The Handiman's Guide to the DJI V.2 ESC

Theory, Troubleshooting, and Repair

by Paul Harden

Introduction. *This guide is the result of repairing several DJI V.2 ESC (Electronic Speed Control) boards suffering premature failures and repaired at the component level. It is shared for those desiring to do the same. It contains some basic theory of operation, ESC board replacement, trouble-shooting steps, oscilloscope waveforms, the schematic diagram (reverse engineered), and PCB parts layout.*

Basic Theory of Operation.

The motors are 3-phase motors with 3 sets of coil windings DJI labels A, B and C. The electrical symbol is shown in **Fig. 1**. In reality, there are 12 coils and 14 fixed magnets as shown in **Fig. 2**. The "A" motor winding is actually four orthogonal windings, as are the "B" and "C" windings, offset by 30 degrees. It takes 168 steps (12 x 14) for one motor revolution.

These are "outrunner" motors, meaning the *outside* sleeve with the fixed magnets is what rotates (the rotor) and the coil windings are fixed (stator), wired direct to the ESC, for a *brushless* motor.

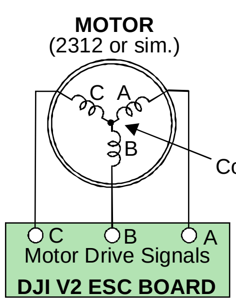


Fig. 1 – Electrical diagram of 3-phase motor and ESC

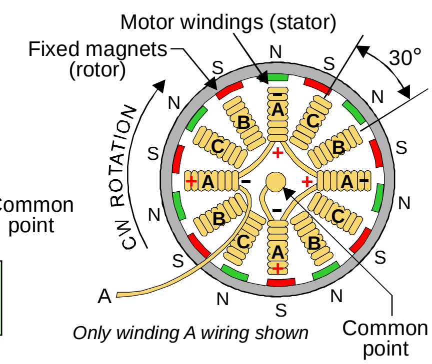


Fig. 2 – Mechanical arrangement of motor, coil windings and rotor

The idea is to energize a coil winding positive (POS=N pole) as it approaches a south (S) magnet, and negative (NEG=S pole) as it approaches a north (N) magnet pole to cause the windings and magnets to attract. This sequenced magnetic attraction is what makes the motor rotate. It is the job of the ESC to energize the windings, in the proper sequence and polarity, to produce the motor speed, direction, and power desired. This 6-step sequencing of the windings is called commutation and shown in **Fig. 3**.

Each ESC board receives *motor control signals* from the **Main Control Board/NAZA-M** controller. This signal is a *pulse width modulated* (PWM) 400 Hz square wave. As the pulse width gets wider, more power is provided to the motors.

Motor Winding	Commutation Sequence → 1	2	3	4	5	6
A	POS	POS	FLOAT	NEG	NEG	FLOAT
B	FLOAT	NEG	NEG	FLOAT	POS	POS
C	NEG	FLOAT	POS	POS	FLOAT	NEG
Windings ON →	AC	AB	CB	CA	BA	BC
OFF →	B	C	A	B	C	A

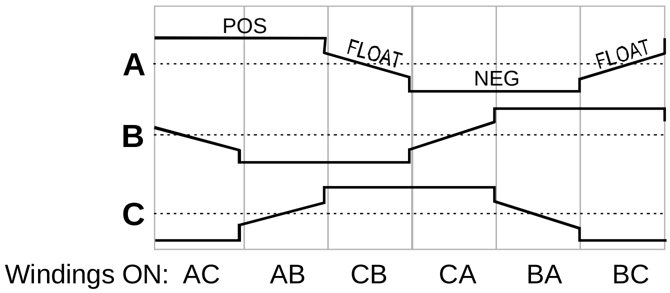


Fig. 3 – Commutation Sequence

The 8051 microprocessor unit (MPU) on the ESC board converts the PWM motor control signal into the six sets of sequential *motor drive signals*. **Fig. 3** shows that two windings are energized (ON) and one is OFF at any given instant.

The MOSFETs turn the selected windings ON and OFF. They convert the 3v MPU drive signals into the battery 11v high current drive for the motor windings. Two MOSFETs are turned ON at a time to route the current through two motor windings at a time. **Fig. 4** shows the case of windings A and B being energized (sequence #2) by Q13 sourcing and Q12 sinking the current to complete the circuit. Windings A and B are also energized in sequence #5 by Q11 as the source and Q12 the sink to reverse the magnetic polarities of the two windings.

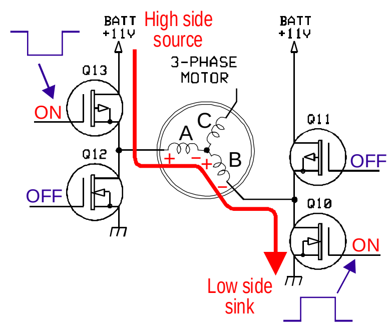
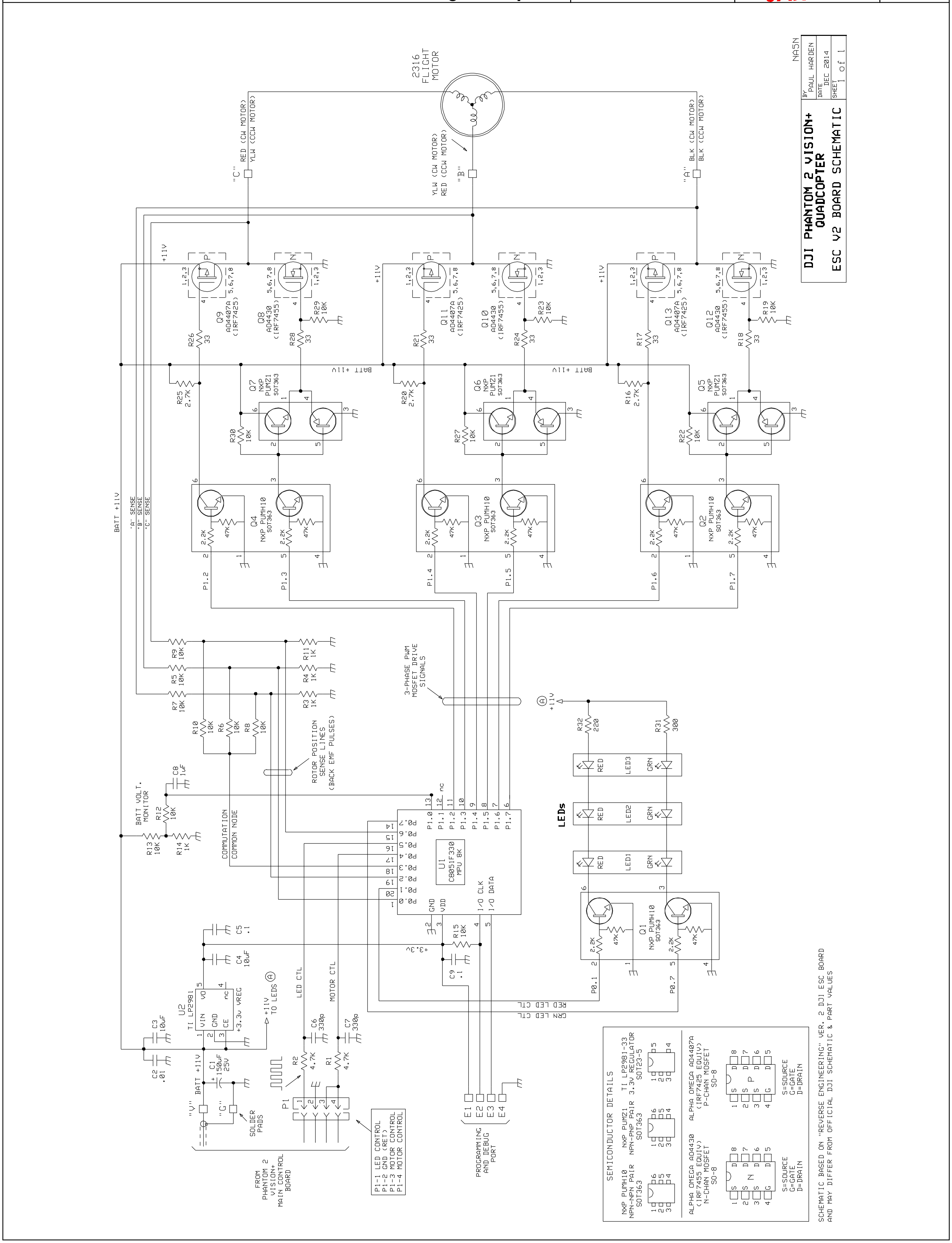


Fig. 4 – Current flow for sequence 2, windings A and B energized.

BEMF. Note that while windings A–B are ON, winding C is OFF or *floating* and generates a voltage pulse (called BEMF) that is used by the MPU to derive the *sensorless* position of the stator and rotor to make any adjustments in motor speed or power.

Oscilloscope waveforms on the following pages show this sequential commutation process in better detail or for troubleshooting purposes.

TITLE **DJI P2V+ ESC Board - Troubleshooting & Repair** | AUTHOR **P. Harden** | DATE **JAN 11 2015** | SHT **2/7**



❶ Testing and ESC Replacement Preparation

1) Remove props; remove P2V+ top cover for ESC board access; keep GPS cable plugged in; remove gimbal clamp.
2) P2V+ normal turn on: RC remote on, then P2V+ quadcopter battery on; motors off. Range extender not needed.
3) Check +11v ESC input voltage and +3.3v microprocessor (MPU) voltage.

FAIL: No +11v: Check battery and +11v and GND wires soldered to ESC. **No 3.3v**: Check U2 voltage regulator.

❷ ESC Motor Control Inputs

*The **Main Control Board/NAZA-M** issues separate motor control signals to each ESC board and motor based on the throttle, yaw, and direction commands from the RC remote joy sticks. **ESC motor control signals** are 400Hz pulse width modulated (PWM) square waves. The microprocessor (MPU U1) internal clock "counts" how long the pulse is HI to control the speed of the motor from off (<1mS or <40% duty cycle) to full throttle (about 1.8mS or 75% duty cycle). PWM allows for precise motor speed control. PWM signal is on the 4-pin connector P1 and cable from the Main Control Board.*

1) **Oscope** setup: Ch.1 2v/div; Ch.2 5v/div; sweep 1mS/div; trigger: Ch.1. PWM signal best seen at R2.
2) With motors off, PWM pulse width (PW) should be <1mS or about 37% duty cycle. (**Fig. 5**)
3) Turn on motors to idle. PW should be about 1.2mS or 47% duty cycle with motor drive signals active. (**Fig. 6**)
4) Increase motor speed. PW approaches about 1.8mS or 70-75% duty cycle at full throttle. (**Fig. 7**)
5) Turn off motors (leave P2V+ powered on). PWM returns to 37% duty cycle and motor drive A, B and C signals off.

FAIL: No PWM signal at R2 indicates a bad cable at P1 or a problem with the Main Control Board, not the ESC.

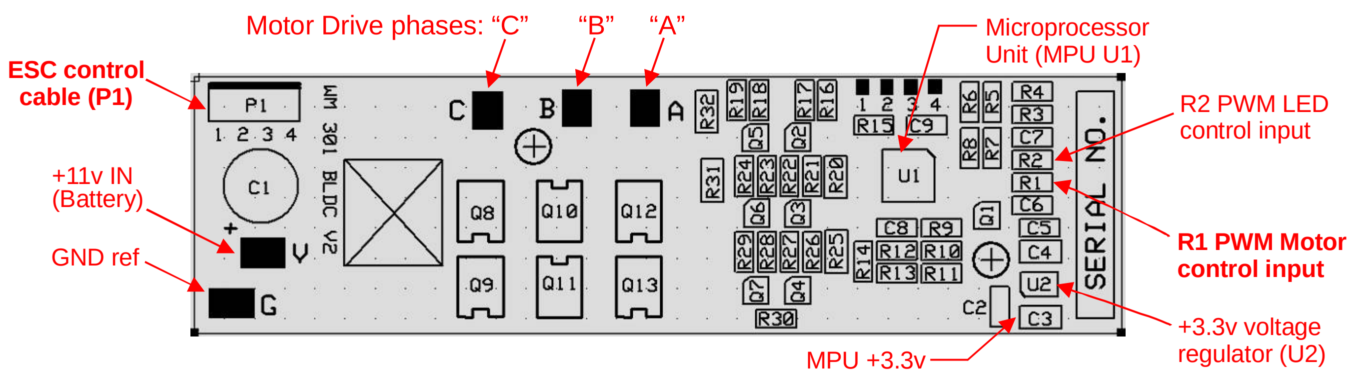
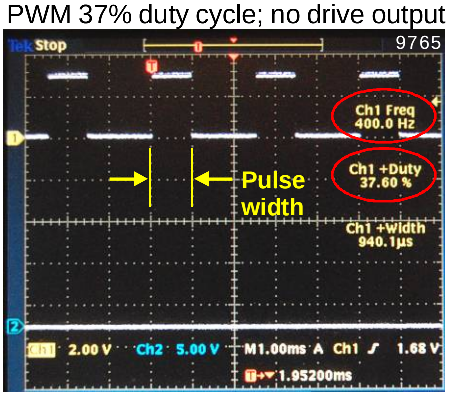


Fig. 5 – P2V+ ON; motor OFF
PWM 37% duty cycle; no drive output

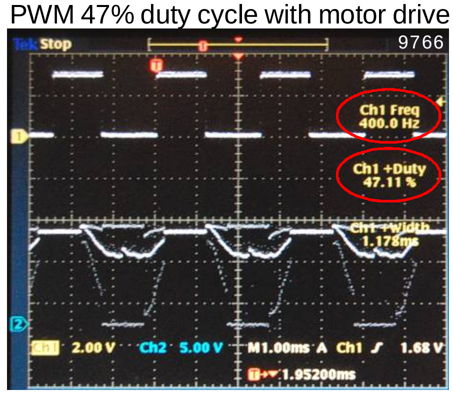


CH 1: PWM motor control input (at R1)
CH 2: Motor drive "A"

OK: 400Hz PWM signal at 37% duty cycle (about 1mS) indicates P2V+ is ready to fly (GPS, home point set, etc.)

Fail: If no 400Hz PWM, check GPS cable and for 6+ satellites, ESC control cable connected at P1, or possible failure of Main Control Board.

Fig. 6 – P2V+ on; motor on idle
PWM 47% duty cycle with motor drive

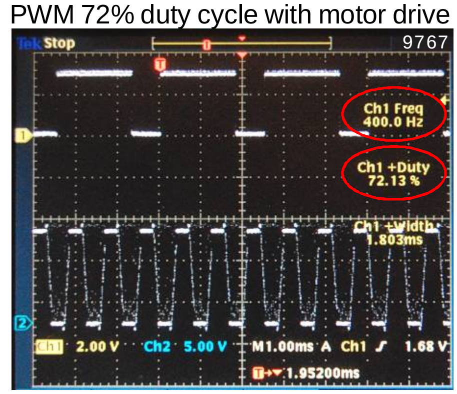


CH 1: PWM motor control input (at R1)
CH 2: Motor drive "A," "B" and "C"

OK: 400Hz PWM at 47% (about 1.2mS) indicates ESC and motors at proper idle speed.

Fail: If no motor drive output on phase "A," "B" and/or "C," problem is likely the MOSFETs for the failed phase(s) .
Goto Step 3 - Motor drive signals

Fig. 7 – P2V+ ON; motor full throttle
PWM 72% duty cycle with motor drive



CH 1: PWM motor control input (at R1)
CH 2: Motor drive "A," "B" and "C"

OK: 400Hz PWM signal at >70% duty cycle (about 1.8mS) indicates P2V+ speed control is functioning normally.

Fail: If speed does not ramp up to full throttle, there may be a problem in the commutation or BEMF sense circuitry.
Goto Step 5 - BEMF sensing

❸ ESC Motor Drive Signals

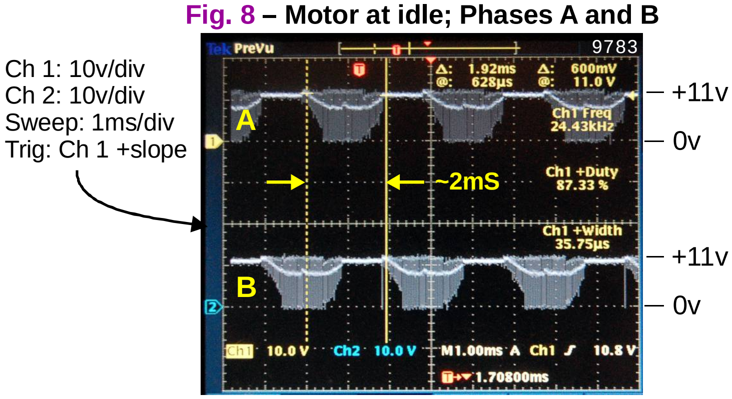
The Phantom 3-phase motor drive signals are the three motor wires soldered to the ESC board and labeled A–B–C. Only two of the three phases are energized at a time to step the motor in the proper direction (CW or CCW) and desired power. The MPU firmware converts the input PWM motor control signals into the 3–phase motor drive signals. These low-current 3v MPU drive signals are applied to an array of six MOSFETs to deliver the battery+11v high-current pulses required by the motor windings.

A MOSFET is basically a semiconductor switch; ideally, it is either ON for full current flow, or OFF for no current flow. They precisely deliver the appropriate power to the motor for the desired speed. Pulses are used to energize the motor windings. Thus, each motor drive signal (A–B–C) are "bursts" consisting of narrow pulses for precise speed control. It is important to note that each MOSFET drive burst powers the rotor to the next stator winding. Motors consist of 12 stator windings and 14 rotor magnetic poles. It takes 14 motor drive bursts per winding to complete one motor revolution.

1) **O-scope setup**: Ch.1 10v/div; Ch.2 10v/div; sweep 1mS/div; trigger: Ch.1
   Ch.1 to motor drive wire "A" (black) for the reference phase.
2) Turn on motor to idle. Observe 11v drive bursts on Ch. 1 (motor drive A)
3) Place Ch.2 probe on motor drive B channel (**Fig. 8**), then motor drive C (**Fig. 9**)
4) Observe proper phase sequencing between phases A–B and A–C; should be 120° (1mS at idle) apart.
5) Observe proper 3-phase sequencing at higher motor speeds.

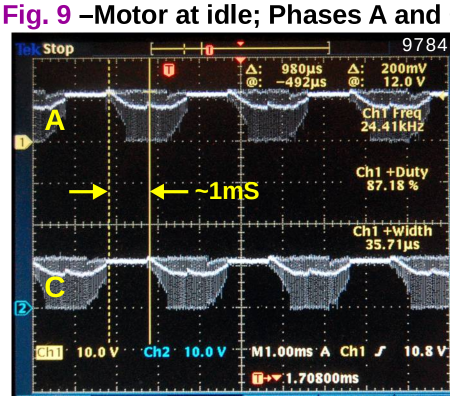
NOTE: Since motor speed is constantly changing, triggering may be difficult. Try single sweep to capture waveforms.
FAIL: No drive burst on one or more motor drive lines is likely failed MOSFETs associated with the bad channel.
Blown MOSFETs are the main failure item on the ESC boards. A blown MOSFET is usually visibly destroyed.

Fig. 8 – Motor at idle; Phases A and B



CH 1: Motor drive "A"
CH 2: Motor drive "B"

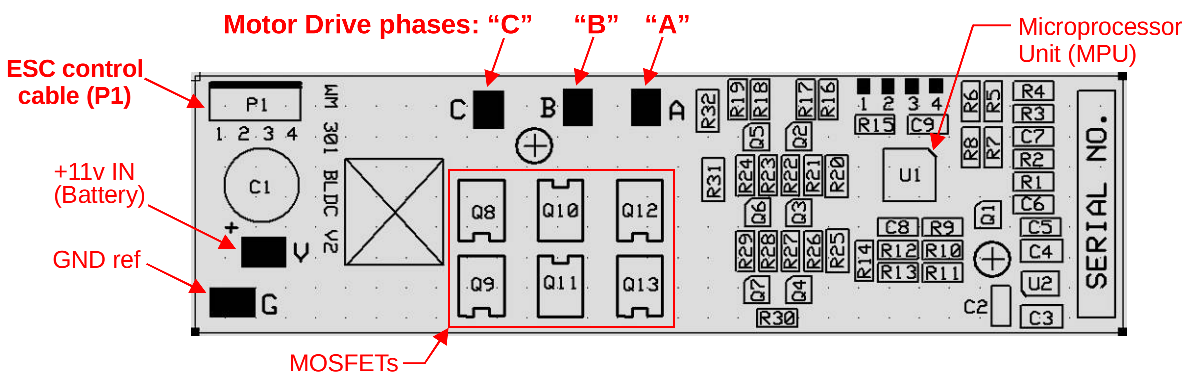
Fig. 9 –Motor at idle; Phases A and C



CH 1: Motor drive "A"
CH 2: Motor drive "C"

OK: Motor phase "B" and "C" drive bursts about 1mS and 2mS from drive "A" indicates the proper 120° phase difference between the 3 phases. Whether "A" to "B" is 1mS or 2mS depends if a CW or CCW motor.

Fail: **If one (or more) of the phases is missing, most likely a MOSFET failure.**
If not 120° between A,B and C, or phase not stable (jumping around), possible failure of BEMF rotor sensing. **Goto Step 5.**



❹ MOSFET High- and Low-side Switching

*In **Fig. 10**, Q13 is the high-side switch (connected to +11v) and Q12 is low-side switch (connected to ground). However, the low- and high-side MOSFETs on the same winding are never turned on at the same time. **Fig. 11** shows the normal current flow used to energize two windings, in this case, A–B.*

The high-side switch (a P-channel MOSFET) is turned on to provide the battery +11v to the proper winding pair; the low-side switch (N-channel MOSFET) sinks current to ground, modulated with the speed control drive pulses.

Checking these inputs with the associated motor drive outputs can isolate a bad MOSFET.

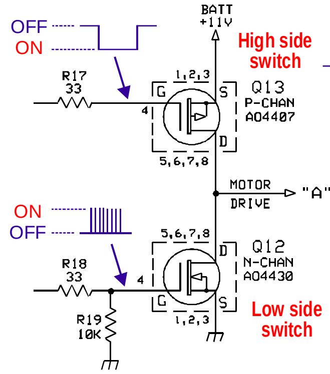


Fig. 10 –High-side and Low-side switching

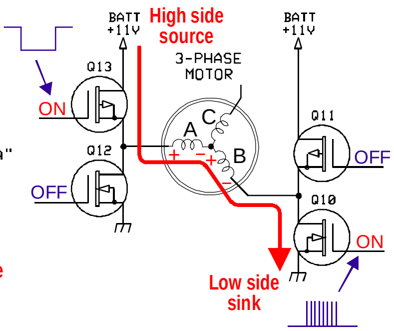
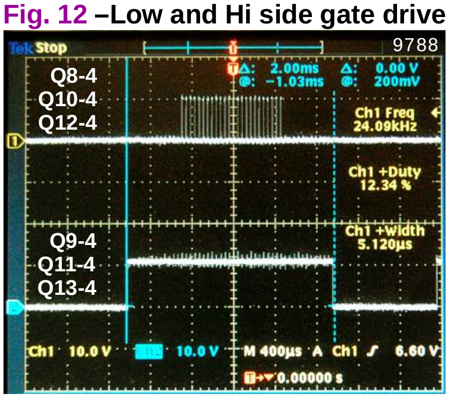


Fig. 11 –High and Low side switching to energize two windings

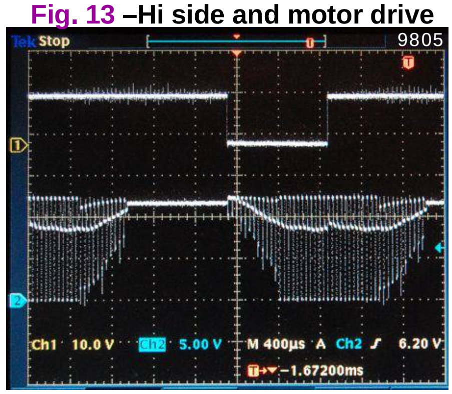
1) **O-scope setup**: Ch.1 10v/div; Ch.2 10v/div; sweep 1mS/div; trigger: Ch.1
2) Turn on motors to idle. Place Ch. 2 probe on Motor Drive "A"
3) Ch. 1 probe, check gate input pin 4 on Q9, Q11 and Q13 for high side drive signal (**Fig. 13**)
4) Ch. 1 probe, check gate input pin 4 on Q8, Q10 and Q12 for low side drive signal (**Fig. 14**)

Fig. 12 –Low and Hi side gate drive



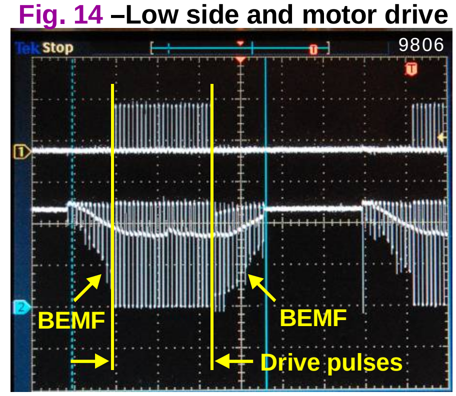
CH 1: Low-side drive "A" (Q12-4)
CH 2: High-side drive "A" (Q13-4)

Fig. 13 –Hi side and motor drive



CH 1: Low-side drive "A" (Q12-4)
CH 2: Motor drive "A"

Fig. 14 –Low side and motor drive



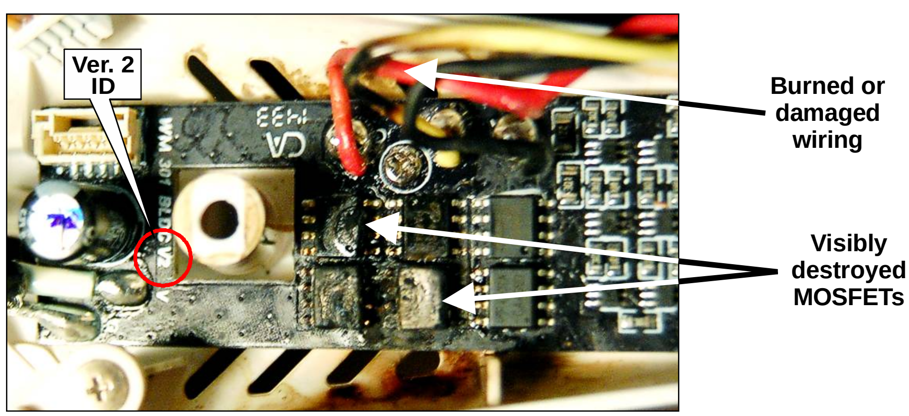
CH 1: High-side drive "A" (Q12-4)
CH 2: Motor drive "A"

OK: Motor phase "B" and "C" drive bursts about 1mS and 2mS from drive "A" indicates the proper 120° phase difference between the 3 phases. Whether "A" to "B" is 1mS or 2mS depends if a CW or CCW motor.

Fail: **If one (or more) of the phases is missing, most likely a MOSFET failure.**
If not 120° between A,B and C, or phase not stable (jumping around), possible failure of BEMF rotor sensing. **Goto Step 0.**

FAILED ESC BOARD

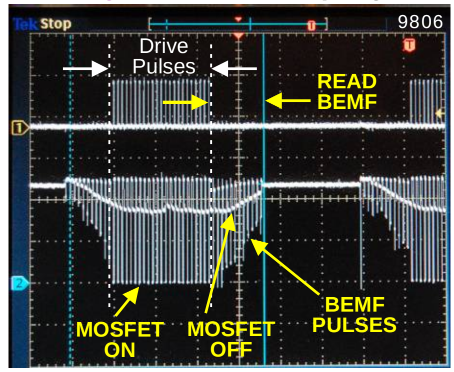
A failed ESC board is usually caused by the failure of one or more MOSFETs. A MOSFET usually fails from excessive current (often caused by shorting out internally), creating excessive heat. The MOSFET chip(s) will usually show signs of excessive heat or being "burned," and often easy to spot. Damage to the printed circuit board may also result.



❺ BEMF Sensorless Rotor Sensing

*The **motor drive signal** to a winding, when the low-side MOSFET is ON, is a burst of numerous pulses for precise speed control. When that MOSFET turns OFF, that drive line is floating. However, the rotor magnets are still moving, and moving past the floating winding, now acting as a generator (producing a voltage) and inducing the drive pulses from the two other active windings. This induced voltage is called the **back electromagnetic force** voltage, or BEMF. The MPU uses the BEMF voltage from the 3 motor drive lines to determine exactly where the rotor is in relation to the windings and adjusts the speed, up or down, as needed. This technique is called a **sensorless motor**, as no physical sensors are used to determine the position of the rotor. **Fig. 15** shows the winding drive pulses when the MOSFET is ON, and the induced BEMF pulses while the MOSFET is OFF, and the period of time BEMF pulses are "read" by the MPU.*

Fig. 15 –BEMF sampling

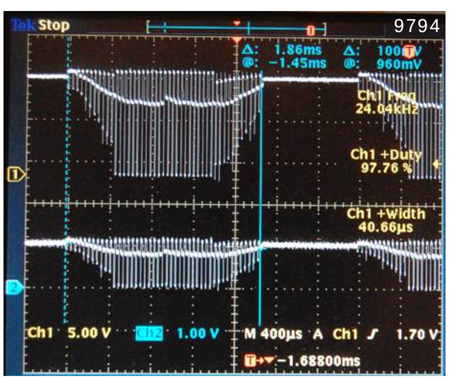


The 3 BEMF sensor voltages, about 11v, are applied to voltage dividers R7-R3 (A winding), R5-R4 (B), and R9-R11 (C) to form 1v BEMF pulses for the MPU (a 3.3v device). However, this voltage is not referenced to ground, but to the common node of the windings (the junction of the 3 windings - which has no electrical connection). The 3 BEMF voltages are summed together by R10, R6 and R8 and applied to the MPU for determining the common node voltage and the reference voltage (Vref) to a voltage comparator internal to the MPU. This comparator, and varying Vref, is a zero-crossing detector of the BEMF, effectively removing the BEMF "ramp" for accurate rotor position determination.

BEMF feedback is an important function of the ESC in properly controlling the speed and power control of the motor. With this scheme, speed and power adjustments are being applied to the motor constantly. If you've wondered how the Phantom can hover in place "solid as a rock," this is why. The motor speed is being checked and corrected constantly and several times within one motor revolution. BEMF is disabled during motor start up until idle speed is stable.

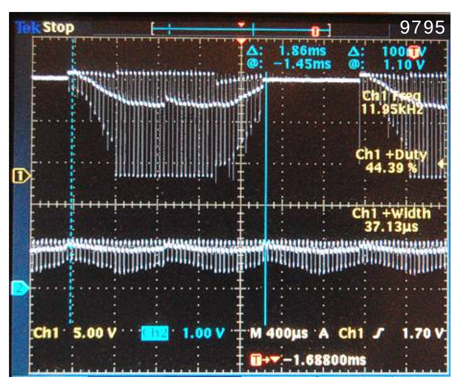
1) **O-scope setup**: Ch.1 5v/div; Ch.2 1v/div; sweep 400uS/div; trigger: Ch.1
   Ch. 1 to motor drive "A" signal
2) Turn on motors to idle. Place Ch. 2 probe on Motor Drive "A"
3) Ch. 1 probe to junction of R7–R8, drive "A" BEMF (**Fig. 16**)
4) Ch. 1 probe to junction R6–R8, BEMF common node sum (**Fig. 17**)
5) Repeat step 3 for drive and BEMF "B" (R5–R6) and "C" (R9–R10)

Fig. 16 –BEMF Voltage Divider



CH 1: Motor drive "A"
CH 2: BEMF, junction of R7-R8

Fig. 17 –BEMF Common Node Sense



CH 1: Motor drive "A"
CH 2: BEMF sum, junction R6-R8

OK: BEMF feedback sensing and the MPU are functioning normally

Fail: **If one of the BEMF signals is missing or incorrect (unlikely) with the motor running,** check the resistors in the associated voltage divider network. If BEMF OK at the MPU, it may be a failure in the MPU firmware. Lastly, turn off motor and move rotor by hand for smooth, consistent rotation. Any unusual resistence could indicate a bad bearing or debris (dirt, sand) in the motor.

❻ The LEDs

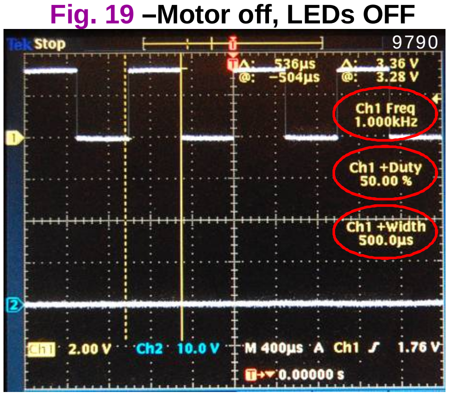
Fig. 18 –PWM LED Control Signal

Pulse width	Duty Cycle	LED color
500uS	50%	LEDs OFF
400uS	40%	Yellow
300uS	30%	Green
200uS	20%	Red

*The **Main Control Board/NAZA-M controller** issues separate LED control signals to each ESC board for illuminating the Phantom status LEDs on each arm. The LEDs are physically mounted on the underside of the ESC boards. **LED control signals** are 1000Hz pulse width modulated (PWM) square waves. The microprocessor (MPU U1) internal clock "counts" how long the pulse is HI to determine which color LED to illuminate. See **Fig. 18**. There are three green and three red LEDs on each ESC/arm. The MPU activates one output port line for the green LEDs, another port for RED, and both ports for YELLOW. These port signals are buffered by transistors Q1 (0v=LED on). The LED PWM signal is on the 4–pin connector P1 and cable from the Main Control Board. LED blinking and blinking rate is controlled by the Main Control Board, not the ESC.*

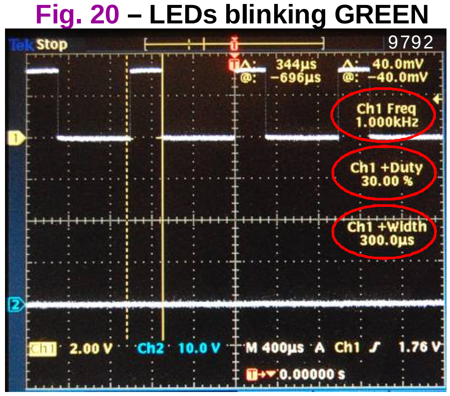
1) **Oscope setup**: Ch.1 2v/div; Ch.2 - not used; sweep 1mS/div; trigger: Ch.1. PWM LED signal best seen at R1.
2) Turn on PV2+. In NAZA-M mode, LEDs will flash yellow, green-red while searching GPS, and finally green with 6 satellites (ready to fly). This is ample time to observe the LED PWM changes for the three different colors.
3) Check Q1-3 and Q1-6 for collectors going LO (0v) to turn on respective LEDs.

Fig. 19 –Motor off, LEDs OFF



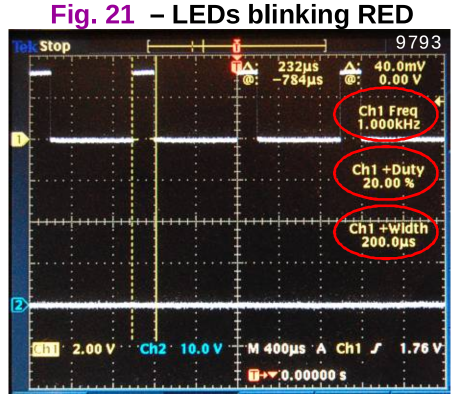
CH 1: LED CTL, R1
CH 2: None

Fig. 20 – LEDs blinking GREEN



CH 1: LED CTL, R1
CH 2: None

Fig. 21 – LEDs blinking RED



CH 1: LED CTL, R1
CH 2: None