FOCE Motor Stalling Tests June 2011
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02-July-2011

Introduction
Soon after the redeployment of FOCE in May 2011, it was noticed that the aft and forward fan thrusters would drop out under certain operating conditions. Most notable was drop out when both sets were being operated simultaneously. After a few weeks of attempting to control them manually, it was decided that a systematic approach to the problem should be undertaken.

System Background
FOCE was recovered in December of 2010 after a continuous seven month deployment. Due to the time logged on the current motors and controllers and the fact the next deployment in 2011 was scheduled for twelve months on the seafloor, I decided to replace the motors and motor controllers. Simultaneous to this was an overhaul of the drive train system.

I had previously performed an extensive 21-day motor cycle test in October of 2010. This gave me a baseline for variations in actual motor velocity and electrical power required at each velocity and direction. Based on the results of this data, I had determined that the motors were not optimumly tuned. Tuning the proportional and integral gains of the internal current controller are done with ELMO software on shore. Prior to our 2011 redeployment, I spent extra time carefully tuning the motors while at the test tank. While obviously not at the correct depth and pressure, the motors were operated in the tank with no noticeable problems.

The new motors and controllers were tuned for minimal overshoot and minimum steady state oscillations, with emphasis being put on the steady state response. The deployed parameters were Kp=20,000 and Ki = 10,000. The motor acceleration and deceleration were both set to 1000. As before, the ELMO Whistles were operated in Velocity Mode.

System Schematic
The FOCE flume is comprised of three sections: a center experimental chamber, and two path lengthening wings. A motor is mounted at each end, and each motor drives a pair of thrusters. Motor #1 is located at the aft end of FOCE, while Motor #2 is at the forward end.

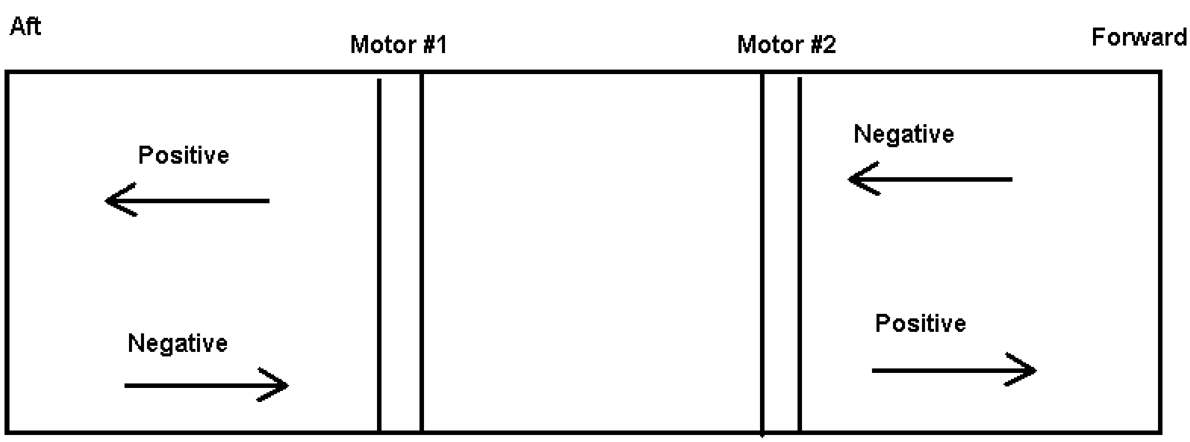

Figure One: Schematic indicating the flow of water current relative to motor spinning directions.

Figure Two: Motor #1 (Aft). The view is looking into the flume.

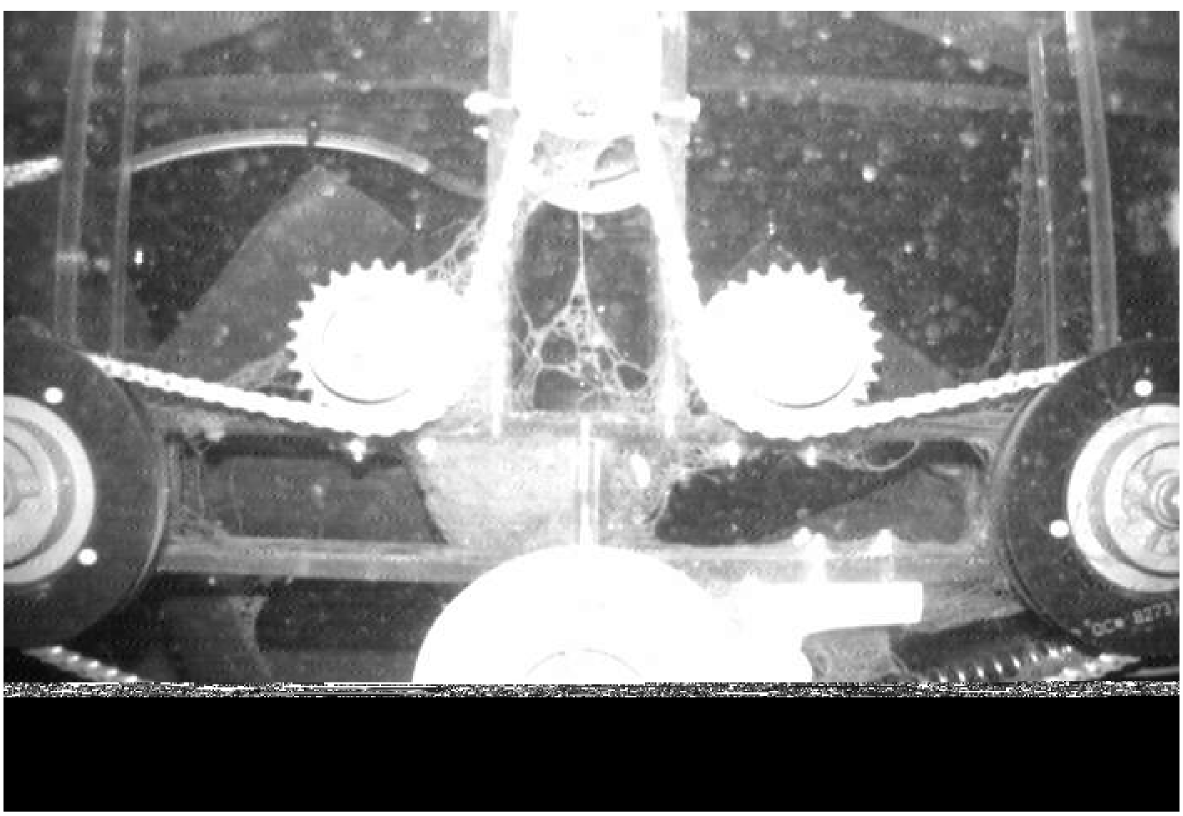

Figure Three: Motor #2 (Forward) looking into the flume.

Description of Malfunction
After deployment, it was soon discovered that commanding a motor to a high velocity from a zero standstill would cause the motor to stall. A solution to this was incrementally increasing the velocity in steps. However, once at the desired velocity, turning on the second set of thrusters would cause either the original motor, or both, to stall. Thinking this might be a transient problem, we left the motor(s) running continuosly. Randomly, one or both motors would stall as well.

Compounding the problem was the fact that one or more hagfish had entered the flume. As has happened on previous deployments, the hagfish got caught in our drive train and caused a partial chain derailment. This, unfortunately, occurred on both sets of thrusters. Thinking this alone may have been our problem, we sent the ROV Ventana down to reattach our chains. After a successful chain repairing dive, it was found that the motors did start operating, but our original problems quickly resurfaced.

Because we had previously filled our Enriched Seawater Distribution System (ESW-DS) with liquid CO2, we decided to take a step back to fully investigate the motor issues in order to conserve the enriched seawater.

Motor Investigation
For four days from June 27th to June 30th 2011, Kent Headley and I performed a series of tests to attempt to isolate the motor problem. As this was being performed remotely, we could not utilizie the Code Composer software from ELMO. At our disposal was the FOCE GUI, RDV, a back door serial console to the ELMO Whistle, an SSH session through Putty.exe, and visual feedback from our two engineering cameras.

Initially, we downloaded all of the programmable variables from the motor controllers and compared them to the previous deployment. The only descrepancies were the Kp and Ki gains and the acceleration (AC) and deceleration (DC). Previously, Kp=12,000 and Ki=40,000 while AC and DC were set to their minimum value of 100. We tried updating our controllers with these values and discovered that the motors ran even worse. The peak-to-peak variation in the motor velocites doubled. We reinstalled our deployed gains and the velocity variations decreased accordingly.

Next, we investigated the error codes we were receiving. Specifically, reading back the SR register indicated an undervoltage condition. An undervoltage condition usually implies some sort of current limiting condition. We then looked into our Continuous Limit (CL) and Peak Limit (PL). As deployed, CL=5A and PL=10A. These limits were set based on the power available from our 36V DC-DC converter and the fuses protecting each of the ELMOs. Believing these two parameters to be at their highest values for safety purposes, we began to lower them in an effort to see either an overcurrent or undervoltage in our monitored SSDS data. While the motors continued to stall out, we saw no indication of any error condition in our logged data.

Eventually, after reading a section in the ELMO Software Manual, it was determined that CL and PL are actually limits for the individual phases currents for the motor. Also, the undervoltage condition is triggered by the motor terminal voltage, not the input bus voltage. Knowing this, we determined that we could easily increase both our continuous and peak current limits. We set CL=10, and PL=20. These are the reccommended maximum values for our particular model.

We then ran the motors at various velocities and noticed a much more consistent operation. We stopped/started the motors a number of times with no failures. We left them both running over night to check for steady state problems. The following morning, both motors were still running.

Systematic Testing
The following day, June 30th, I ran the motors through incrementally increasing velocites through both directions through the flume. I held each velocity for ten minutes before moving on. I used the GUI for the motor commands. Table one displays the results of the tests.

		1728						1729					
M1	M2	Com V	Mean	Var	StdDev	M1 V	M1 I	Com V	Mean	Var	StdDev	M2 V	M2 I
-12	12	-81	-87.96	167.06	12.93	36.25	0.94	81	81.36	15.89	3.99	35.96	0.51
-15	15	-101	-104.23	118.86	10.90	36.25	0.91	101	101.76	9.21	3.03	35.95	0.55
-18	18	-121	-123.73	136.52	11.68	36.25	0.94	121	121.39	9.70	3.11	35.96	0.63
-20	20	-135	-137.41	149.29	12.22	36.24	1.03	135	135.18	7.41	2.72	35.96	0.74
-24	24	-162	-163.43	60.12	7.75	36.24	1.13	162	162.19	9.60	3.10	35.95	0.87
-30	30	-202	-201.99	57.80	7.60	36.23	1.38	202	202.18	13.15	3.63	35.92	1.11
-36 *	36	-243	-244.02	260.63	16.14	36.21	1.41	243	243.60	13.71	3.70	35.91	1.34
-40 *	40	-270	-270.33	224.99	15.00	36.20	1.45	270	270.41	12.58	3.55	35.90	1.47
12	0	81	85.95	216.09	14.70	36.28	0.97	-	-	-	-	35.97	0.10
0	-12	-	-	-	-	36.26	0.51	-81	-87.90	241.15	15.53	35.94	1.14
15	0	101	103.85	135.85	11.66	36.25	1.02	-	-	-	-	35.95	0.76
0	-15	-	-	-	-	36.26	0.42	-101	-105.15	204.05	14.28	35.97	1.03
18	0	121	122.20	176.08	13.27	36.26	1.02	-	-	-	-	35.97	0.48
0	-18	-	-	-	-	36.28	0.43	-121	-123.65	179.27	13.39	35.96	1.00
20	0	135	136.12	95.87	9.79	36.26	1.02	-	-	-	-	35.97	0.40
0	-20	-	-	-	-	36.28	0.42	-135	-137.17	146.61	12.11	35.94	1.13
24	0	162	163.46	72.75	8.53	36.25	1.13	-	-	-	-	35.97	0.44
0	-24	-	-	-	-	36.26	0.34	-162	-163.84	163.12	12.77	35.94	1.21
30	0	202	202.12	120.30	10.97	36.25	1.35	-	-	-	-	35.94	0.38
0	-30	-	-	-	-	36.25	0.35	-202	-202.67	210.68	14.51	35.93	1.36
36	0	243	244.12	126.44	11.24	36.22	1.56	-	-	-	-	35.95	0.38
0	-36	-	-	-	-	36.24	0.42	-243	-244.20	187.27	13.68	35.94	1.61
40	0	270	270.83	160.45	12.67	36.22	1.70	-	-	-	-	35.95	0.46
0	-40	-	-	-	-	36.25	0.41	-270	-271.14	184.33	13.58	35.91	1.73

Table One: Compiled Results

The commanded and measured velocities are in encoder ticks/second. To convert to fan thruster RPMS,

Fan RPM = (10 * counts/sec)/67.5

The 67.5 factor includes both our 15:1 internal gear reduction and the reduction of the drive train itself.

The tests began with Motor #1 in the negative direction, and Motor #2 positive. SIAM instruments 1728 (motor 1), 1729 (motor 2), and 1730 (power monitor) were captured for each of the ten minute cycles. The mean, variance, and standard deviation of each velocity, motor bus voltage, and motor bus current were calculated. Two data sets (when M1=-36 and M2=-40) had temporary stalls. I quickly restarted those motors to capture as much data as possible. The statistics have the stall time removed.

When I changed motor directions half way through the test, I could not get both motors to stay on simultaneously. I attempted this at different velocities to no avail. I decided to run the motors one at a time for this direction.

While this is far from the most exhaustive test of the motors, there are some interesting results in table one. With M1=Neg and M2=Pos, M2 ran considerably quieter. However, M1 seemed to quiet down at -24 and -30. Perhaps this is indicating a mechanical resonance?

With M1=Pos and M2=Neg, all velocity measurements were pretty noisy. Is this due to the direction of the ambient current through the flume? (fighting harder in one direction?). Are the loads and friction in the drive train identical in each direction?

The 36V bus voltage and currents are fairly unremarkable; they're mostly what I expected. However, with M1=Neg, and M2=Pos, the currents for M1 are consistently higher than M1 until the top few velocities. Why is M1 working harder in this case? It's interesting that the velocities for M1 are also noisier at these measurements. I did not capture any live video, but I do remember seeing M1 oscillate more than M2 for these first tests. The SSDS plots for each of the ten minute cycles are included at the end of this report.

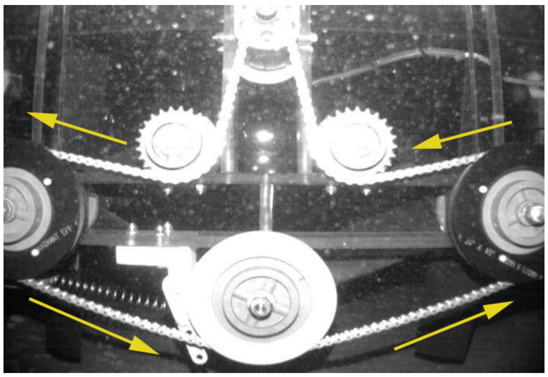

Figure Four: M1 Negative

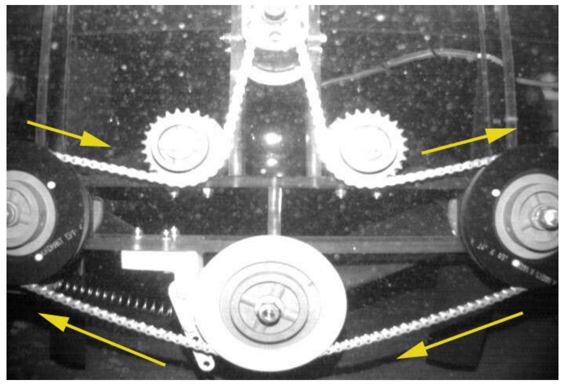

Figure Five: M1 Positive

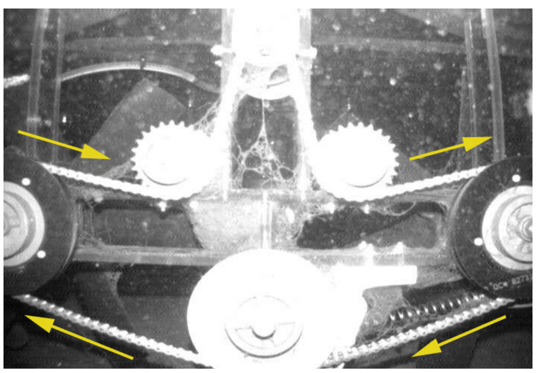

Figure Six: M2 Negative

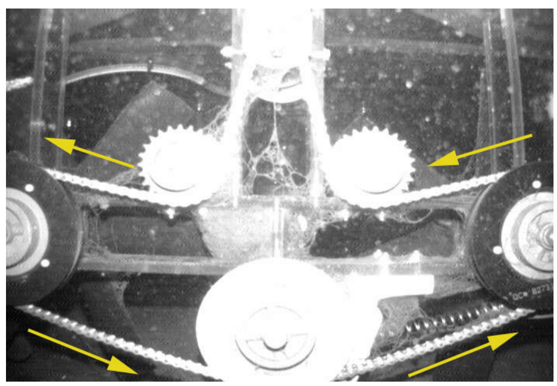

Figure Seven: M2 Positive

Conclusion

As things stand right now, we can operate both motors simultaneously with M1=Neg and M2=Pos. With M1=Pos and M2=Neg, we are limited to one motor or the other. Ed has been running some endurance tests over the July 4th weekend, so the performance of those will need to be studied. The question remains, then, why do the motors work in one direction and not the other. Is this a mechanical limitation based on how things were built? Do the thruster blades experience more load in one direction? It is possible for the Kp and Ki parameters to be adjusted. Doing this in-situ is a bit of a challenge, but we now know the operating points where failure occurs. We can adjust the PI parameters at these points and watch the effects.

Another possible method to overcome our stalling is to change the ELMOs from velocity mode to torque mode. Kent Headley is currently studying this suggestion.

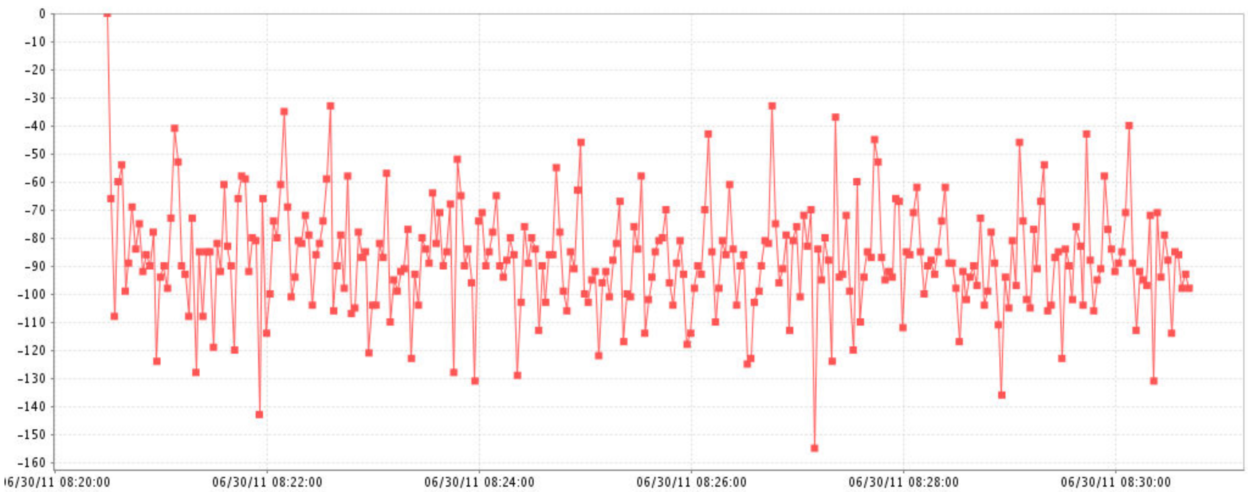

Figure Eight: Motor #1 at -12 RPM (Motor #2 at +12 RPM)

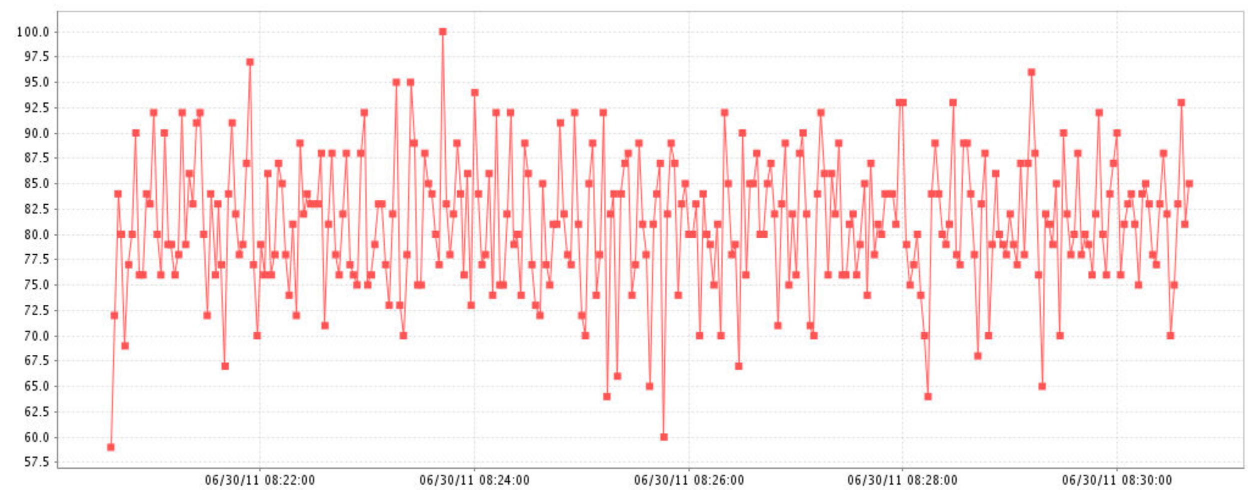

Figure Nine: Motor #2 at +12 RPM (Motor #1 at -12 RPM)

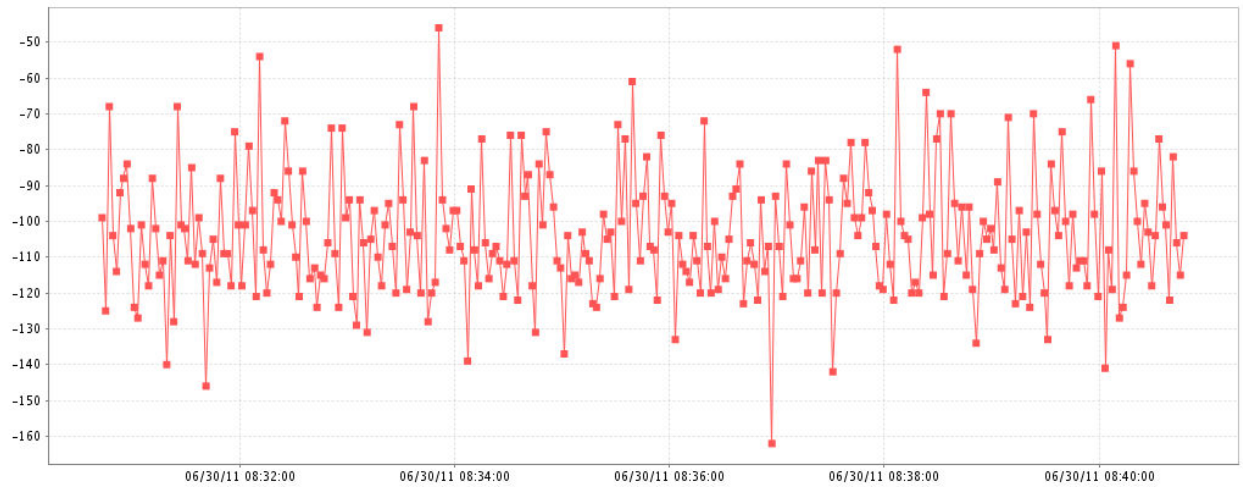

Figure Ten: Motor #1 at -15 RPM (Motor #2 at +15 RPM)

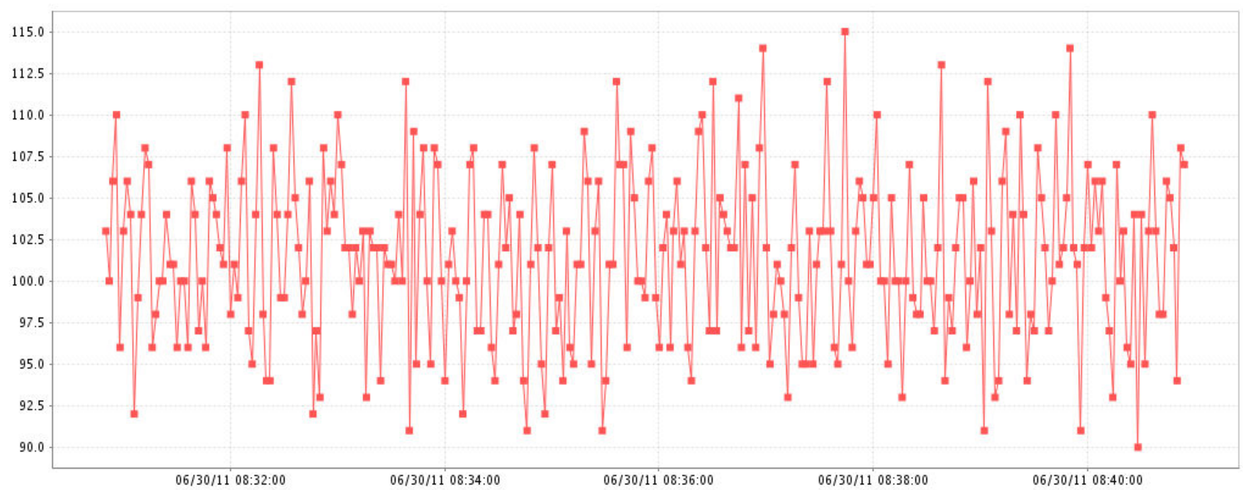

Figure Eleven: Motor #2 at +15 RPM (Motor #1 at -15 RPM)

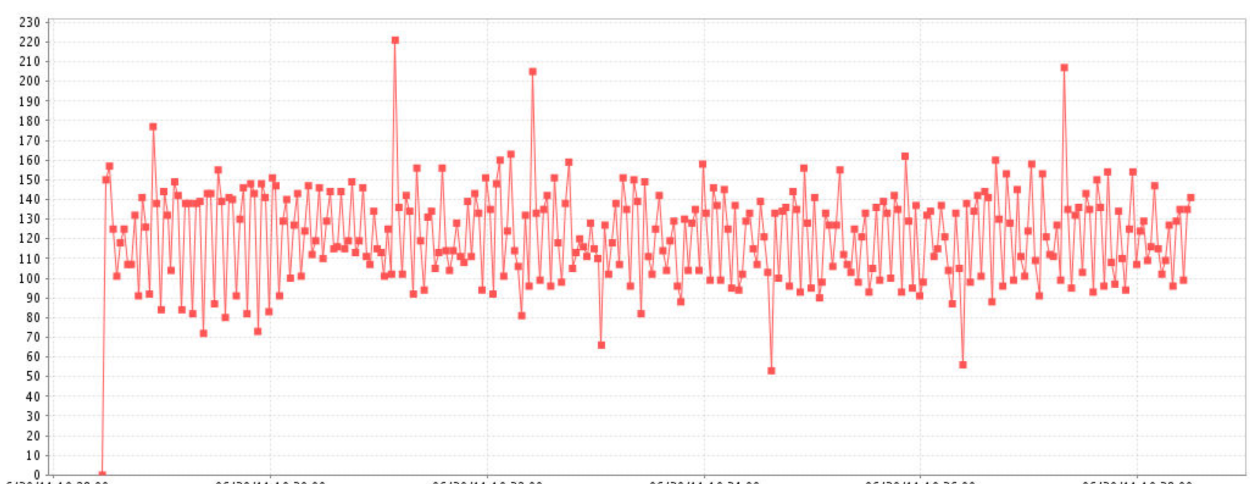

Figure Twelve: Motor #1 at -18 RPM (Motor #2 at +18 RPM)

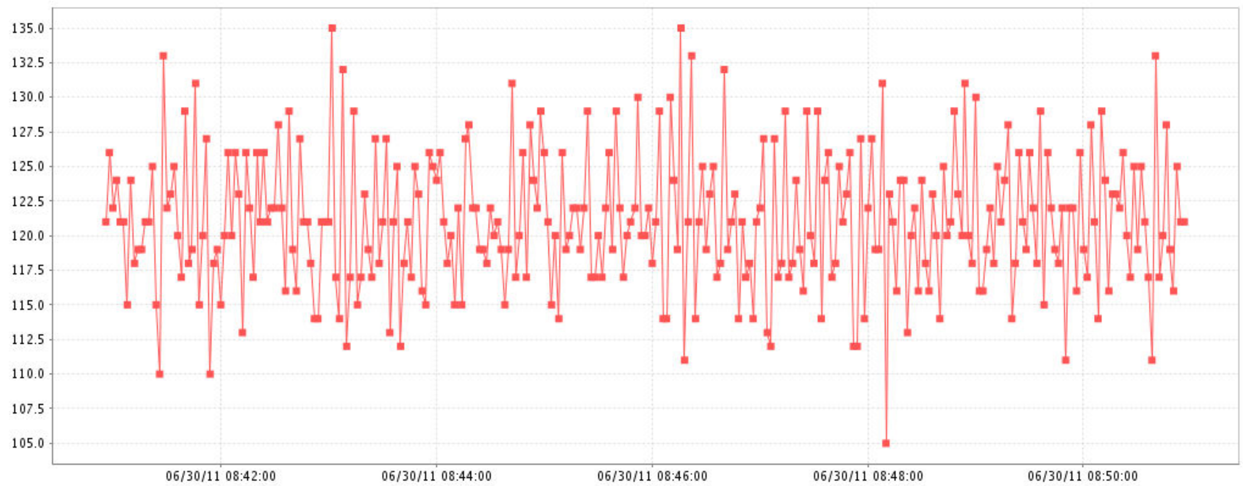

Figure Thirteen: Motor #2 at +18 RPM (Motor #1 at -18 RPM)

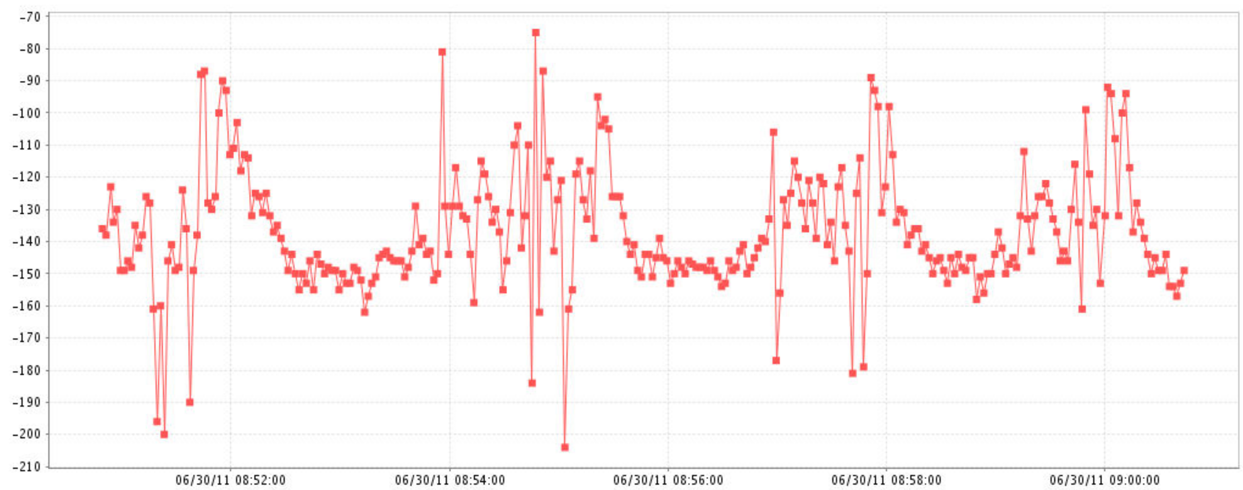

Figure Fourteen: Motor #1 at -20 RPM (Motor #2 at +20 RPM)

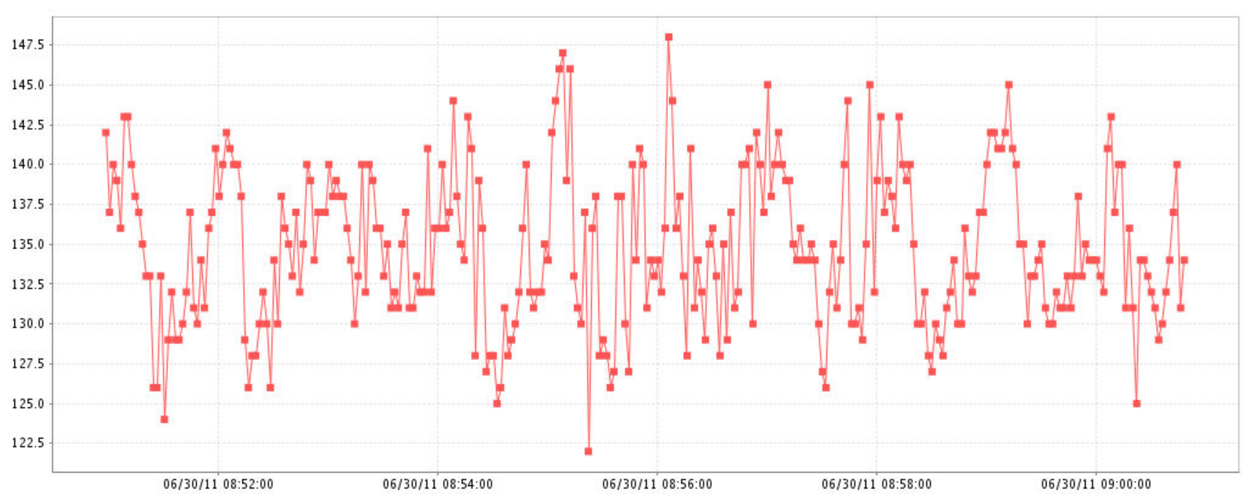

Figure Fifteen: Motor #2 at +20 RPM (Motor #1 at -20 RPM)

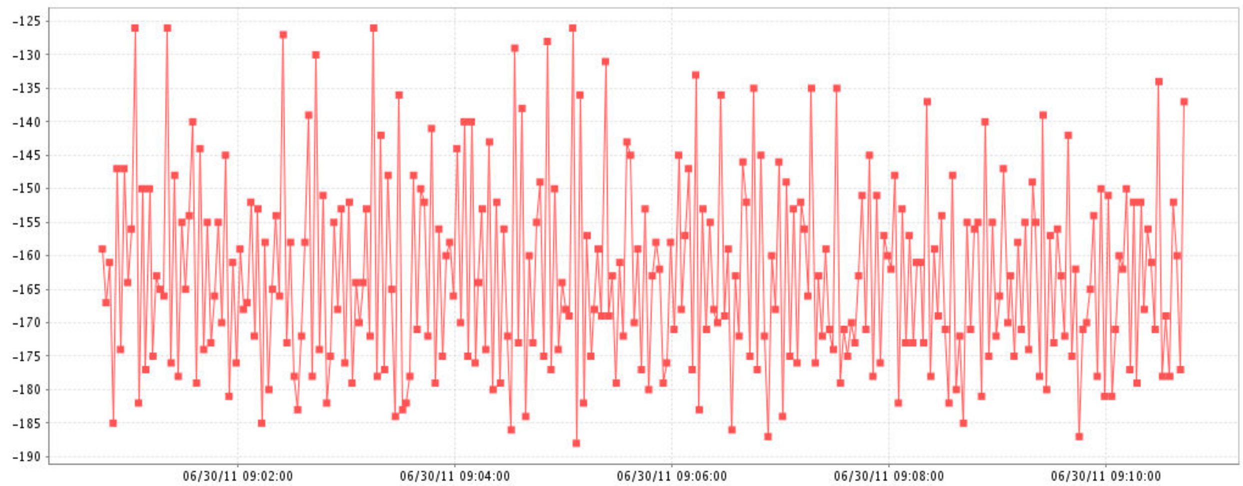

Figure Sixteen: Motor #1 at -24 RPM (Motor #2 at +24 RPM)

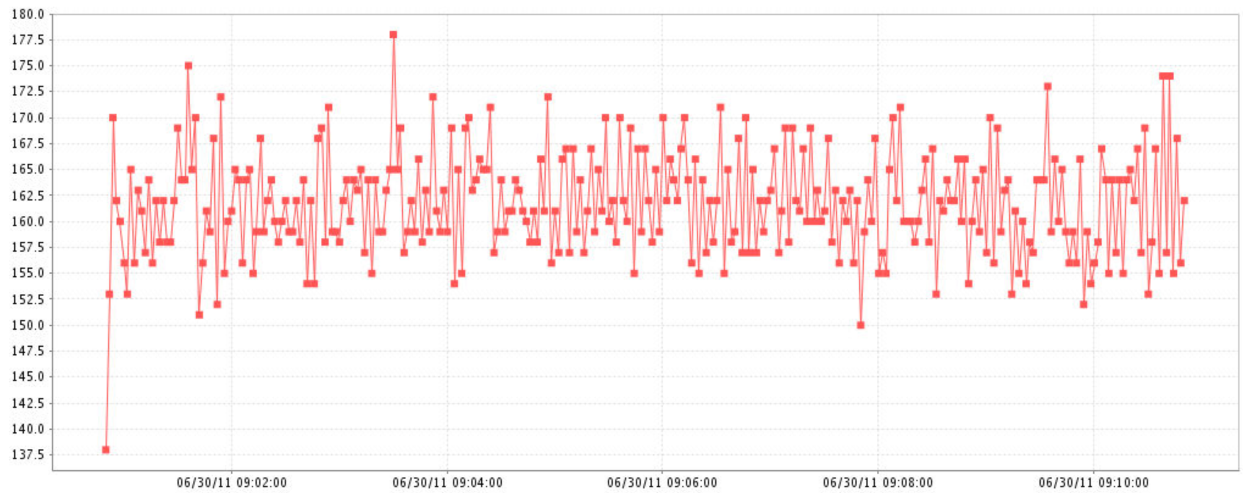

Figure Seventeen: Motor #2 at +24 RPM (Motor #1 at -24 RPM)

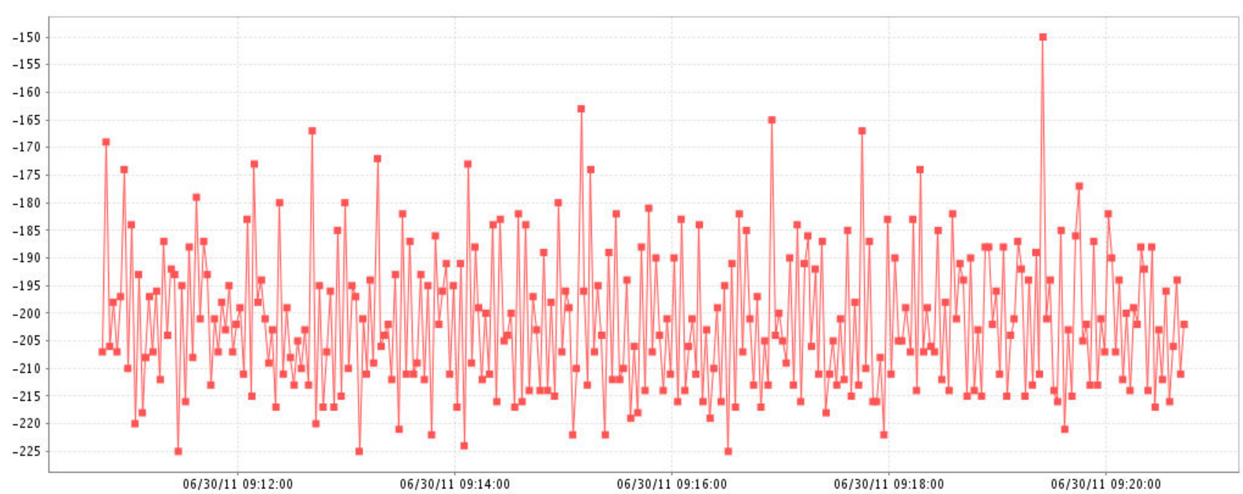

Figure Eighteen: Motor #1 at -30 RPM (Motor #2 at +30 RPM)

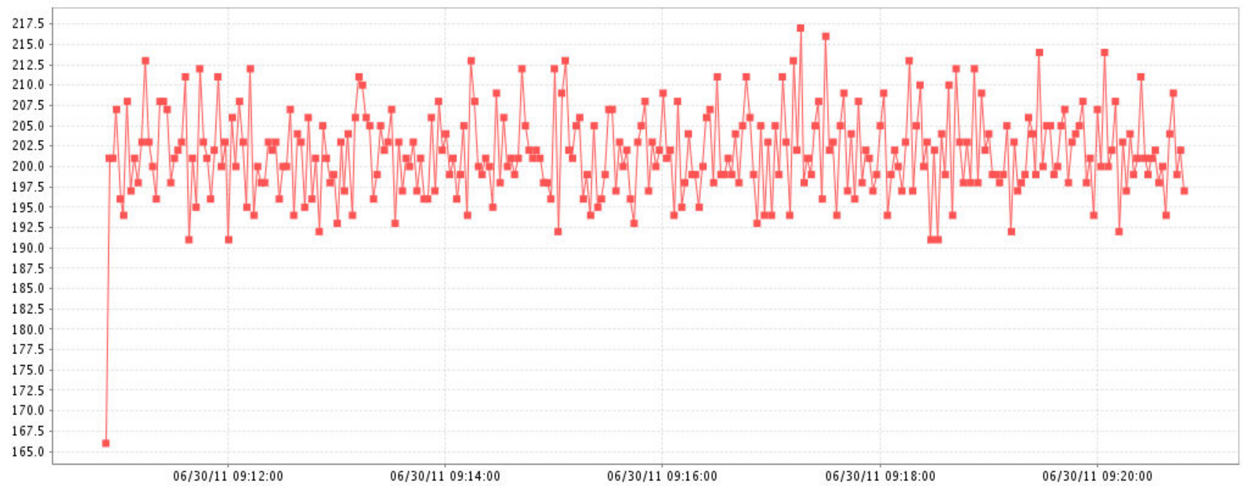

Figure Nineteen: Motor #2 at +30 RPM (Motor #1 at -30 RPM)

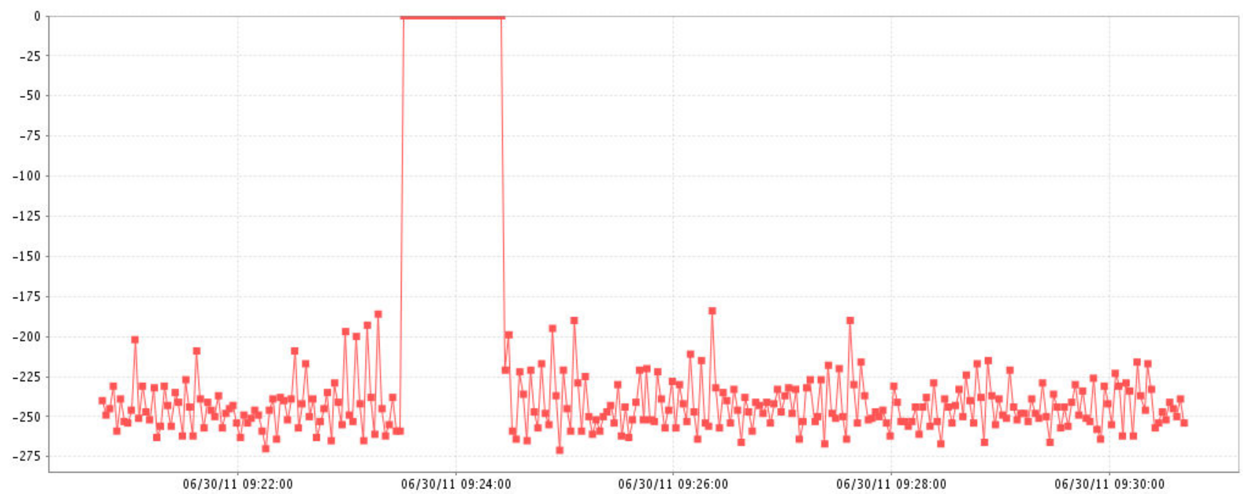

Figure Twenty: Motor #1 at -36 RPM (Motor #2 at +36 RPM)

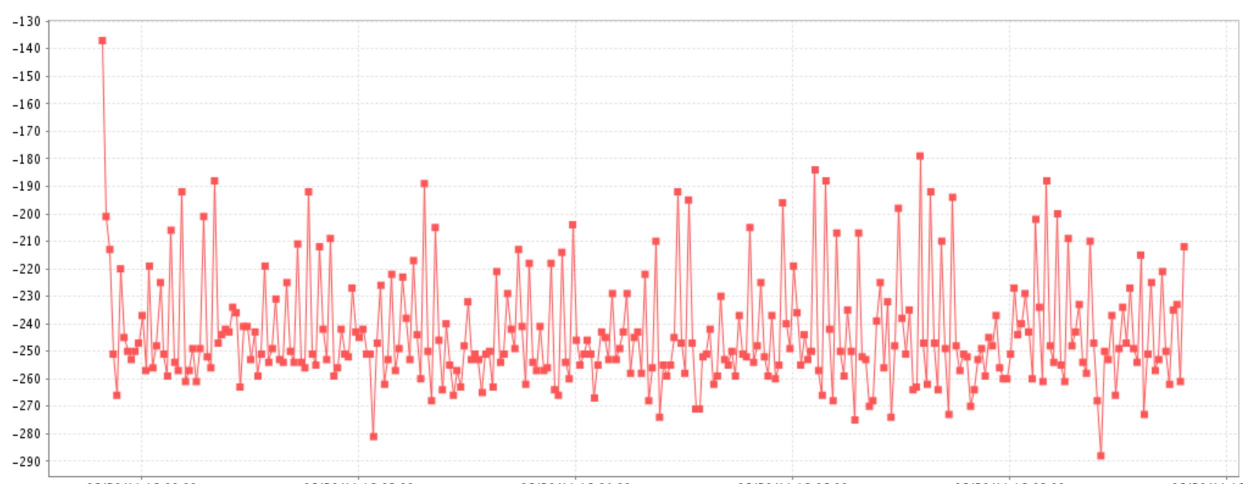

Figure Twentyone: Motor #2 at +36 RPM (Motor #1 at -36 RPM)

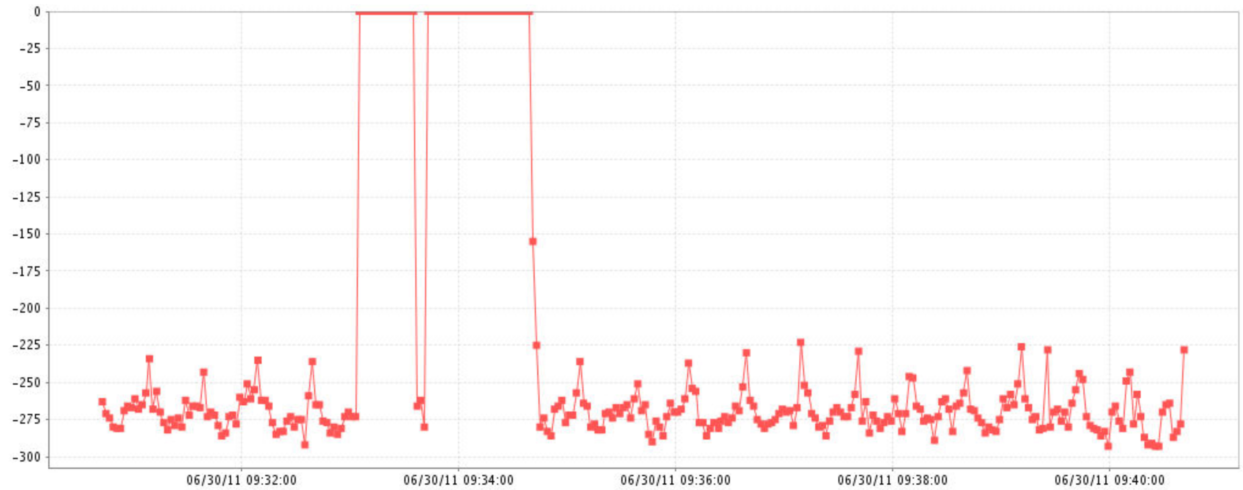

Figure Twentytwo: Motor #1 at -40 RPM (Motor #2 at +40 RPM)

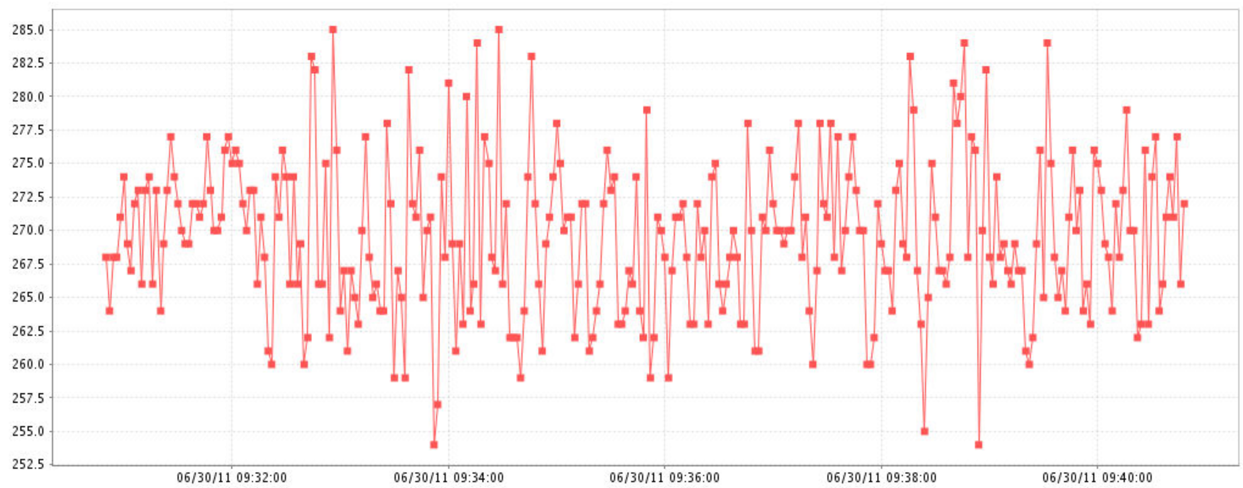

Figure Twentythree: Motor #2 at +40 RPM (Motor #1 at -40 RPM)

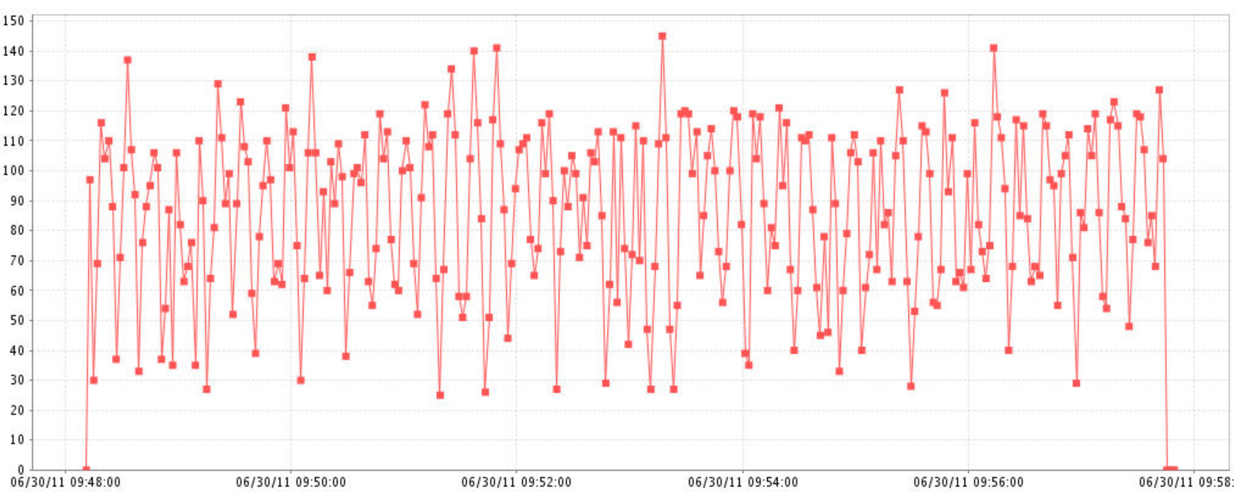

Figure Twentyfour: Motor #1 at +12 RPM (Motor #2 at 0 RPM)

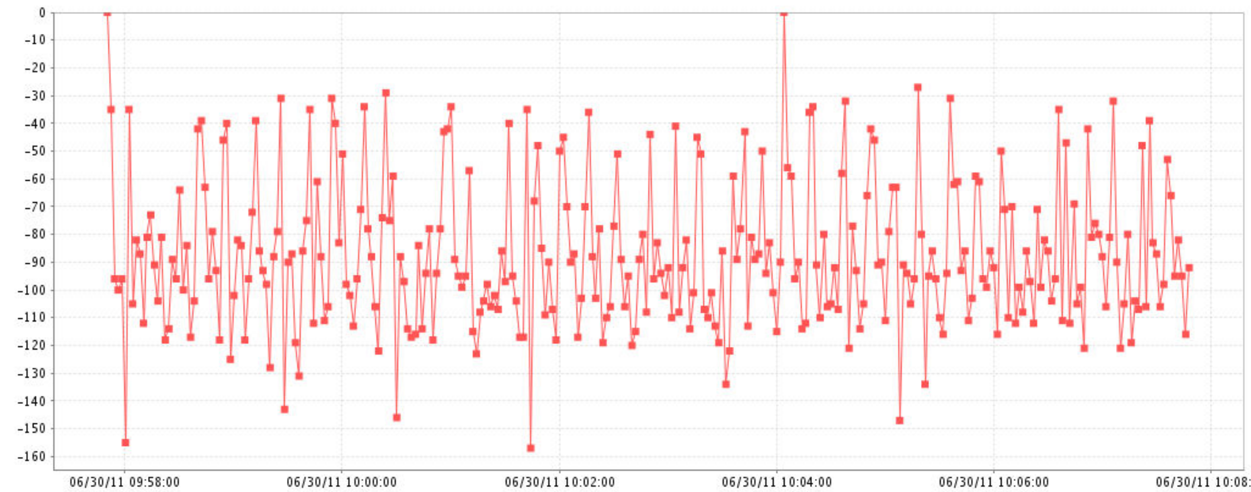

Figure Twentyfive: Motor #2 at -12 RPM (Motor #1 at 0 RPM)

Figure Twentysix: Motor #1 at +15 RPM (Motor #2 at 0 RPM)

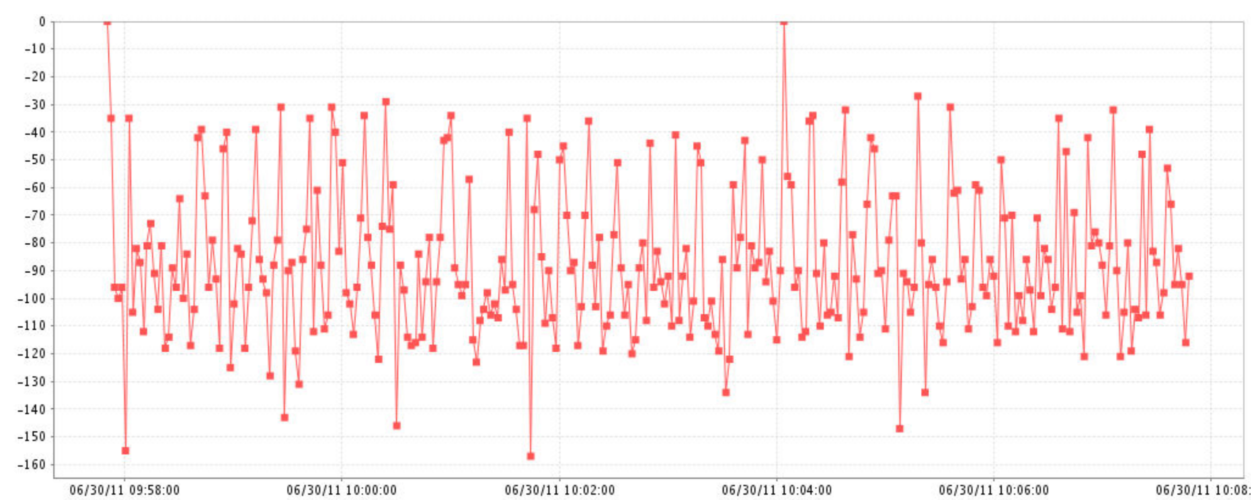

Figure Twentyseven: Motor #2 at -15 RPM (Motor #1 at 0 RPM)

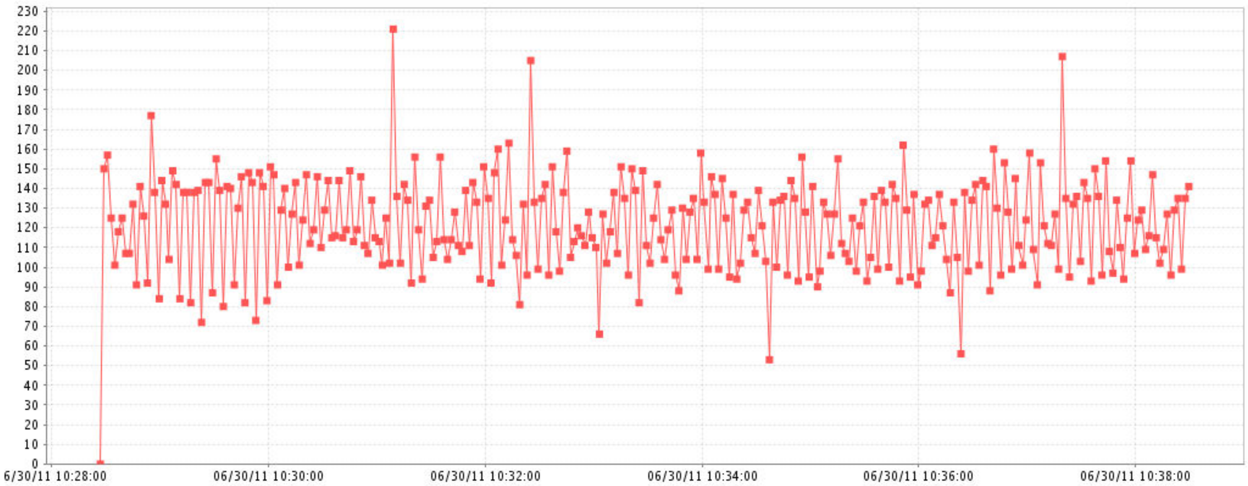

Figure Twentyeight: Motor #1 at +18 RPM (Motor #2 at 0 RPM)

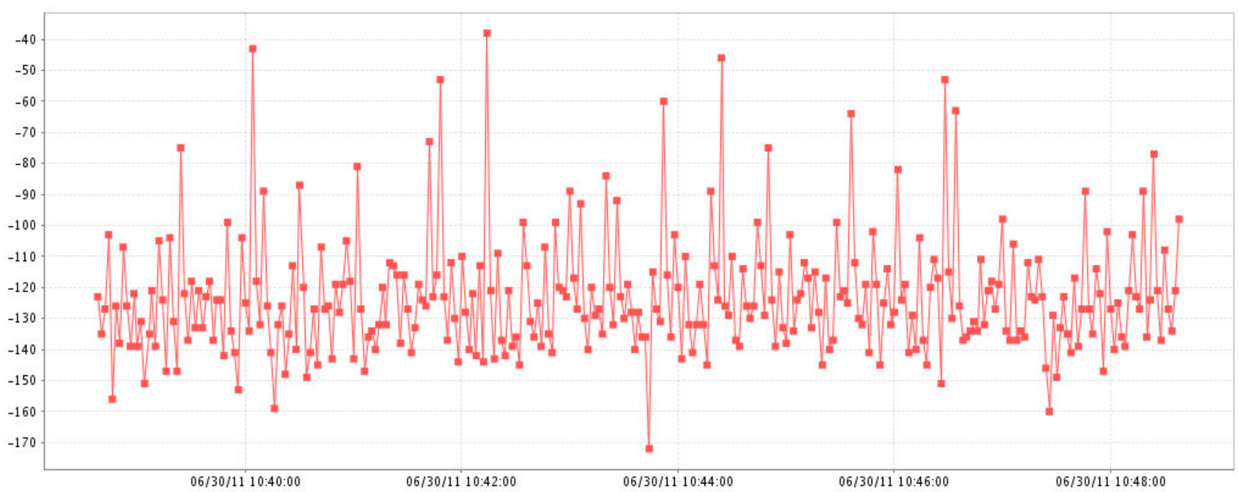

Figure Twentynine: Motor #2 at -18 RPM (Motor #1 at 0 RPM)

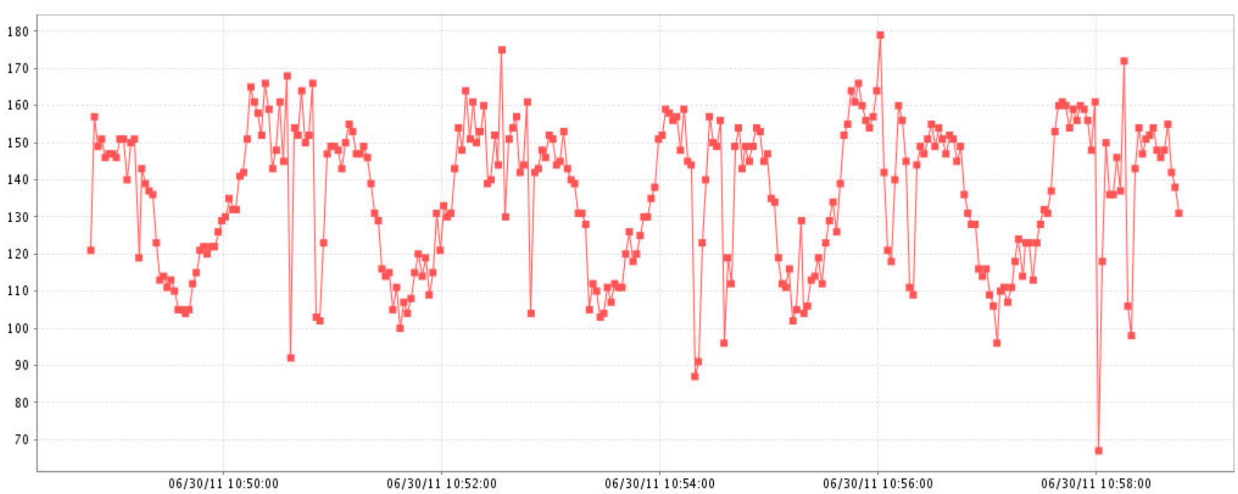

Figure Thirty: Motor #1 at +20 RPM (Motor #2 at 0 RPM)

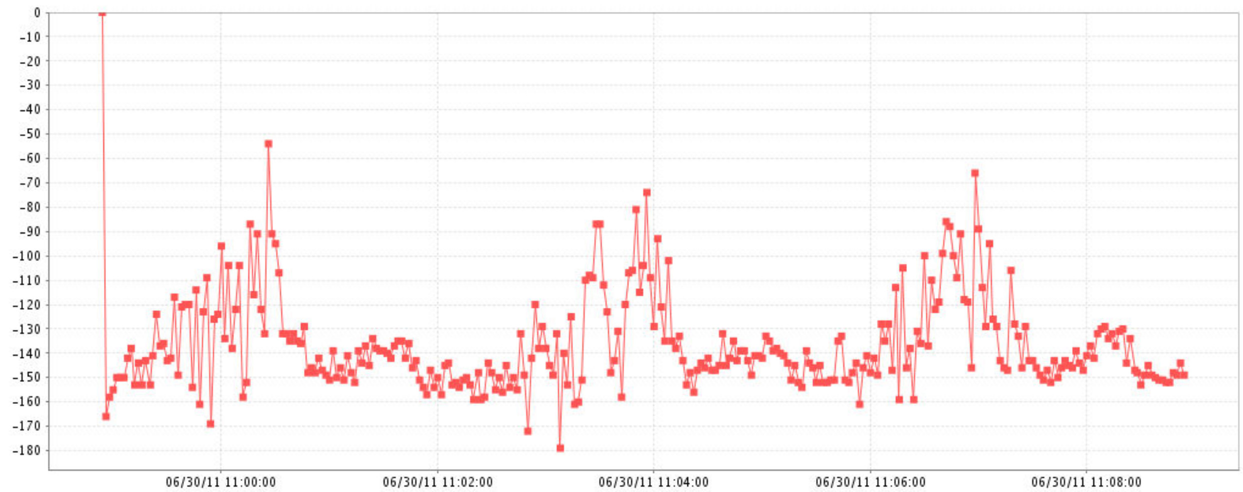

Figure Thirtyone: Motor #2 at -20 RPM (Motor #1 at 0 RPM)

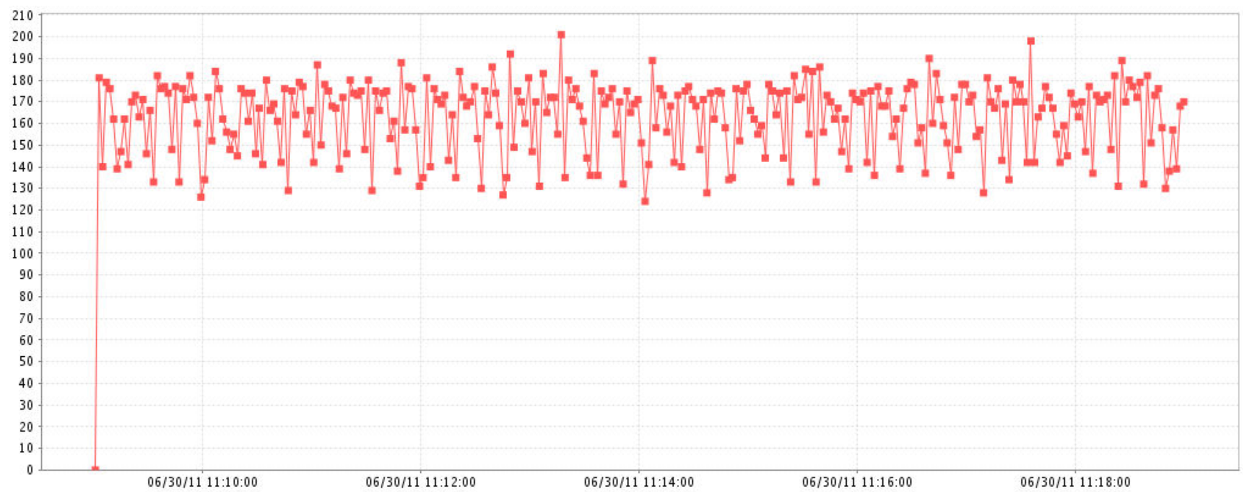

Figure Thirtytwo: Motor #1 at +24 RPM (Motor #2 at 0 RPM)

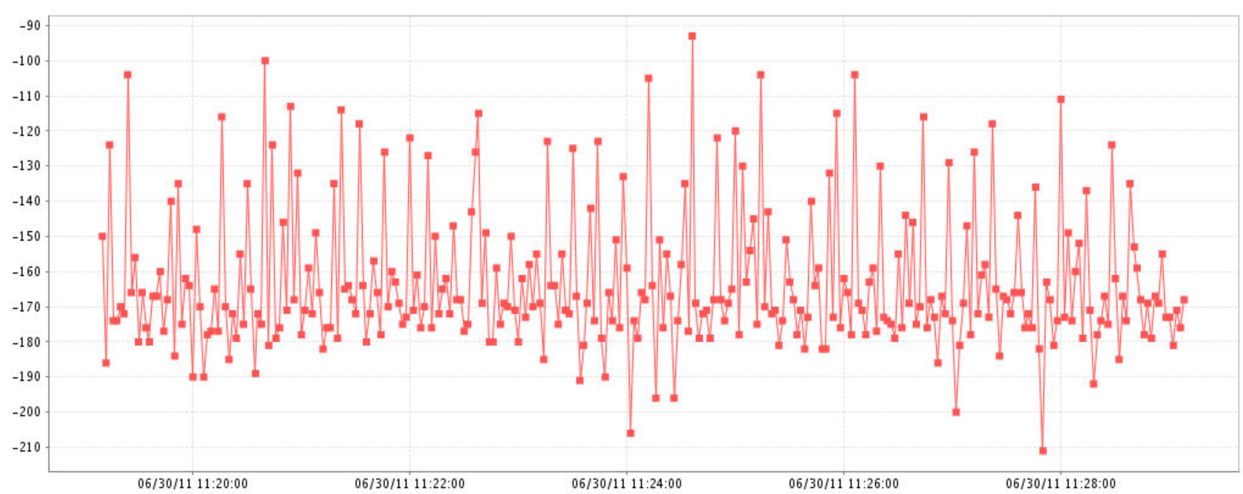

Figure Thirtythree: Motor #2 at -24 RPM (Motor #1 at 0 RPM)

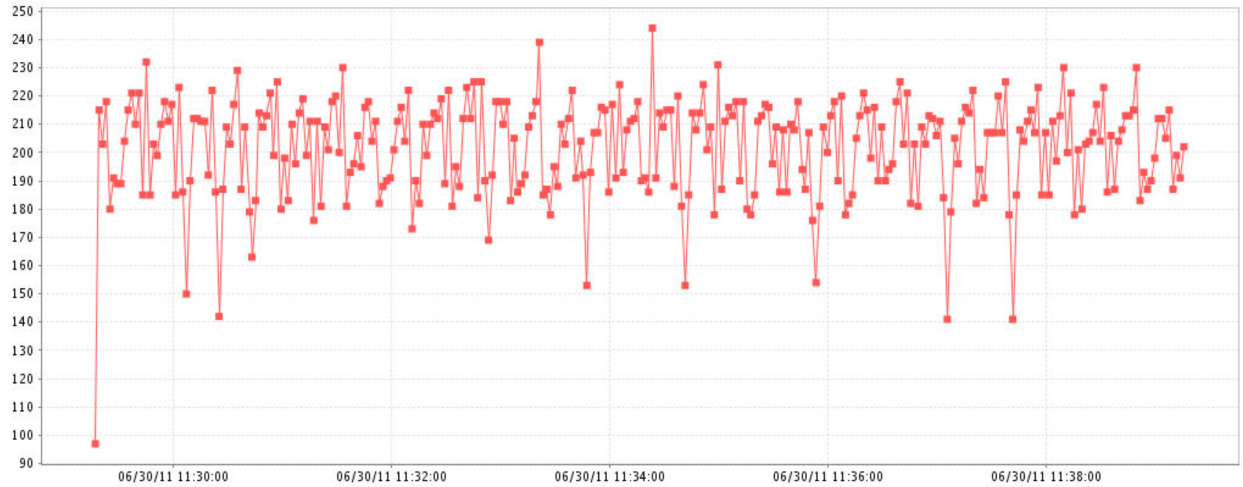

Figure Thirtyfour: Motor #1 at +30 RPM (Motor #2 at 0 RPM)

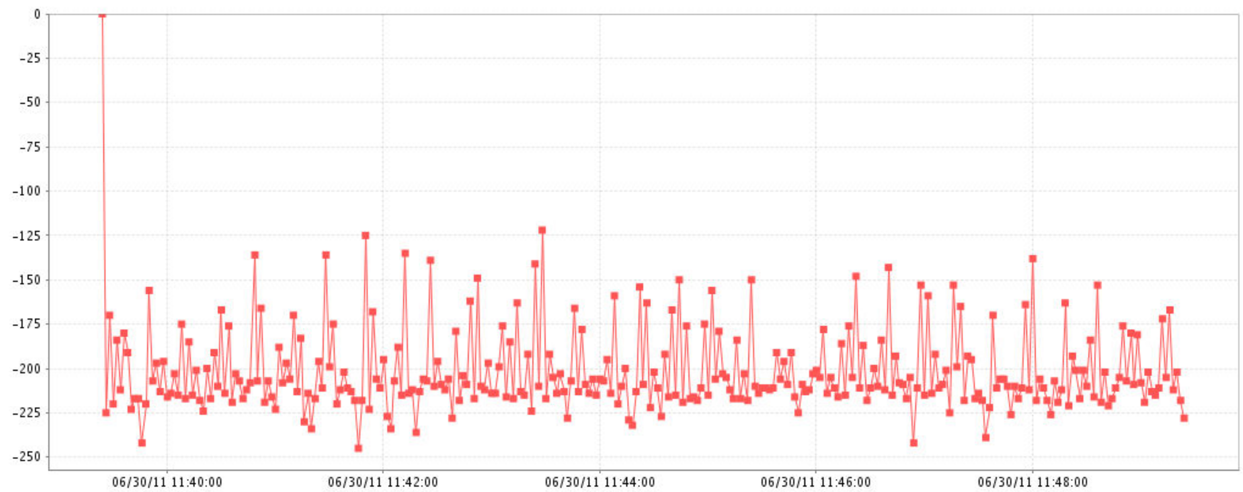

Figure Thirtyfive: Motor #2 at -30 RPM (Motor #1 at 0 RPM)

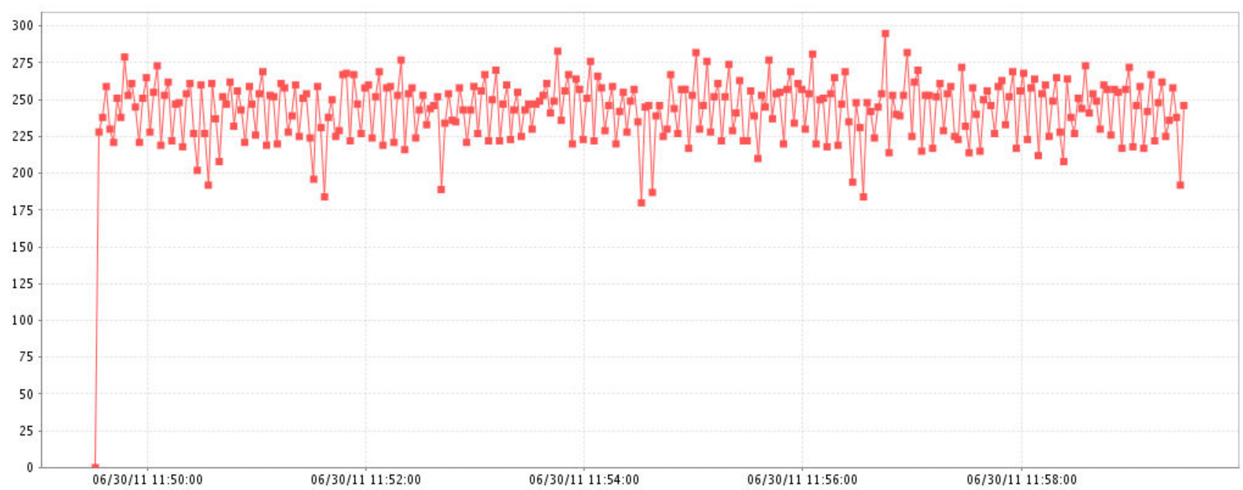

Figure Thirtysix: Motor #1 at +36 RPM (Motor #2 at 0 RPM)

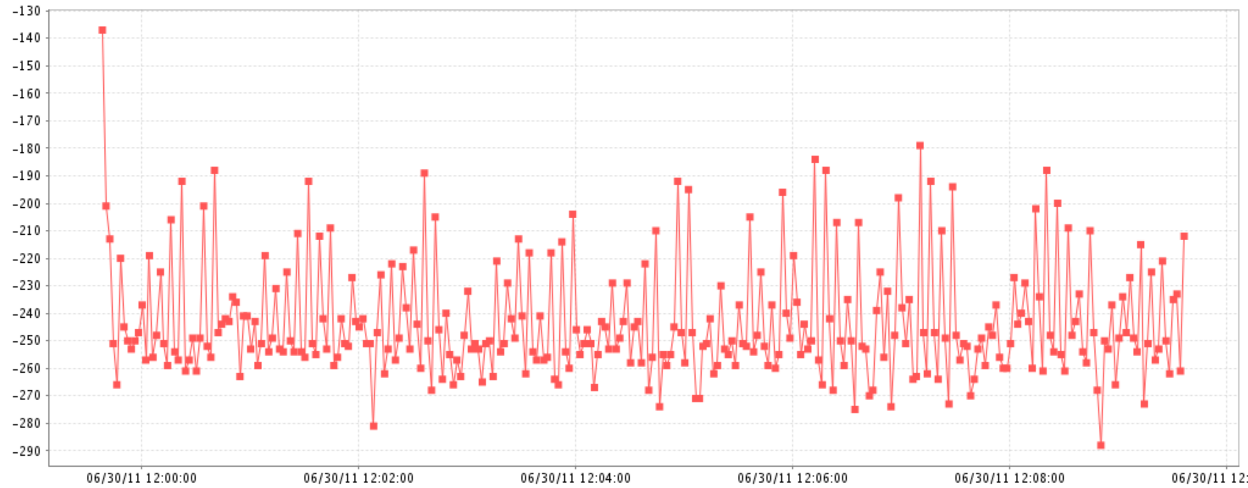

Figure Thirtyseven: Motor #2 at -36 RPM (Motor #1 at 0 RPM)

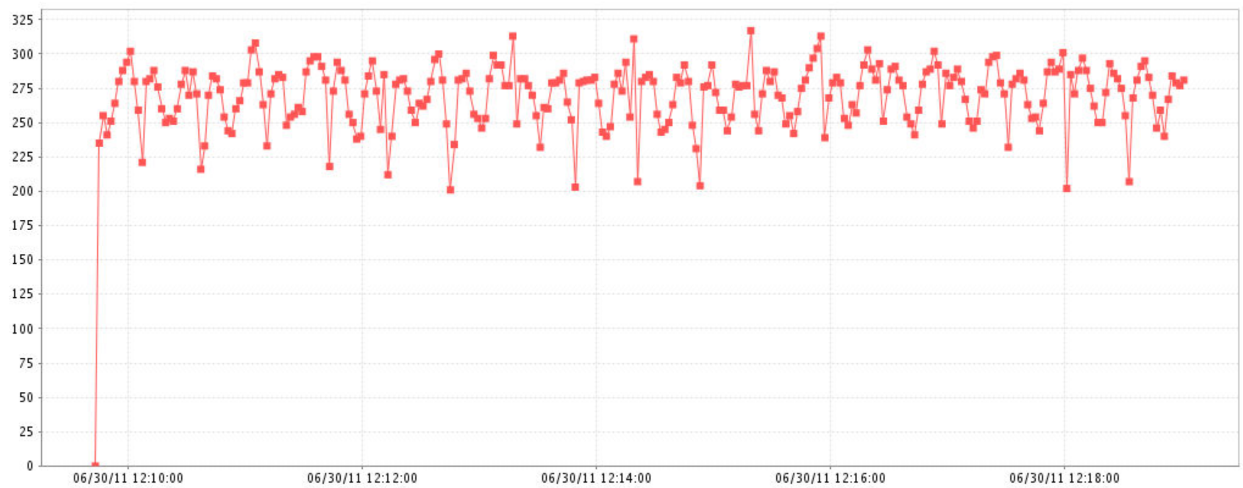

Figure Thirtyeight: Motor #1 at +40 RPM (Motor #2 at 0 RPM)

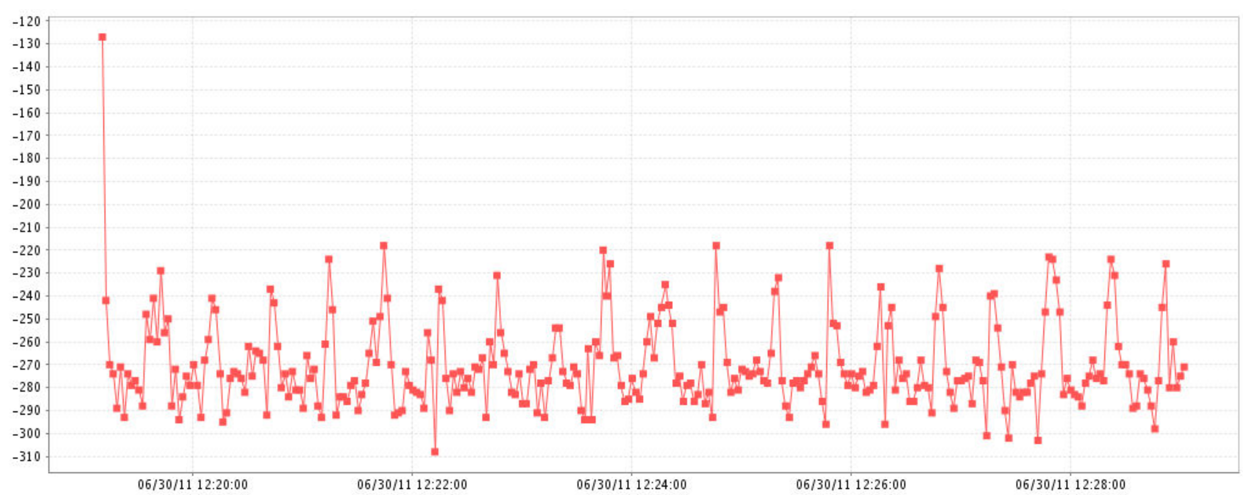

Figure Thirtynine: Motor #2 at -40 RPM (Motor #1 at 0 RPM)

Figure Forty: Motor #1 Complete Test

Figure Fortyone: Motor #2 Complete Test