Synopsis
A series of tests has been done to try to isolate the cause of the motor failures during the June 2009 FOCE deployment, in which the motors would stop running after 10-20 seconds, when commanded to speeds between ~50-340 counts/sec (8-50 RPM shaft speed)

Procedure
The FOCE motor test fixture was used to test the FOCE motors in several configurations to isolate the contribution of several system components to the load seen by the power supply:

- motor w/ drive train [in ~10C air]
- motor w/ drive train [in ~4C water]
- motor w/o drive train
- motor w/o drive train w/o oil

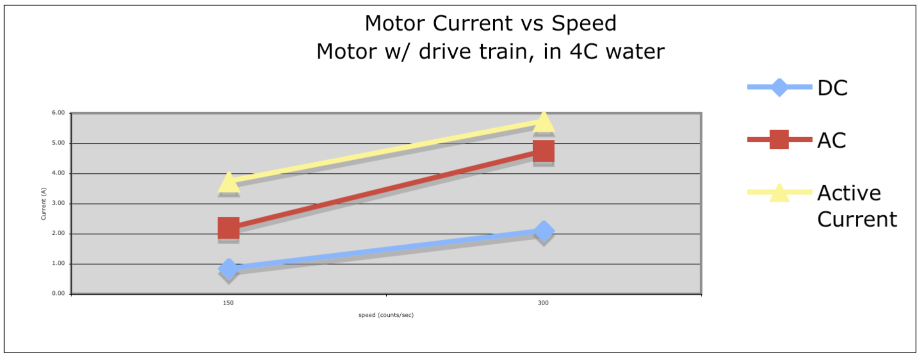
Each configuration was run at two speeds (150 and 300 counts/sec) to cover a large portion of our operation space with a 2x change in velocity.

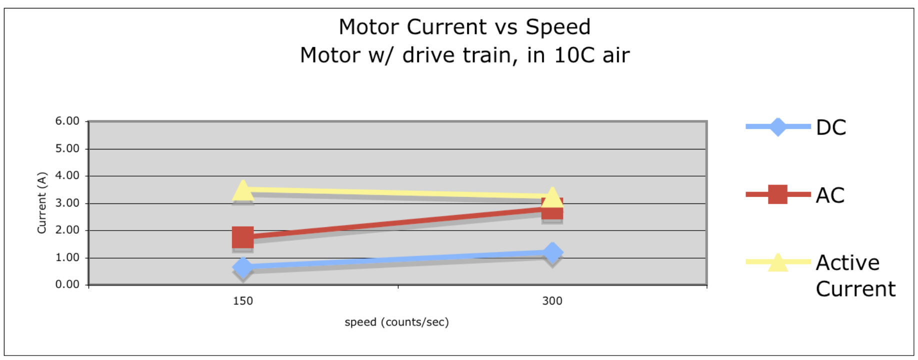
A comparison of these configurations isolates the contribution of the water loading, the drive train loading and the loading of the oil.

For each scenario, the step response of the system was recorded using Elmo Scope, and the steady state power supply current was recorded using a DVM in both AC and DC modes. The Elmo Scope application records the startup and steady state waveforms for motor currents, velocity and Elmo DC bus voltage. None of the measurements of current are an exact RMS representation, since the DVM is a filtered average of a PWM waveform, and the Elmo Scope application shows Active Current (the torque producing current component) and the sinusoidal phase currents. However, a side by side comparison indicates that they are reasonably proportional, and so any of these provides a reasonable basis for comparing the relative power consumption of each configuration.

Analysis

The first two plots (see Data Section) show motor current vs speed, measured in terms of AC and DC currents measured with a DVM, as well as the approximate steady state Active current reported by Elmo Scope. The graphs show that while these are different, they are essentially proportional, and so any should be valid for comparing (qualitatively but proportionally) the power used by different configurations.

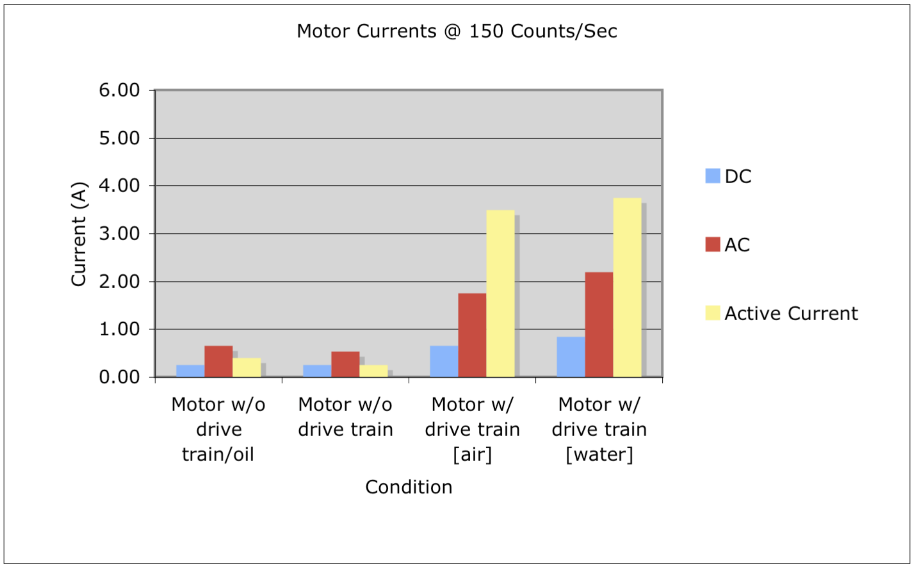


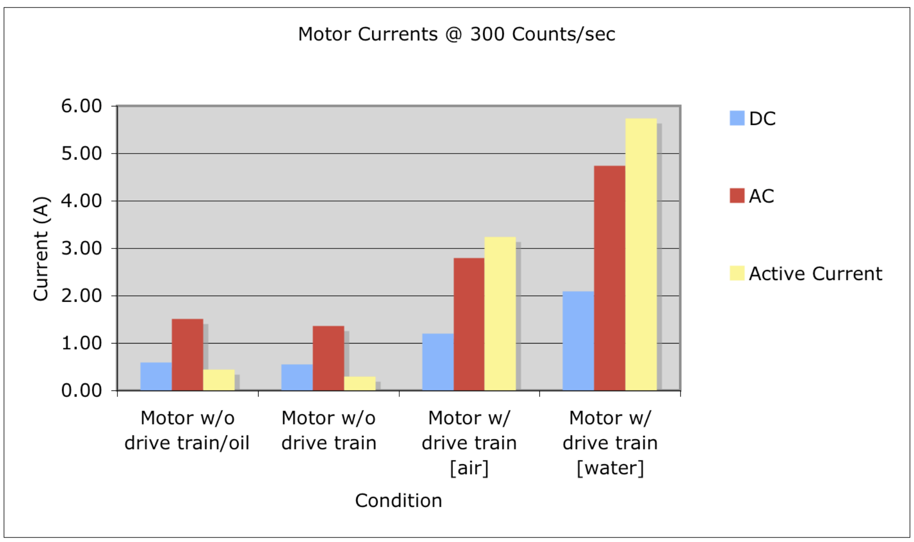


In water, the *difference* in current (not absolute current) required to double the speed is greater than in air by a factor of about 4.

The next two plots (see Data Section) show current consumption vs configuration, each at a different speed (left to right):

- motor w/o drive train or oil
- motor w/o drive train (w/ oil)
- motor w/drive train (in air)
- motor w/ drive train (in water).





There is a significant difference in the amount of current drawn between the cases with and without the drive train. The difference between the cases in air and water are larger at the higher speed (by factor of about 4).

The active current (see Elmo Scope output below) can go above the current limit set for the DC power supply; this may be because the Elmo PWM scheme may be effectively lowering voltage to increase apparent current to the drive to produce the required torque. We need to repeat the measurements with a current probe and voltage measurement to capture the exact behavior at the power supply terminals.

Observations/Conclusions

- When the motors have been sitting cold for some time, they will often fail to start even at low speeds (100 counts/sec). The power supply indicates an over-current that apparently causes the Elmo drive to reset, though we need to verify this. In our test fixture, they can be started at very low speeds (50 counts/sec); after running at this speed for a few minutes, the speed can be incrementally increased. After this warm up, the motors can be commanded to the higher speeds from zero without a problem.

- Even when warmed up, the motors will not run at more than about 240 counts/sec for more than 20 sec or so. Because this exceeds the current limit we have set for the Elmo, the drive will drop the torque command (current) down, resulting in a lower velocity. The current limit we have set (5A) may correspond to the Elmo drive's Active current, not necessarily the power supply current. If that is true, it isn't clear how it relates to the current seen by the power supply, but we may be able to increase this limit to attain the top end of our desired speed range. Otherwise, we are running up against the limit of our power supply.
- The largest contributor to loading at low temperature appears to be the drive train, though at high speed the water also adds considerable load as well
- It is a little surprising that the oil viscosity did not appear to contribute much, if anything to motor loading
- There is a relatively large overshoot in current (but not in velocity) on startup; this may indicate some "stiction" (see Elmo Scope plots)
- When the Elmo drive resets as noted above, it assumes the configuration values stored in flash memory. The Elmo Composer software throws an error when writing values to flash, and it appears that some configuration values are not written. As a result, some configuration values (LL, HL, VL, VH and possibly others) are set to factory defaults on Elmo reset. We should change the Elmo driver software to explicitly write all relevant (the ones we set that are not factory defaults) parameters at service startup to ensure that they have the intended values. Some of the parameters specified are already being set by SIAM software, and these would not cause a motor failure if they are set to factory defaults, so they are not likely to have caused a problem.

Recommendations

- Examine the drive train to find and reduce the sources of steady state loading and stiction
- Use current probe and scope to look at step response current and voltage during cold startup/Elmo restart under the different load/temperature scenarios – is 36V bus dropping?
- Confirm the appropriate setting of the current limit configuration using the FOCE electronics and increase it if possible
- Add explicit configuration settings at service startup to Elmo service and find out what causes the error with Elmo composer
- Review the tuning and flash settings for the deployment Elmos before they go out

Data

Power Supply	36V 5A
Motor Config	**[4C; In Water; 150,300 Counts/Sec]** **Motor w/ drive train** [10C; In Air; 150,300 Counts/Sec] Motor w/ drive train [4C; Water; 150/300 Counts/sec] Motor w/o drive train [10C; In Air; 150,300 Counts/Sec] Motor w/o oil ~~Motor w/o magnetic coupling~~ [20C; in Air; 150,300 Counts/Sec] ~~Motor w/o magnetic coupling~~
Elmo Config	MC=20; PL[1]=10;PL[2]=3; CL[1]=5;CL[2]=0;CL[3]=60; LL[2]=-1080;HL[2]=1080;HL[3]=1000000000; VL[2]=-340;VH[2]=340; AC=100;DC=100;SD=1000000000; UM=2;PM=1;RM=0; SF=0;TS=90
Notes	[4C; In Water; 150,300 Counts/Sec] Motor w/ drive train - could not start motor at 150 counts/sec initially (would stall) had to bring up very slowly from 50 c/s in increments of 20 c/s or so. - After running for several minutes at 190, the motor could be started at 150 - At 300 c/s, motor current limits (LC=1) and drops back to 240 c/s after several seconds (sometimes a few seconds later than the scope capture)
Results	Step Response/Steady State (20 s) Plots (CurrentA, CurrentB, Vcommand, Vactual, BusVoltage, ActiveCurrent, ReactiveCurrent) Active Current (150/300): 3.75/5.75 DC current (150/300):0.85/2.10 AC current (150/300): 2.2/4.75

Power Supply	36V 5A
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Notes	-
Results	Step Response/Steady State (20 s) Plots (CurrentA, CurrentB, Vcommand, Vactual, BusVoltage, ActiveCurrent, ReactiveCurrent) Active Current (150/300):3.5/3.25 DC current (150/300):0.65/1.2 AC current (150/300): 1.75/2.8

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Elmo Config	MC=20; PL[1]=10;PL[2]=3; CL[1]=5;CL[2]=0;CL[3]=60; LL[2]=-1080;HL[2]=1080;HL[3]=1000000000; VL[2]=-340;VH[2]=340; AC=100;DC=100;SD=1000000000; UM=2;PM=1;RM=0; SF=0;TS=90
Notes	-
Results	Step Response/Steady State (20 s) Plots (CurrentA, CurrentB, Vcommand, Vactual, BusVoltage, ActiveCurrent, ReactiveCurrent) Active Current (150/300):0.25/0.30 DC current (150/300):0.25/0.56 AC current (150/300):0.53/1.37

Power Supply	36V 5A
Motor Config	[4C; In Water; 150,300 Counts/Sec] Motor w/ drive train [10C; In Air; 150,300 Counts/Sec] Motor w/ drive train [4C; Water; 150/300 Counts/sec] Motor w/o drive train **[10C; In Air; 150,300 Counts/Sec]** **Motor w/o oil** ~~Motor w/o magnetic coupling~~ [20C; in Air; 150,300 Counts/Sec] ~~Motor w/o magnetic coupling~~
Elmo Config	MC=20; PL[1]=10;PL[2]=3; CL[1]=5;CL[2]=0;CL[3]=60; LL[2]=-1080;HL[2]=1080;HL[3]=1000000000; VL[2]=-340;VH[2]=340; AC=100;DC=100;SD=1000000000; UM=2;PM=1;RM=0; SF=0;TS=90
Notes	-
Results	Step Response/Steady State (20 s) Plots (CurrentA, CurrentB, Vcommand, Vactual, BusVoltage, ActiveCurrent, ReactiveCurrent) Active Current (150/300):0.4/0.45 DC current (150/300):0.26/0.60 AC current (150/300):0.65/1.52

[Attachments]

- Elmo Scope trace plots
- Analysis spreadsheet