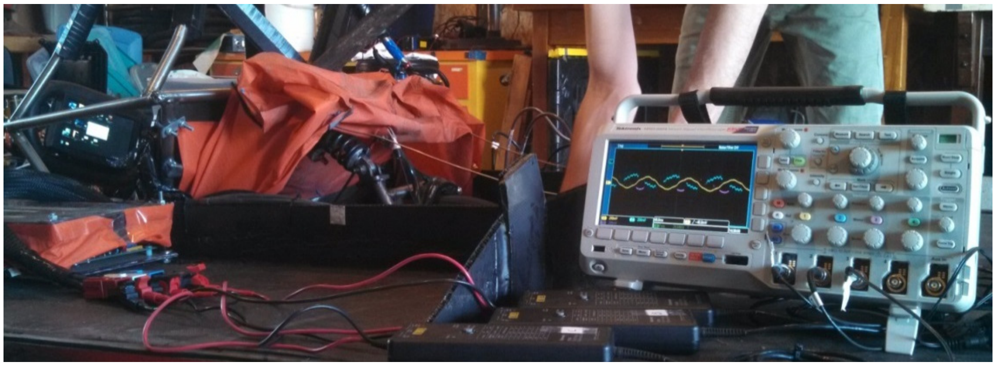


FIGURE 7: TYPICAL SETUP USED DURING TESTS CHECKING BACK EMF AND MOTOR CURRENT

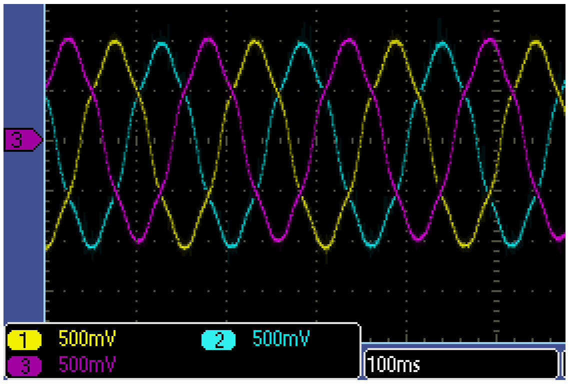


FIGURE 8: NORMAL BACK EMF. PROBES 1-3 ARE MEASURING THE VOLTAGE BETWEEN EACH PHASE (V_{AB}, V_{BC}, V_{AC})

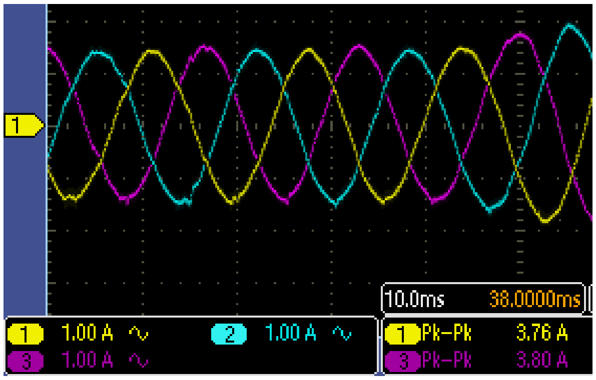


FIGURE 9: NORMAL MOTOR CURRENT. PROBES 1-3 ARE CONNECTED TO EACH MOTOR PHASE

To rule out mechanical issues as a source of the problem, the motor was disassembled, physically examined, and the bearings replaced. After this, the team tested the motor's back EMF. To do this the team detached the motor from the motor controller and connected voltage probes to the power line of each phase. The motor was then manually spun to induce a magnetic field in the stator which in turn produced voltage waveforms that could then be read by the MSO2024 (Figure 7). The resulting waveforms (Figure 8) indicated that the permanent magnets were good and this was not a mechanical issue. Next, the team examined the motor phase currents to check for hard shorts in the stator windings; however normal current waveforms ruled out that possibility (Figure 9).

With mechanical issues ruled out, the team moved on to examine the hall-effect signals which serve as magnetic encoders for commutation. Testing under normal driving conditions showed that the hall-effect waveforms would deform wildly during motor events (Figure 10). To determine if there was an issue with the hall-effect sensors themselves the team examined each hall-effect output signal as the motor was manually spun. Even at relatively high speeds the hall-effect waveforms were perfectly formed (Figure 11), indicating that the hall-effect issue was a symptom, not a cause.

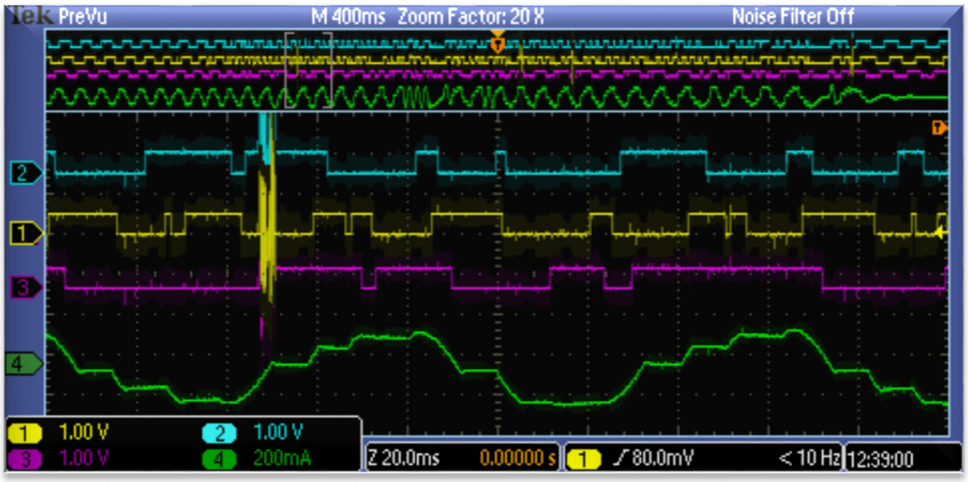


FIGURE 10: ERRATIC HALL EFFECT SIGNALS DURING MOTOR EVENTS. PROBES 1-3 ARE CONNECTED TO THE HALL-EFFECT SIGNAL LINES WHILE PROBE 4 SHOWS THE PHASE CURRENT.

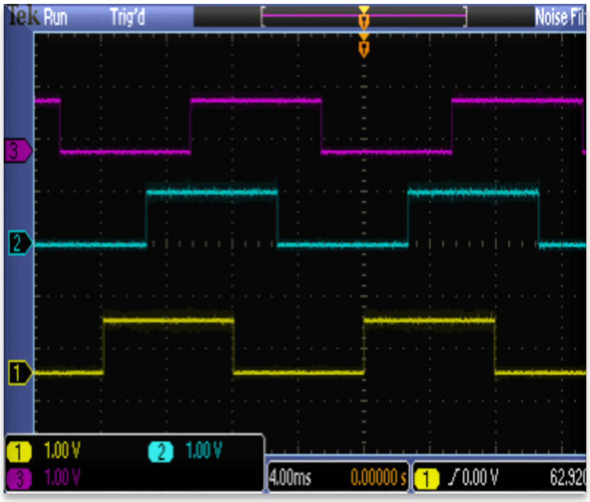


FIGURE 11: HALL EFFECT SIGNALS WHEN MOTOR WAS MANUALLY SPUN

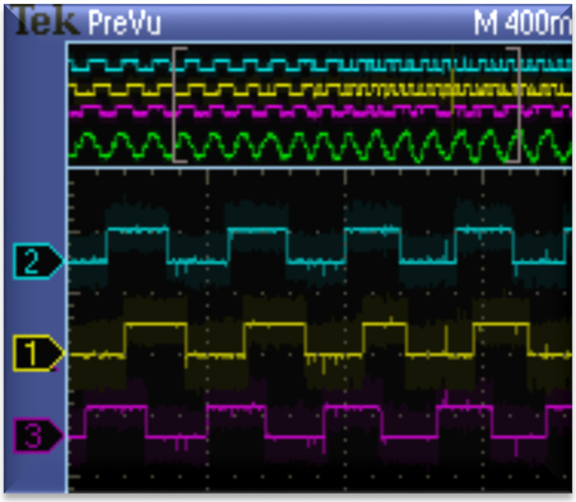


FIGURE 12: HALL EFFECT SIGNALS WITH MOTOR POWERED UNDER NORMAL DRIVING CONDITIONS

In order to gain a close up look at the observed behavior, the team utilized the MSO024's ability to capture data over a relatively large time interval and zoom in to time spans of 0.2 seconds. Comparing the waveforms while the motor was being manually spun (Figure 11) and waveforms while the motor was being powered (Figure 12) revealed significant noise in the hall-effect sensor output during normal operation. The team prototyped a low-pass filter (Figure 13) and placed it on the hall-effect output to try and reduce the noise.

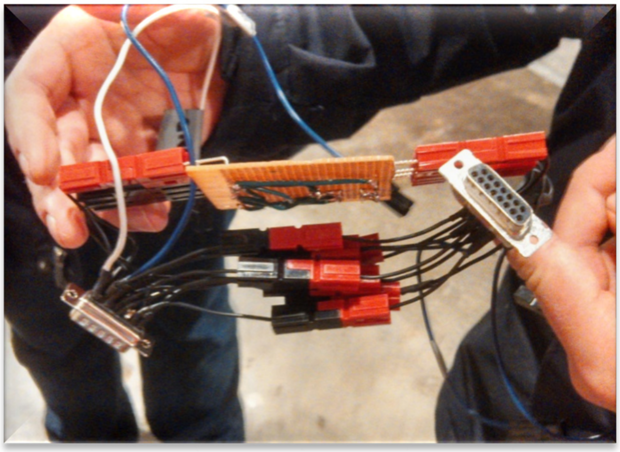


FIGURE 13: LOW PASS FILTER TO ELIMINATE HALL EFFECT SIGNAL NOISE

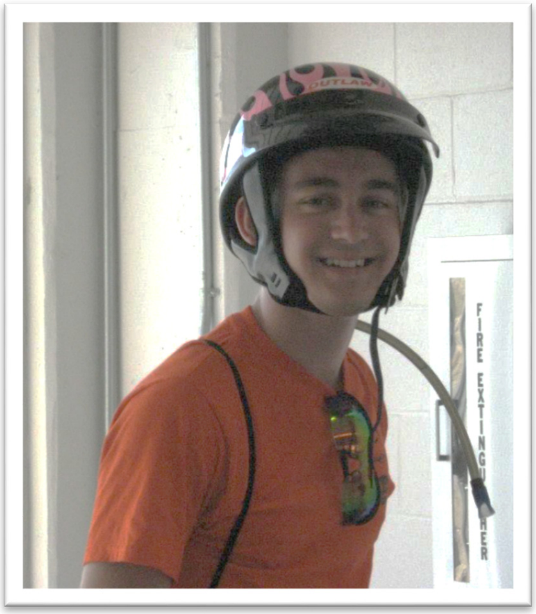
FIGURE 14: CHARGE DELAY DUE TO LOW PASS FILTER ON HALL EFFECT SIGNAL LINE

The low pass filter successfully attenuated the excess noise which noticeably improved the motor's operation. However the filter introduced an undesirable side effect. The time delay caused by the charging capacitors (Figure 14) caused the motor to behave erratically and ultimately rendered the solution ineffective. With the promising results from the low-pass filter it was suspected that there may be noise on the hall-effect power input. To test this theory, decoupling capacitors were installed on each hall-effect power line to filter the DC power signal and attenuate the noise while avoiding issues caused by an in-series filter. Further testing showed a marked improvement with only small capacitor values, and additional parallel capacitance solved the issue entirely.

CONCLUSION

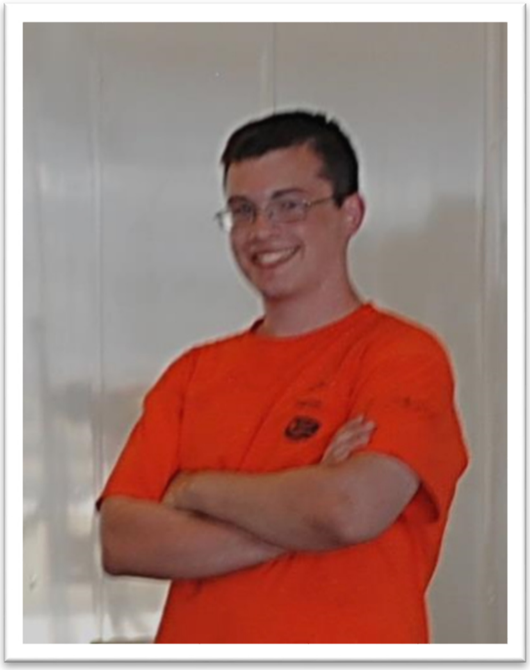
The motor's problems with commutation and torque production were caused by noise on the power lines for the motor's hall-effect sensors. This problem was clearly visible using the MSO2024 and the team would not have been able to solve this issue without it. The oscilloscope allowed the team to rule out mechanical failure as a source of our problem, and saved the motor from being sent in for an expensive refurbishment. By examining the hall-effect signals we were able to observe what was happening inside the motor during each period of violent shuddering and narrow in on the electromagnetic noise that was the culprit. In addition, the MSO2024 was essential to refining the solution by showing how the low-pass filter affected the hall-effect output signal. The oscilloscope's small footprint allows it to fit on a solar vehicle and allows it to be easily transported to international races. In addition, a low power draw allows it to be powered from an onboard inverter.

ABOUT THE AUTHORS



Simon Crocker is the Electrical Team Captain and driver for the OSU Solar Vehicle Team. During the 2013 Formula Sun Grand Prix, Simon drove the Phoenix to a first place victory on the final day of the event. He is currently pursuing a BS in Electrical and Computer Engineering with minors in Computer Science and Spanish.

Wilkins White is the current Business Captain and former Array Captain of the OSU Solar Vehicle Team. Prior to the 2013 Formula Sun Grand Prix, Wilkins led the team that upgraded the Phoenix with a hand-soldered and encapsulated 22.5% efficient solar array. Wilkins is currently pursuing a BS in Electrical and Computer Engineering with a minor in Computer Science.



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