Using MCLV-2 with motorBench™ Development Suite to support alternative current and/or voltage ratings

MCU16 Applications Team

1 Scope

This document describes how to use the dsPICDEM™ MCLV-2 Development Board, with alternative current and/or voltage ratings, with motorBench™ Development Suite 2.0.

1.1 Supported usage

Supported usage includes

- Use of generated code with current and/or voltage ratings that differ from the standard values included as part of motorBench™ Development Suite.
  - The generated code in motorBench™ Development Suite is derived from the Motor Control Application Framework (MCAF) R3.
  - Standard values are 24Vdc and a commanded current limit of 2.29A.
  - The only supported PIM is the dsPIC33EP256MC506 External Op-Amp PIM.
- Alterations to MCLV-2 to support higher or lower maximum output current
- Alterations to MCLV-2 to support higher or lower maximum DC link voltage

1.2 Unsupported usage

The following use cases are not supported at this time:

- Use of motorBench™ Development Suite with any board other than MCLV-2, MCHV-2, or MCHV-3
- Alterations to MCHV-2 or MCHV-3 to support higher or lower maximum output current or DC link voltage
- Use of Self-Commissioning with MCLV-2, MCHV-2, or MCHV-3 boards that have any modifications to the following circuitry:
  - power supply (aside from removal of jumper J6 in MCLV-2)
  - current or voltage sensing
  - inverter stage
- Use of PIMs other than dsPIC33EP256MC506 External Op-Amp PIM; the Internal Op-Amp PIM is not supported at this time.

Note also that this document does not cover modifications to either MCHV-2 or MCHV-3, although many of the subjects covered in this document may be applicable to motor drive boards in general.

1.3 Design responsibility

We have tried to make explanations in this document as simple as possible, to help in understanding it and evaluating the required changes to hardware and firmware. Please use this document as a starting point, following its guidelines as closely and correctly as possible, and applying good engineering practices when implementing any modifications.

1.4 Table of contents

2 Brief instructions

2.1 Overview

Use of MCLV-2 boards with alternative current and/or voltage ratings involves following the steps outlined below and described in detail in section 3:

- **Determine motor parameters.** For the measurable parameters (R, L, Ke, J, B, Tf), either use the Self-Commissioning feature of motorBench™ Development Suite with an unmodified MCLV-2 (cutting jumper J6 is permitted; see section 3.1.1 for operation at voltages other than 24V), or measure parameters externally through other means and enter them as "overrides" in the Self-Commissioning step of motorBench™ Development Suite. It is also necessary to determine the rated current of the motor (see section 6.1).
- **Determine appropriate current and voltage ratings of the MCLV-2.** This involves understanding the limiting factors of the MCLV-2 board (see section 4), with or without modifications as appropriate.
- **Modify key components of the MCLV-2, if necessary.** This may include replacing current sense resistors, gain resistors, and/or DC link capacitors.
- **Measure current sense gains, if necessary.** MCLV-2 has a layout-related issue that may require measuring current sense gains manually, so that they are properly taken into account in the MCAF.
- **Enter key parameters into motorBench™ Development Suite.** The current and voltage ratings of the board must be entered, along with any current sense gain compensation factors.
- **Run autotuning and generate code.**
- **Compile and run the code**
- **Spin the motor!**

2.2 Quickstart Guide for the Impatient

The detailed instructions in section 3 are lengthy and require some understanding of background information given in sections 4-8. This section is an abbreviated set of instructions for using motorBench™ Development Suite and the Motor Control Application Framework with modified MCLV-2 boards.

Note: These abbreviated instructions are not a substitute for reading the rest of this document. Power electronics and motor control have challenges that can result from subtle interactions between hardware and software. When in doubt, choose conservative voltage and current ratings, increasing them only after completing appropriate testing and analysis.

2.2.1 Determine motor parameters

Determine the parameters listed below, either using the Self-Commissioning feature of motorBench™ Development Suite, or through other means. External equipment can sometimes be used, or these parameters may be in the datasheet.

2.2.1.1 Nameplate parameters

This information cannot be measured by Self-Commissioning, and must be obtained from the motor datasheet.

- Number of poles
- Rated current: Please read section 6.1 regarding rated motor current! Motor manufacturers are notoriously bad at giving clear guidance on rated current, and it is important to interpret the datasheet correctly.
- Nominal and maximum speed
    - Nominal speed is the expected maximum motor speed at its rated voltage with no mechanical load
    - Maximum speed is the absolute maximum allowable speed of the motor under any conditions (overvoltage or flux-weakening)

2.2.1.2 Primary parameters

- Rs: Stator resistance, ohms line-to-neutral (= half of line-line resistance)
- Ld, Lq: Stator inductance, H line-to-neutral (= half of line-line inductance)
    - d- and q-axis inductances should be very similar for surface-mount permanent-magnet synchronous motors. If you must enter parameters from the data sheet, just use the same value for Ld and Lq.

- Ke: Back-emf, Vrms/kRPM line-to-line (= V/(rad/s) line-to-neutral × 128.255)
- B: Viscous damping, N·m/(rad/s)
- Tf: Coulomb friction, N·m
- J: Moment of inertia, N·m/(rad/s^2) = kg·m^2

Accuracy needed for these parameters varies. Of the mechanical parameters, which are harder to measure, Tf does not affect control loop tuning at all, B has modest impact, and J is important to determine the velocity loop tuning.

2.2.2 Determine appropriate current and voltage ratings for MCLV-2

To support a desired motor, the drive electronics should be well-matched to the motor's current and voltage ratings. For example:

Motor ratings		Drive ratings		Comments
Voltage	**Current**	**Voltage**	**Current**	
24V	2.5A	24V	3A	Well-matched. Drive has reasonable design margin for extra current.
24V	2.5A	24V	6A	OK, but motor only uses a fraction of drive rated current. Worse signal-to-noise ratio
24V	2.5A	24V	2A	Can't operate full rated current of motor, but may be ok for some applications
24V	2.5A	24V	1A	May not be able to start motor (torque-limited)
24V	2.5A	12V	3A	Motor speed will be limited
24V	2.5A	48V	3A	OK. Operating from 24Vdc (to match the motor) is recommended; operating from 48Vdc may cause excess current ripple.
6V	2.5A	48V	3A	Not a good fit.

This means that if the desired motor's ratings are not a good fit for the unmodified MCLV-2 (24Vdc nominal, 2.29A maximum command current) then modifications to the MCLV-2 may be needed.

Current and voltage ratings for the modified MCLV-2 depend on which modifications are needed.

- If one of the test cases mentioned in section 5 is appropriate, see the appropriate column of Table 13 or Table 1.
- In other circumstances, see the following subsections to determine appropriate ratings.

Table 1: Summary of voltage and current ratings (abbreviated from Table 13). "Base" = unmodified, highlighted values are changes from the unmodified MCLV-2.

#	Parameter	Base	TC1	TC2	TC3	TC4	Comments
I01	Full-scale current, nominal	4.40A	11.00A	4.40A	4.40A	2.20A	
I08	Current command limit	2.29A	7.68A	2.29A	2.29A	1.14A	
V01	Full-scale voltage, nominal	52.8V	52.8V	52.8V	52.8V	52.8V	
V02	Maximum instantaneous DC link voltage	50.0V	50.0V	63.0V	50.0V	50.0V	Determined by C53 and C54
V04	Overvoltage threshold, nominal	28.0V	28.0V	51.0V	28.0V	28.0V	
V07	Nominal operating voltage	24.0V	24.0V	48.0V	12.0V	24.0V	
V09	Undervoltage threshold, nominal	14.0V	14.0V	14.0V	10.0V	14.0V	
V10	Maximum operating voltage, UI	26.0V	26.0V	49.0V	26.0V	26.0V	MCAF R3: V04 = V10 + 2V
V11	Minimum operating voltage, UI	16.0V	16.0V	16.0V	12.0V	16.0V	MCAF R3: V09 = V11 – 2V

2.2.2.1 DC link voltage

- Full-scale voltage (V01) is the nominal DC link voltage that corresponds to maximum ADC input.
  For the MCLV-2, take AVdd = 3.3V and multiply by the voltage divider ratio used to sense DC link voltage.
  This is 52.8V for the unmodified MCLV-2.

- Minimum and maximum operating voltage (V10, V11) are the normal limits of the DC link voltage. MCAF R3 has a 2V margin from these values to under- and overvoltage thresholds for MCLV-2, so for example if the desired overvoltage threshold is 51V, then 49V should be entered in motorBench™ Development Suite as the maximum operating voltage. Leave appropriate design margin below the rated voltages of capacitors C53 and C54, and below MOSFETs Q1-Q6. See section 4.2 for more information.

2.2.2.2 Current ratings

- Full-scale current (I01) is the nominal phase current that corresponds to maximum ADC input. For the MCLV-2, this is a bipolar current sense input, so take AVdd=3.3V and divide by 2KRs where K is the DC gain of current sense amplifiers and Rs is the sense resistor value used. (The unmodified MCLV-2 has K=15, Rs = 25mΩ, with a full-scale current of 4.4A)
- Current command limit (I08) is the maximum amplitude of the synchronous-frame (dq) current command. This essentially represents the amplitude of motor phase currents.

A conservative shortcut for the current command limit (I08) is to use the lesser of the following values:

- Half of the full-scale current
- 7.68A — do not exceed this rating unless carefully managing thermal behavior of the board (use forced-air cooling, operate for short periods of time, verify thermal measurements like those in section 4.1.5, etc.)

Please note that it is very easy to overestimate a current rating for the drive circuitry. It may appear to work, but an overestimated current rating may result in any of the following:

- Accidental hardware overcurrent faults
- Poor performance in current control
- Overheated or damaged circuitry, including but not limited to the following components:
  - Power transistors Q1-Q6
  - Sense resistors R12, R16, R32
  - Electrolytic capacitor C53

Operation above the default limit of 2.29A requires changes in some or all of the following circuit components:

- Current sense gain resistors (R19, R20, etc.)
- Electrolytic capacitor C53
- Overcurrent trip circuitry (R54, R53, C30) — **note**: the existing circuit values are vulnerable to short spikes and can cause false overcurrent faults. See section 4.1.5.3 for more information.
- Removal of jumper J6

See section 4.1 for more information in determining current rating, or test case TC1 in section 5.2 for example of component changes.

2.2.3 Modify key components of the MCLV-2, if necessary

Follow directions in section 3.3. (That section is short, and there's no feasible way of summarizing further.)

2.2.4 Measure current sense gains, if necessary

MCLV-2 contains a layout issue which requires scaling factor corrections for the current sense gains. These correction factors depend on the value of the sense resistors. If using one of the cases TC1-TC4 as outlined in section 5, measuring the current sense gains is not necessary; we have included recommended correction values in section 3.5.1.1. (TC1, TC2, and TC3 are consistent with the default values in motorBench™ Development Suite; TC4 requires adjustment for Rs = 50mΩ.)

Otherwise, see details in section 7.

A shortcut to determining these correction factors is to linearly interpolate between the base compensation factors and ideal values, using the conductance of the current sense resistors. If the current sense resistors are replaced, compute a coefficient $\alpha = G_s / 40$ S. Each current sense compensation coefficient can be calculated as $\alpha \times$ the unmodified board + $(1-\alpha) \times$ ideal gains, with examples shown below in Table 2.

The predicted values for an MCLV-2 modified with Rs=50mΩ come very close to measurements shown in section 3.5.1.1.

Table 2: Interpolating current sense gain correction factors

Board type	**Rs**	**Gs = 1/Rs**	**α**	K_{AA}	K_{AB}	K_{BA}	K_{BB}
Unmodified MCLV-2 board	25mΩ	40 S	1.0	0.891	-0.030	-0.004	0.965
Ideal gains		0	0.0	1.000	0.000	0.000	1.000
Modified MCLV-2 board	50mΩ	20 S	0.5	0.946	-0.015	-0.002	0.982
Modified MCLV-2 board	33.3mΩ	30 S	0.75	0.918	-0.022	-0.003	0.974

2.2.5 Enter key parameters into motorBench™ Development Suite

Enter values listed in Table 3.

Table 3: Abbreviated list of settings of motorBench™ Development Suite 2.0

Setting	**Parameter**	**Comments**
Forward Path → Inverter → Minimum DC Link Voltage	V11	Impacts undervoltage software threshold
Forward Path → Inverter → Maximum DC Link Voltage	V10	Impacts overvoltage software threshold
Forward Path → Inverter → Maximum current	I08	Continuous current rating (FOC, dq frame amplitude)
Forward Path → Voltage Sensor → Full Scale Reading	V01	Nominal ADC full-scale voltage
Forward Path → Current Sensor → Full scale reading	I01	Nominal ADC full-scale current
Forward Path → Current Sensor → Compensation		Current compensation gain factors. See section 2.2.4

2.2.6 Complete the design process in motorBench™ Development Suite

- Run autotuning and generate code
- Compile and run the code
- Spin the motor

3 Detailed instructions

3.1 Determine motor parameters

For the purposes of running a motor with motorBench™ Development Suite and the MCAF, there are three ways of determining motor parameters.

1. **Consult the motor datasheet.** This is necessary to determine rated speed and current of the motor; there is no way to measure these ratings. Please read section 6.1 regarding rated motor current! Motor manufacturers are notoriously bad at giving clear guidance on rated current, and it is important to interpret the datasheet correctly.
2. **Run Self-Commissioning within motorBench™ Development Suite**. As of version 2.0, only an unmodified MCLV-2 board is supported. (Cutting jumper J6 is permitted; see section 3.1.1 for operation at voltages other than 24V.) Known cases where Self-Commissioning may not be successful are:
   a. **Low resistance or inductance**
   b. **High starting current**
3. **Measure the motor parameters with external equipment.**

The recommended method is to use Self-Commissioning within motorBench™ Development Suite, on an unmodified MCLV-2 board, as this provides high confidence that the parameters are expressed in the correct engineering units, and are measured under controlled circumstances. Note that this may require two MCLV-2 boards:

- An unmodified MCLV-2 board used for Self-Commissioning
- The MCLV-2 board intended for eventual use with generated code, including any required modifications

If Self-Commissioning cannot be used successfully, the other options — consulting the datasheet and/or measuring motor parameters with external equipment — must be used instead.

3.1.1 Operation of Self-Commissioning at voltages other than 24V

Motor parameters should be measured with an appropriate DC link voltage; a motor designed to operate at 12V should use Self-Commissioning with a 12V DC link voltage. Operation at a higher voltage may cause a hardware overcurrent trip due to excessive ripple currents

To run Self-Commissioning with MCLV-2 at voltages other than 24V, jumper J6 should be cut, and a separate power supply should be used with the MCLV-2 power stage. This is not considered a modification that would invalidate use with Self-Commissioning.

The DC link voltage used during Self-Commissioning will need to be entered in motorBench under Forward Path → Voltage Source → Output before starting Self-Commissioning.

3.2 Determine appropriate current and voltage ratings for MCLV-2

Please read sections 4 and 5. If one of the test cases in section 5 is a good match for the desired application, we recommend using it, since each of these test cases has already undergone substantial investigation and testing, and in the event further support is needed, we can provide that support more quickly than with other choices of current and voltage rating. In particular, the following information is necessary. (Asterisks denote intermediate values that are important to understand, but not required to enter into motorBench™ Development Suite.)

- Motor current amplitude
  - *Rated inverter output current (thermal limit)
  - *Minimum hardware overcurrent threshold
  - Full-scale: Nominal phase current that corresponds to maximum ADC input
  - Maximum output current command
- DC link voltage
  - *Rated instantaneous maximum voltage
  - *Rated quasistatic maximum voltage (see section 4.2.4.2.2)
  - Full-scale: Nominal DC link voltage that corresponds to maximum ADC input

  - Normal operating range
  - Overvoltage software trip
  - Undervoltage software trip

3.3 Modify key components of the MCLV-2, if necessary

3.3.1 Increased current capability

We recommend the following changes as in test case 1; see section 5.1 for more information.

- Changing the current sense gain resistors to decrease the current sense gain
- Using a larger electrolytic capacitor (C53)
- Replacing selected resistors with 0.1% tolerance components

We **do not recommend** decreasing the current sense resistors; see section 3.4 for more information.

3.3.2 Decreased current capability

We recommend increasing the current sense resistors as in test case 4; see section 5.5 for more information.

We do not recommend increasing the current sense gain; this reduces signal bandwidth.

3.3.3 Modified DC link voltage range

We recommend cutting jumper J6 and providing DC link power to pins 1 and 2 of terminal block J7. Barrel connector J2 (2.1mm ID, center positive) still requires 24V input for control power, but a smaller adapter can be used, such as the CUI SWI25-24-N-P5 or Tri-Mag L6R18-240.

Note: both DC link power and control power must be isolated power sources, to avoid ground loops when using UART communications or the ICSP connector for programming or debugging.

Voltages above 24V should replace ceramic capacitor C54 with 1000pF 100V NP0 1206.

Voltages above 48V may require changes in electrolytic capacitor C53, resistor divider R5-R6, or transistors Q1-Q6. This is discussed further in Section 4.2.9.

3.4 Measure current sense gains, if necessary

MCLV-2 contains a layout issue which requires scaling factor corrections for the current sense gains. These correction factors depend on the value of the sense resistors. If using one of the cases TC1-TC4 as outlined in section 5, measuring the current sense gains is not necessary; we have included recommended correction values in section 3.5.1.1.

Otherwise, see details in section 7.

3.5 Enter key parameters into motorBench™ Development Suite

3.5.1 motorBench™ Development Suite 2.0

Figure 1 shows the “Define” screen of motorBench™ Development Suite 2.0. The areas that need to be edited are the Motor and the Forward Path area. The way to edit these are to click on the “Show Details…” button and then make particular parameter changes, as shown in Figure 2.

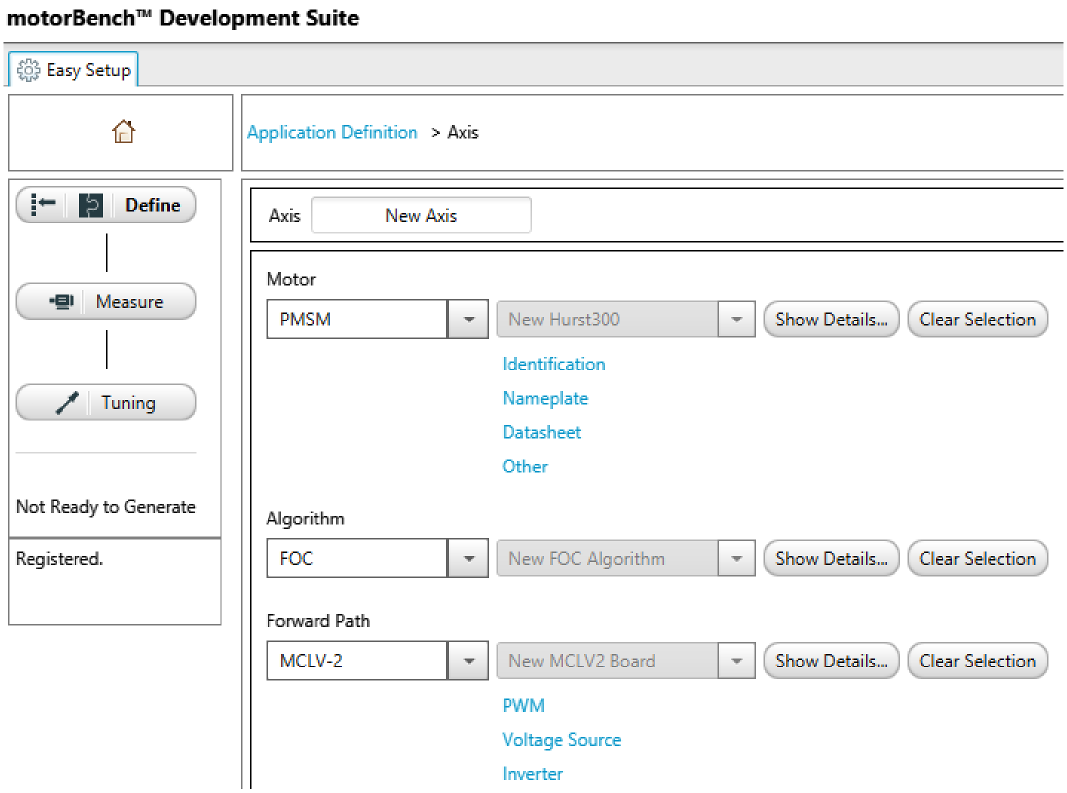

Figure 1: Entering parameters into motorBench™ Development Suite 2.0 (high-level view)

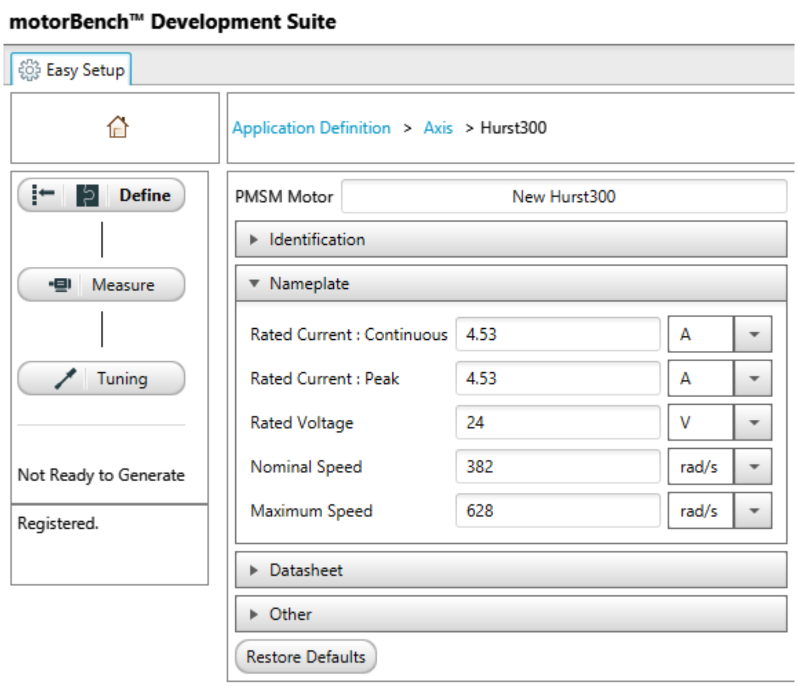

Figure 2: Entering parameters into motorBench™ Development Suite 2.0 (detailed view)

Depending on the results of the previous sections, many of the settings listed in Table 4 may need to be changed. The "Parameter" column refers to the parameter ID shown in Table 13 (see section 5.1). Rows shaded in light gray indicate settings that do not need to be adjusted or cannot be adjusted.

Table 4: Settings of motorBench™ Development Suite 2.0

Setting	Parameter	Comments
Motor → Nameplate → Rated Current (Continuous)		Continuous current rating (FOC, dq frame amplitude). See section 6.1.
Motor → Nameplate → Rated Current (Peak)		Disregard.
Forward Path → Voltage Source → Output		This should be set to the DC link voltage used during Self-Commissioning. This value is not used in autotuning or code generation.
Forward Path → Voltage Source → Max Current		No need to adjust; this is not used in autotuning or code generation.
Forward Path → Inverter → Minimum DC Link Voltage	V11	Impacts undervoltage software threshold
Forward Path → Inverter → Maximum DC Link Voltage	V10	Impacts overvoltage software threshold
Forward Path → Inverter → Maximum current	I08	Continuous current rating (FOC, dq frame amplitude)
Forward Path → Voltage Sensor → Full Scale Reading	V01	Nominal ADC full-scale voltage
Forward Path → Voltage Sensor → Equivalent time constant		Disregard.
Forward Path → Current Sensor → Full scale reading	I01	Nominal ADC full-scale current
Forward Path → Current Sensor → Equivalent time constant	T01	There should be no need to adjust; see section 4.1.3.
Forward Path → Current Sensor → Compensation		Current compensation gain factors. See section 3.5.1.1.

3.5.1.1 Entering current compensation gain factors

The current sense compensation gains discussed in section 8 should be modified if the MCLV-2 current sense resistors are changed.

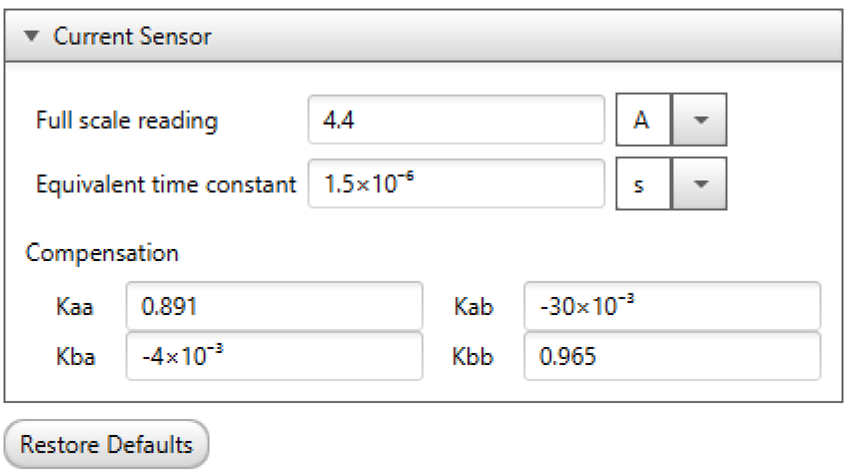

Figure 3: Entering current compensation factors in motorBench™ Development Suite 2.0

These correction factors have been measured on several MCLV-2 boards, both with unmodified current sense resistors and with the TC4 rework (increased value sense resistors). Preliminary correction factors that are the best fit for the population tested are shown in Table 5. (Note that values K_{AA}, K_{AB}, K_{BA}, K_{BB} are named CURRENT_KAA, CURRENT_KAB, CURRENT_KBA, CURRENT_KBB, respectively, in MCAF R3.)

Table 5: Current sense gain correction factors for test cases TC1-4.

Board type	K_{AA}	K_{AB}	K_{BA}	K_{BB}
Unmodified 25mΩ current sense resistor (TC1-3)	0.891	-0.030	-0.004	0.965
50mΩ current sense resistor (TC4)	0.944	-0.015	-0.002	0.980

3.6 Run autotuning and generate code

The autotuning and code generation features of motorBench™ Development Suite behave the same regardless of the current- and voltage-related settings.

3.6.1 Verify generated values

While not necessary, checking the generated values can help increase confidence that the generated code takes into account any settings changed while following the steps in section 3.5.

Filename	Parameter	Comments
aux-files/parameters.html	`sat.currentMaximumCommand`	This should be the minimum of the continuous dq-frame ratings of the MCLV-2 and the motor.
parameters/sat_PI_params.h	`CURRENT_MAXIMUM_COMMAND`	The comment should indicate the same value (rounded to the nearest realizable fixed-point value) as `sat.currentMaximumCommand`.
parameters/fault_detect_params.h	`VDC_OVERVOLTAGE_THRESHOLD`	This should match the intended overvoltage threshold value (parameter V04 in Table 13)
parameters/fault_detect_params.h	`VDC_UNDERVOLTAGE_THRESHOLD`	This should match the intended undervoltage threshold value (parameter V09 in Table 13)
parameters/adc_params.h	`CURRENT_KAA, CURRENT_KAB, CURRENT_KBA, CURRENT_KBB`	This should match the intended current compensation factors

3.6.1.1 Verifying current sense gains

(Optional step)

After compiling and running the code (see next step), if verification of current sense gains is desired, the following simple test is recommended:

- Apply 24V control power to board (J2)
- **Do not apply** voltage to Vdc (J7) – make sure that jumper J6 is not connected
- Do not connect motor to motor terminals (J7)
- Run X2Cscope and connect to the MCLV-2 board
- With drive disabled, connect a current-limited isolated-output laboratory supply between the source terminals of one pair of low-side MOSFETs (Q2, Q4, Q6) according to Table 6.
- Set current-limited isolated-output laboratory supply to some current I1 that is 50%-80% of the rated current of MCLV-2
- Measure current with an accurate DMM
- Read motor.iabc.a, motor.iabc.b, and motor.iabc.c

Table 6: Connection of current source for verification of current correction factors

		Expected value of		
Lab supply +	Lab supply -	iabc.a	iabc.b	iabc.c
Q2 (phase C)	Q6 (phase A)	+I1	zero	-I1
Q6 (phase A)	Q2 (phase C)	-I1	zero	+I1
Q2 (phase C)	Q4 (phase B)	zero	+I1	-I1
Q4 (phase B)	Q2 (phase C)	zero	-I1	+I1
Q4 (phase B)	Q6 (phase A)	+I1	-I1	zero
Q6 (phase A)	Q4 (phase B)	-I1	+I1	zero

Note: the sign of the values in the table is correct: positive current in the MCLV-2 is current out of a particular phase.

Deviation between the current measured in X2Cscope and the expected current should be less than 0.5% of I1 in most cases. If the voltage on AVdd differs significantly from 3.3V due to the LM3940's tolerance, this may cause common-mode gain error for the nonzero cases.

3.7 Compile and run the code

No changes. This works the same way for any range of motors.

3.8 Spin the motor

No changes. This works the same way for any range of motors.

4 Limiting factors of MCLV-2

This document discusses the limitations of MCLV-2 due to current and voltage.

4.1 Current

4.1.1 Relevant parameters required for use with motorBench™ Development Suite

Several parameters are required for use with motorBench™ Development Suite:

- Full-scale ADC current
- Equivalent time constant of the current sense circuitry
- Drive current rating

Specific values are given in section 5.1, covering the test cases considered in this document and the unmodified MCLV-2.

Issues involving these parameters are discussed in detail in the following sections.

4.1.2 Full-scale ADC current

With an AVdd = 3.3V ADC input range, the current sense inputs are offset at AVdd/2 and cover the range ±AVdd/2 at the ADC input.

Working backwards to include the current sense resistors, the full-scale current is ($\pm AVdd/2KR_s$), where K is the current sense amplifier gain, and R_s is the sense resistor.

For example, an unmodified MCLV-2 has a current sense amplifier gain of K=15, and a sense resistor Rs = 25mΩ, so it has a full-scale current of 3.3V/0.75 = 4.4A.

4.1.3 Equivalent time constant

The equivalent time constant of current-sense circuitry on the phase currents (see Figure 17 on p.34), is used for autotuning to ensure current loop stability. Essentially the current sense circuitry is modeled as $V/I = K/(1+\tau s)$ for some equivalent time constant τ that models the dynamics of this circuitry below the sampling rate. Contributing factors to this time constant are

- RC filter on the op-amp output, namely R17 × C20 for phase A and R55 × C20 for phase B. This is 1.0µs for the unmodified MCLV-2 with nominal tolerances; with 1% resistors and 10% capacitors it could be as high as 1.11µs
- RC filter on the op-amp input – on the order of 2KΩ × 56pF = 112ns
- Op-amp 3dB bandwidth – the dynamics of the differential amplifier circuit can be approximated as K/(1+T1*s) where K is the gain of the diff-amp and T1 = K/(2π × GBW). This time constant T1 is dependent on the gain; for a default gain of 15, it is 0.24µs.

For internal development, we used 1.0 µs. A more conservative estimate would be 1.11 + 0.11 + 0.24 = 1.46µs, rounding up to 1.5µs to cover uncertainties in gain-bandwidth.

4.1.4 Current rating

There are several main limiting factors of motor current:

- keeping the motor below its rated current level
  - peak current: avoiding iron saturation, demagnetization
  - continuous current: keeping magnet wire insulation below its rated temperature
- keeping the components on the MCLV-2 below their rated current level
  - peak current: avoiding signal saturation, excessive input voltage levels, and instantaneous thermal limits
  - continuous current: keeping components below their rated temperature
- keeping the MCLV-2 from triggering the hardware overcurrent trip
- component tolerance issues

The first of these is motor-related, and has nothing to do with the drive circuitry.

MCAF R3 does not have any feature to provide transient peak currents in excess of the continuous current limit, so that leaves only the last three points:

- thermal limitations (keeping components below their rated temperature)
- overcurrent trip threshold
- component tolerance issues

Thermal limitations are determined primarily by the transistors and current sense circuitry, which need to be kept below their rated values. More conservative designs also leave enough engineering margin in transistor junction temperature, so that a short-circuit event can be detected and stopped before the transistor exceeds its safe operating area (SOA).

The overcurrent trip threshold is determined by the circuit values, specifically the shunt resistors, current sense gain, and overcurrent fault detection.

Since the continuous current limit is set in software, and is subject to component tolerances (unless components are exactly equal to their nominal values, 1.0A in software is not identical to the nominal 1.0A in hardware), the thermal limitations and overcurrent trip threshold must be analyzed in view of these component tolerances.

A reminder that "rated current" in this document refers to the dq-frame amplitude, and is discussed in sections 6.1.1 and 6.1.2.

4.1.5 Thermal limitations

MCU16 Applications performed tests on an MCLV-2 board modified as in Test Case 1 to determine the inherent limitation of the board under natural convection.

We found that 8.68A was a reasonable maximum current, which produced 88.5°C maximum case temperature for a local ambient temperature near the board of 30.5°C. This provides sufficient margin for the transistors to survive one overcurrent event and still be kept within their SOA, as long as the MCLV-2's overcurrent trip circuitry operates correctly.

The MCLV-2 board should not be insulated within a tightly-enclosed chamber without ensuring another means of extracting sufficient excess heat — for example, a fan to provide forced-convection cooling.

4.1.5.1 Summary of test setup and results

We measured the MOSFET case temperature of Q1, Q3, and Q5 using a type T thermocouple soldered to the drain pin and some Amprobe TMD-55W thermocouple meters to log temperature over time. (These MOSFETs have the drain at Vdc; MOSFETs Q2, Q4, and Q6 have drain pins which are switching nodes; measuring their case temperature generally requires electrical isolation.) We used a fourth type T thermocouple to measure ambient temperature ≈5cm above the board. We also used a FLIR i5 thermal camera as a secondary check of hot spots and other thermal behavior over a larger section of the MCLV-2 board. The test setup is shown in Figure 4 and Figure 5.

We applied constant amplitude current to a WAI 27-110 alternator stator (24V 45A) under FOC through a 3-phase bank of 10A 100mV ±0.25% laboratory shunts. We set our FOC software to automatically adjust the commutation angle every 2 seconds, to allow thermal equalization but permit spot measurements through the laboratory shunts of phase current.

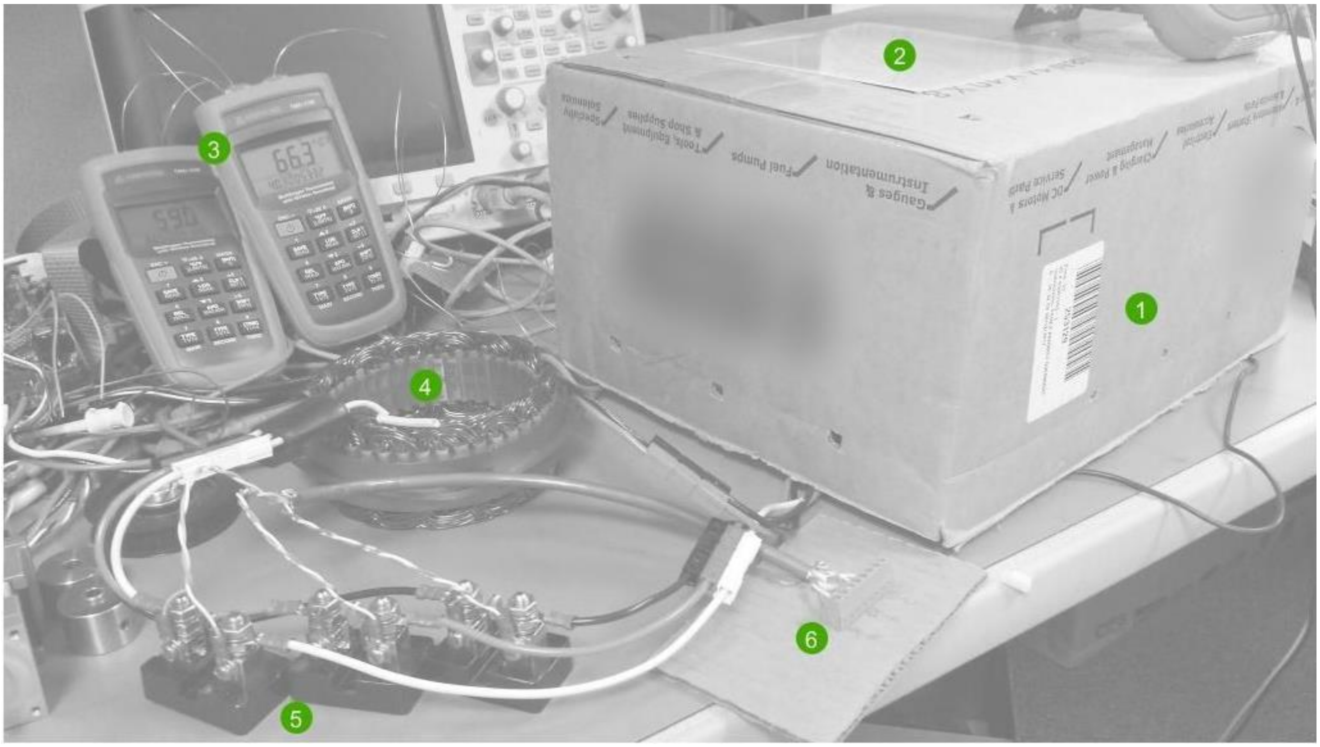

Figure 4: Test setup for determining thermal rating of MCLV-2 board. Numbered items shown are (1) cardboard box to act as a shield from unwanted convection currents, (2) IR-translucent window for thermal camera observation (this ended up not working well, and we moved the window halfway-open to allow observation using the thermal camera, but reduce the risk of unwanted convection currents), (3) TMD-55W thermocouple meters, (4) 24V alternator stator, (5) laboratory shunts, (6) terminal block for measuring Kelvin connections on shunts

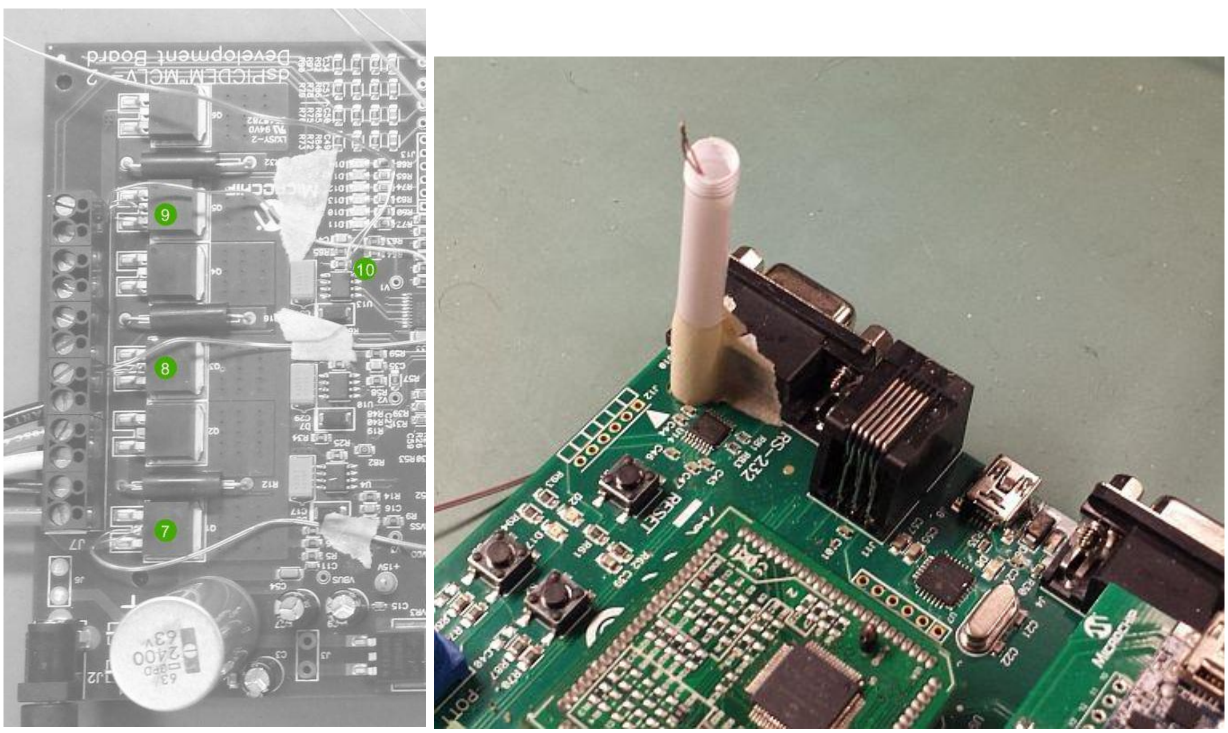

Figure 5: Thermocouple setup. Items shown in left picture are (7), (8), (9): type T thermocouples soldered to drain pins of Q1, Q3, Q5, and in right picture is a fourth type T thermocouple measuring ambient temperature near the MCLV-2 board.

The highest current tested was with an RMS value of 1/√2 times (8.68A, 8.89A, 8.71A) measured on phases A, B, and C, respectively; temperature readings during this test are shown in Figure 6. The highest temperature reached on the case of Q3 of 88.5°C after roughly 72 minutes of operation. The case temperature of Q5 was very similar, reaching 87.5°C; Q1 reached approximately 71°C. The transistors Q3-Q5 tend to run hotter, both because they are further from the edge of the board, and because there is additional heating from current sense resistors R16 and R32.

Readings from the thermal camera at the end of the test, shown in Figure 7, were consistent with the thermocouples, indicating 86.4°C on Q5 and 85.1°C on Q3. The hotspot of the board was current sense resistor R16, reaching 103.4°C.

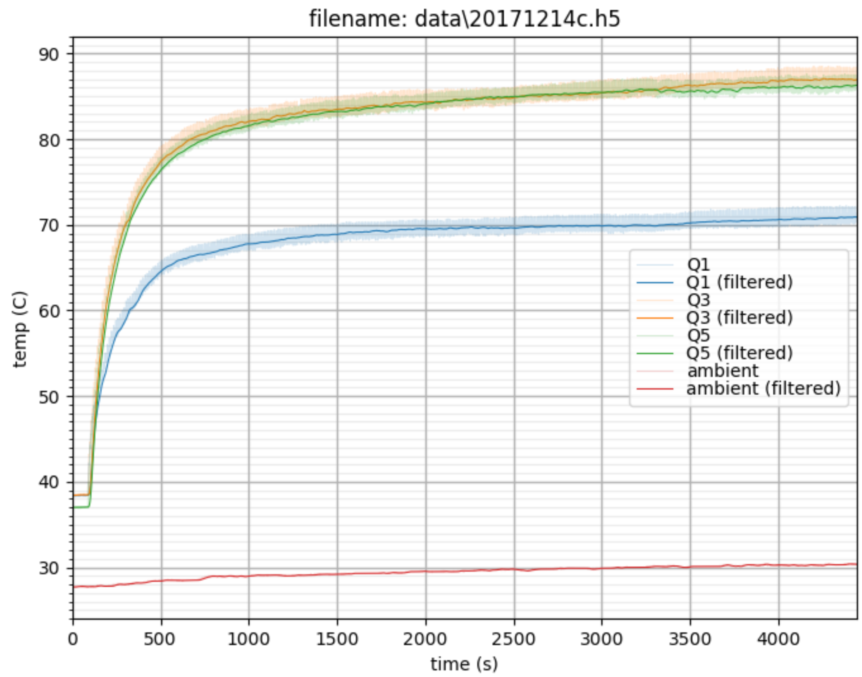

Figure 6: Graph of thermocouple readings during current rating test

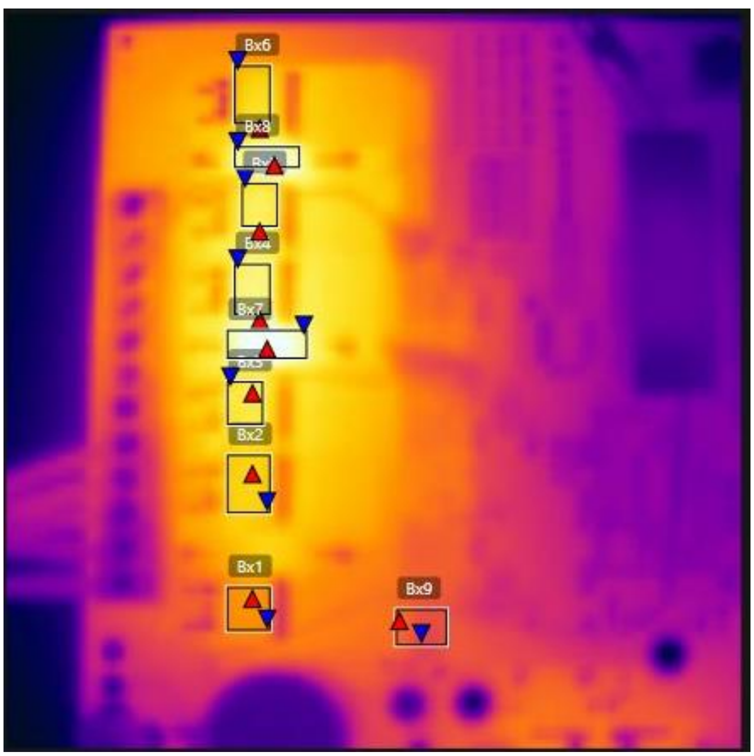

Figure 7: Thermal camera picture at end of current rating test

4.1.5.2 Single-pulse SOA

Transistors Q1-Q6 are ON Semiconductor FQB55N10 devices. Figure 8 shows the single-pulse safe operating area graph from the datasheet. The horizontal dashed line at 210A represents transconductance-limited current behavior, where the device turns on across a load such as a DC link capacitor which can deliver high current for short periods of time. The maximum pulse time lines (e.g. 10µs, 100µs, 1ms, etc.) correspond to a pulse which would raise the junction temperature to its maximum of 175°C from a case temperature of 25°C.

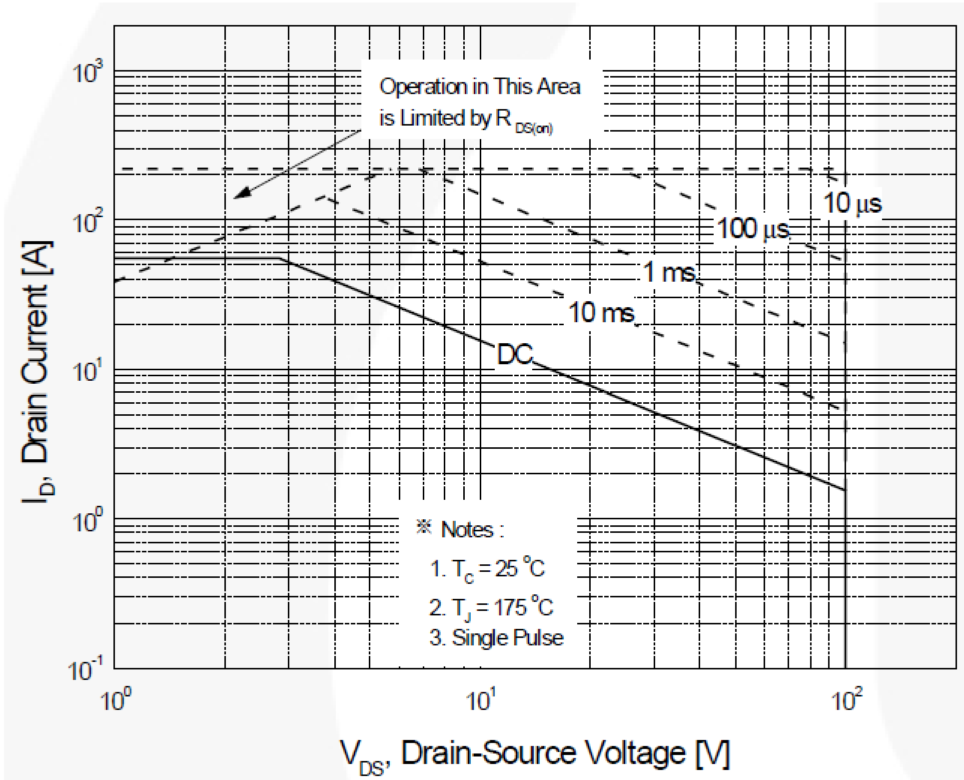

Figure 8: ON Semiconductor FQB55N10 single-pulse safe operating area graph (Figure 9 from datasheet)

For case temperatures above 25°C, we need to use the transient thermal response, shown in Figure 9.

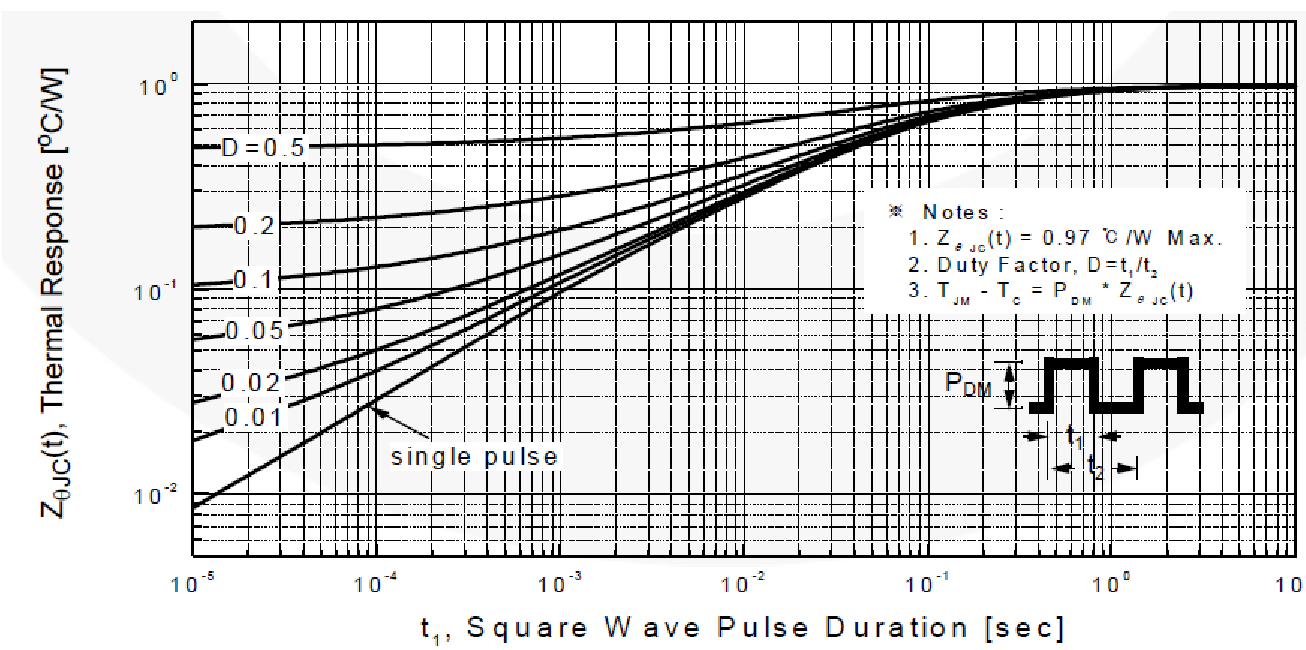

Figure 9: ON Semiconductor FQB55N10 transient thermal response curve graph (Figure 11 from datasheet)

The single-pulse curve in the graph is essentially linear in this log-log plot, and in particular the thermal impedance $Z_{\theta jc}$ is approximately proportional to the square root of the pulse duration: from 10µs to 100µs, a factor of 10, the thermal resistance increases by about a factor of three. (Presumably this is affected by the dynamics of thermal diffusion of heat in the junction to nearby thermal capacity.)

We can calculate the junction temperature rise above the case temperature for short pulses — for example, a short-circuit current of 210A across 48V for 30µs has $Z_{\theta jc} \approx 0.015$°C/W (from the graph), so temperature rise should be 210A × 48V × 0.015°C/W = 151°C, which is roughly the same conditions shown on the SOA graph of TC = 25°C, TJ = 175°C. The same information is shown on these two graphs. All they really say is that $\Delta T_{JC} = IVZ_{\theta jc}$ with thermal impedance proportional to the square root of the pulse duration.

For 48Vdc, at elevated case temperature these characteristics mean that the allowable short-circuit $t_{sc} \approx t_1 \times (\Delta T_{JC} / I_{max} / V_{max} / Z_1)^2$ where t_1 is some reference time e.g. 10µs and Z_1 is the junction-to-case thermal resistance for a single pulse of duration t_1 (0.009°C/W for a 10µs pulse in this case) — if we plug in 210A and various values of Vdc we get the allowable short-circuit times for the FQB55N10 shown in Table 7.

Table 7: Maximum short-circuit pulse time

		maximum short-circuit pulse time t_{SC} (microseconds)				
T_c	max ΔT_{JC}	V_{dc} = 48V	V_{dc} = 36V	V_{dc} = 24V	V_{dc} = 18V	V_{dc} = 12V
25°C	150°C	27.3	48.6	109.4	194.4	437.4
75°C	100°C	12.2	21.6	48.6	86.4	194.4
80°C	95°C	11.0	19.5	43.9	78.0	175.5
85°C	90°C	9.8	17.5	39.4	70.0	157.5
88.5°C	86.5°C	9.1	16.2	36.4	64.6	145.5
90°C	85°C	8.8	15.6	35.1	62.4	140.5
95°C	80°C	7.8	13.8	31.1	55.3	124.4
100°C	75°C	6.8	12.2	27.3	48.6	109.4
105°C	70°C	6.0	10.6	23.8	42.3	95.3
110°C	65°C	5.1	9.1	20.5	36.5	82.1
115°C	60°C	4.4	7.8	17.5	31.1	70.0
120°C	55°C	3.7	6.5	14.7	26.1	58.8
125°C	50°C	3.0	5.4	12.2	21.6	48.6
130°C	45°C	2.5	4.4	9.8	17.5	39.4
135°C	40°C	1.9	3.5	7.8	13.8	31.1
140°C	35°C	1.5	2.6	6.0	10.6	23.8
145°C	30°C	1.1	1.9	4.4	7.8	17.5
150°C	25°C	0.8	1.4	3.0	5.4	12.2

Times less than 10 microseconds are shaded yellow; times less than 5 microseconds are shaded orange.

To survive a single-pulse short-circuit event, the overcurrent trip circuitry must detect and respond with a reasonable safety margin.

With the 88.5°C maximum case temperature, and 48Vdc, the overcurrent trip circuitry must detect and respond in less than 9.1µs in order to keep junction temperature below 175°C during a single-pulse short-circuit event.

4.1.5.3 Overcurrent trip response time

The circuit in Figure 10 on p. 22 shows the MCLV-2 overcurrent trip circuitry. Total response time is dictated approximately by the sum of the following sources shown in Table 8. (TC1 = test case 1, “unmod” = unmodified current sense circuitry)

Table 8: Contributing factors to overcurrent trip response time

Source	Delay (µs)		Comments
	TC1	unmod	
Settling time of current sense amplifier	0.48 (K=6)	1.2 (K=15)	Settling time for DC link current sense opamp, of 5τ, with τ=1/(2π·GBW/K), where K is the op-amp gain
Rise time of RC filters (R54, C31, R53, C30)	4.6	0.15	Time for RC circuit to transition from zero current (a_1Vdd with a_1 = 0.5) to the trip point (threshold at a_2Vdd with a_2 = 0.95) = τ·ln ((1- a_1)/ (1- a_2)), with τ = sum of RC time constants
LMV7239 comparator propagation delay	0.1		
Propagation delay from FLT32 input to PWM output	0.015		DS70000657H parameter MP20
logic level 74ACT244	0.01		
gate drive propagation delay	1.7		=Qg/Ig: FQB55N10 has maximum total gate charge of Qg = 98nC IR2181 has 1.8A sink capability but we have a 33Ω series resistor from gate to IR2181 V_{OL} of 0.1V. The minimum threshold voltage of 2.0V tells us we have a worst-case minimum current, while the MOSFET is switching off, of Ig = (2.0V-0.1V)/33Ω = 57.6mA. This is probably overconservative; other methods estimate typical turn-off time of approximately 0.6µs.
Total	6.9	3.2	

In general, the filtering time in the overcurrent trip circuitry should be as long as possible while still permitting short-circuit detection within a comfortable margin of the single-pulse SOA. This filters out undesirable transients that are discussed in section 4.1.6.4.3.

4.1.5.4 Conclusion

- Currents with a three-phase amplitude ≤ 8.68A or less will keep transistor case temperature ≤ 88.5°C
- Maximum short-circuit pulse time for 48Vdc or less, at this case temperature, is 9.1µs
- Total detection and response time of hardware overcurrent trip is less than 7µs
- This leaves adequate margin to support operation at 8.68A amplitude and withstand a short-circuit event.

4.1.5.5 Increasing the current range

Customers who are operating at DC link voltages below 48V, are willing to forgo the need to survive an overcurrent event, and/or are willing to provide forced convection to transfer heat away from the transistors, may be able to operate the MCLV-2 board at higher currents. Careful effort is needed to validate the use of the board at the desired current value; the MCLV-2 board does not contain any other mechanism (for instance, a thermal sensor in close proximity to the transistors) than the overcurrent sense circuitry to prevent the transistors from exceeding their rated temperature.

4.1.6 Overcurrent trip threshold

The design of hardware overcurrent trip circuitry is often misunderstood. This section outlines key aspects of design and analysis.

4.1.6.1 What is a hardware overcurrent detection circuit supposed to do?

The purpose of a good hardware overcurrent trip circuit is to detect and prevent catastrophic hardware failure, namely the following sequence of events:

- **Output terminal of a half-bridge is short-circuited to one of the DC link terminals** (positive or negative). This could be because a transistor fails shorted, or there is an external short-circuit through the load. Let's assume it is short-circuited to DC+. (Similar behavior occurs if it is short-circuited to DC- because of a failed transistor.[1])
- **The drive turns on the complementary transistor to the short circuit** – in this case, the low-side transistor.
- **Very high current flows across the DC link**, limited by the linear region of the transistor where it acts like a constant current sink. Even if there is a current limit upstream from the DC link, energy stored in the DC link capacitors is dissipated in the transistor.
- **We could detect this high current, but we don't.**
- **This transistor fails after tens of microseconds.**
- **Depending on the failure mode, there may be other cascaded failures** (arcing, or short-circuit between drain and gate).

A properly-designed hardware overcurrent detection circuit will detect high DC link current before the SOA of the transistors are exceeded. If detected in a short time – typically 1-10 microseconds – the power devices can be shut off and avoid permanent damage.

4.1.6.2 What is a hardware overcurrent detection circuit not supposed to do?

Hardware overcurrent detection should not be used for the following purposes:

- Protect transistors from overheating
- Protect motor from overheating
- Act as a current limiter, so that the drive's output current can operate continuously at some current limit
- Detect current controller failure

This is because in all of these cases, there are accuracy or complexity requirements that are difficult to achieve in hardware, and the timescale of an undesirable event is long enough that a solution is more conducive to software implementations. More detailed information is shown below, in Table 9.

Table 9: Detection/prevention of undesirable events

	Requirements				Conducive to		Comments
Goal	Max time (s)	Accuracy	Complexity	Direction	hardware	software	
Protect transistors from catastrophic short circuit	$10^{-6} – 10^{-5}$	low	low	unipolar	yes	no	Must be independent of software; low accuracy: usually factor of 2 between normal and abnormal current)
Protect transistors from overheating	$10^{-3} – 10^{-1}$	high	high	bipolar	poorly	yes	May require thermal modeling based on phase currents
Protect motor from overheating	$10^{1} – 10^{3}$	high	high	bipolar	no	yes	May require thermal modeling based on phase currents
Limit current; operate up to and at current limit	$10^{-4} – 10^{-2}$	high	high	bipolar	no	yes	Belongs in FOC (current controller)
Detect current controller failure	$10^{-4} – 10^{-2}$	high	high	bipolar	no	poorly	Nontrivial to detect

[1] **Note**: An external hard short-circuit from output terminal to DC link negative is **not** detectable via sense resistors in the DC negative link, because short-circuit current then bypasses the sense resistors. There are ways to detect and mitigate this failure mode, but they are outside the scope of this document.

4.1.6.3 What is a hardware overcurrent detection circuit supposed to ignore?

The overcurrent circuit must tolerate the following sources of error:

- noise
- component tolerance
- overshoot during current control transients
- parasitic signal transients (gate drive currents, parasitic inductance)
- ripple current at the PWM frequency

Because of these issues, normally a well-designed overcurrent threshold is somewhat higher than the ADC sensing range.

4.1.6.4 MCLV-2 overcurrent trip circuitry

The MCLV-2 overcurrent trip circuitry is a comparator fed by the DC link current sense line ("IBUS"), shown in Figure 10.

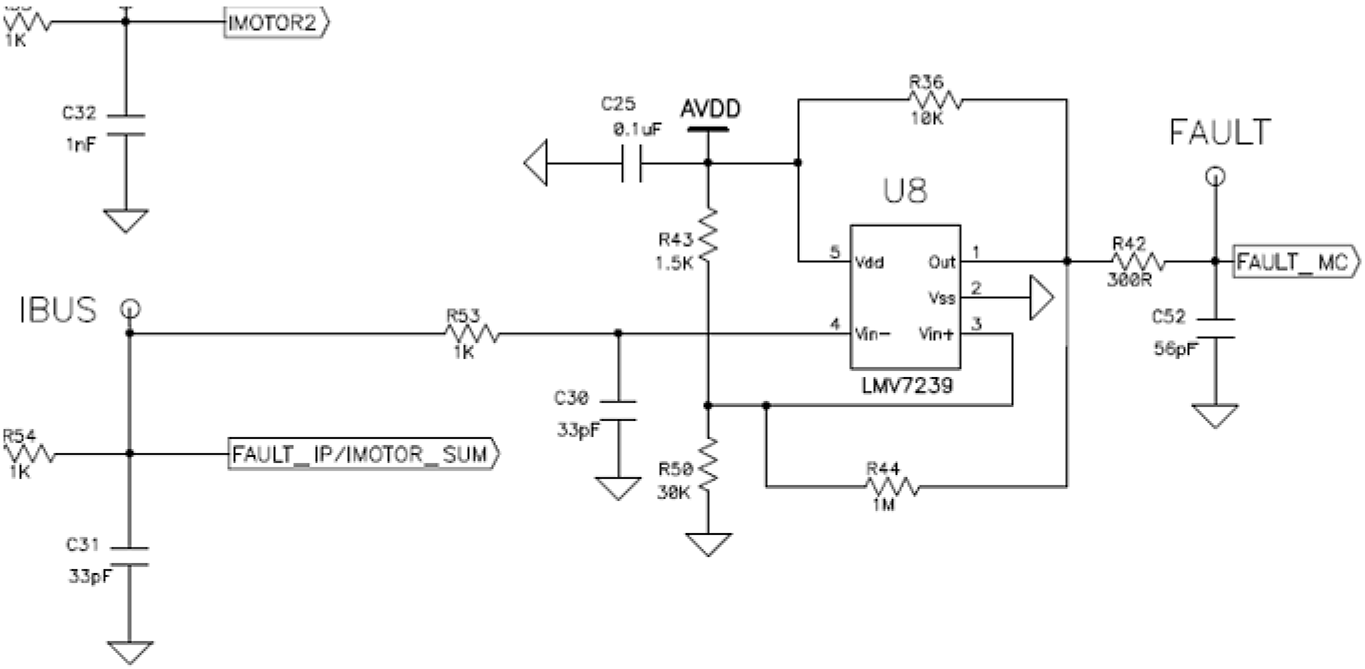

Figure 10: MCLV-2 overcurrent trip circuitry (excerpt from the dsPICDEM™ MCLV-2 Development Board User's Guide, DS52080A page 33)

The nominal full-scale current of MCLV-2 is 4.4A = 1.65V / (25 mΩ × G) where G = 15 is the nominal gain of the current sense circuitry.

The nominal overcurrent trip threshold is determined by the voltage divider R43 and R50, nominally at a voltage of 0.9524 AVdd relative to ground, which corresponds to 0.9048 of full-scale current, which is 3.98A.

The filtering circuitry (R54, C31, R53, C30) acts as a 2-pole low-pass filter with approximate time constant of 66ns, too short to filter out useful transients other than EMI.

Component tolerances can be analyzed in two ways:

- Tolerances of actual overcurrent threshold relative to nominal threshold
- Tolerances of actual overcurrent threshold relative to software current limit

4.1.6.4.1 Relative to nominal

Relative to nominal values of the overcurrent threshold, the following tolerances apply for the unmodified board:

- Shunt resistor tolerance = ±1%
- Gain resistor tolerance = ±2% (one resistor being 1% too high, and the other 1% too low, or vice-versa)

- Vref voltage divider error, which manifests as an offset in Idc current: for a 1:1 voltage divider this is ± 1% of center-to-edge = ±16.5mV
- R43, R50 resistor tolerance: with 1% resistors this represents approx ± 0.2% error in zero-to-full-scale threshold (error gain less than one because the resistor divider ratio is close to 1)
- LMV7239 offset voltage = ±8mV max
- AVdd variability caused by the LM3940 = ±5.1%

The net worst-case tolerance is approximately ±9.78% (=1%+2%+0.2%+5.1%+(24.5mV/1.65V)).

4.1.6.4.2 Relative to software current setting

The MCLV-2 software controls current based on phases A and B (after offset compensation), whereas the overcurrent threshold looks at the DC link current (IBUS). The component tolerances of overcurrent threshold relative to phase currents are the same as relative to absolute current, with the following exceptions:

- Shunt resistor tolerance = ±2% (phase current could be 1% high, DC link current 1% low, or vice-versa)
- Gain resistor tolerance = ±4% (phase current could be 2% high, DC link current 2% low, or vice-versa)
- AVdd variability caused by the LM3940: this cancels out, because it is common to both the ADC channels and the hardware overcurrent trip circuitry
- ADC gain/offset/linearity error– these are normally much smaller than other sources and can usually be neglected, but read the ADC specs. For example, the dsPIC33EP256MC506 (datasheet DS70000657H) has 10-bit ADC gain error of ±2.5 counts (parameter AD23b), or ±0.25%; offset error of ±1.25 counts (parameter AD24b); and INL error of ±0.625 counts below 85°C (parameter AD21b), for a total absolute error of ±4.375 counts or ±0.43%.
- ADC gain/linearity error after offset calibration – ADC readings that have offset calibrated out, after subtracting a baseline reading, will have no offset error but twice the INL, so for the dsPIC33EP256MC506 below 85°C the total error would be ±3.75 counts or ±0.37%.

The net worst-case tolerance is approximately ±8.05% (=2%+4%+0.2%+0.37%+(24.5mV/1.65V))

This puts the hardware overcurrent threshold, in terms of software currents, between 3.66A and 4.30A.

4.1.6.4.3 High-speed transient rejection

There are two sources of high-speed transients that should be ignored by a hardware overcurrent detection circuit:

- Gate drive currents which flow through the shunt resistors
- Parasitic inductance of the shunt resistors

Both these factors appear during a switching transient. Oscilloscope measurements of DC link current (the "IBUS" test point) on an MCLV-2 with unmodified current sense circuitry showed approximately ±0.3V transients on a 1µs timescale:

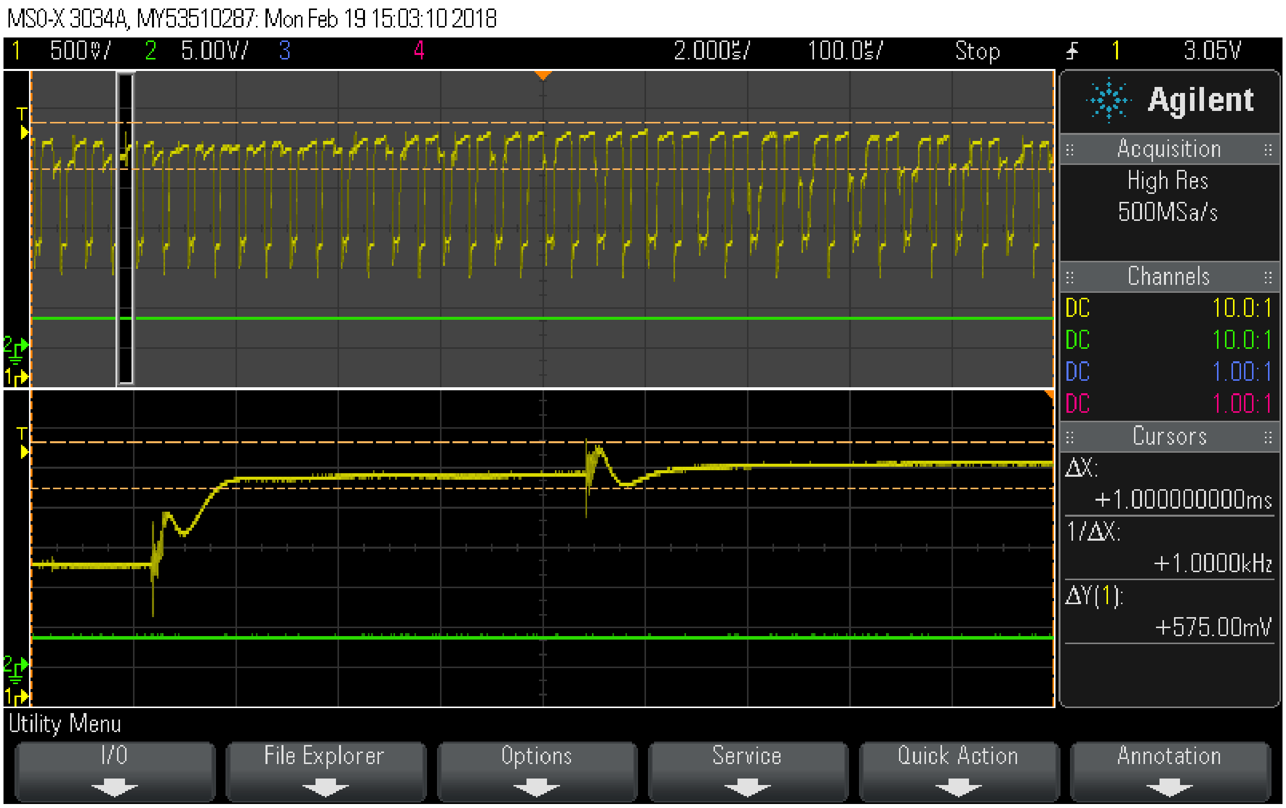

Figure 11: short switching transients in the DC link current ("IBUS") signal

This ±0.3V translates into ±0.8A error; with appropriate hardware modifications this can be filtered out.

4.1.6.4.4 Current ripple

Current ripple at the PWM frequency is superimposed on the average current controlled by the motor drive, and eats into the margin for overcurrent detection.

The worst-case current ripple at the PWM frequency, when using center-aligned PWM, is a peak of VT/12L, where V = the DC link voltage, T = the PWM period, and L = the line-to-neutral motor inductance. This occurs when one phase is being switched at 50% duty cycle and the other two phases are near 0% and 100%, respectively. (RMS current is 1/√3 = 0.577 as much as the peak value.)

For example, a Hurst DMA0204024B101 ("Hurst300") motor with 640µH line-to-line inductance (320µH line-to-neutral), when used with 24Vdc at 20kHz PWM, has a worst-case peak current ripple of 0.31A.

There are no hard guidelines, but one rule-of-thumb would be to allow a peak of 15% of maximum commanded current, and to double-check that the motor does not exceed this, otherwise increase the allowable ratio.

4.1.6.4.5 Control overshoot

Step transients in the input of a current controller can cause overshoot in the response. While this is dependent on control loop performance, an error budget should include a term for control overshoot. Preparing for 10% overshoot is a reasonable value, but this should be verified in individual circumstances by verifying the response to a step change in current.

4.1.6.4.6 Conservative choice of current limit for unmodified MCLV-2

Based on the preceding sections, a conservative choice of software current command limit for an unmodified MCLV-2, driving a Hurst DMA0204024B101 is

3.66A	minimum hardware overcurrent threshold (referred to ADC input)
– 0.80A	false switching transient caused by parasitic transients
= 2.86A	excluding transients faster than sampling rate
÷ 1.25	design margin for current loop overshoot, PWM current ripple
= **2.29A**	Maximum command input to current loop

We budget up to 15% of this, or 0.34A, for peak current ripple, just above that of the Hurst300 motor.

Setting the software current limit more aggressively is possible, but **please understand the consequences before doing this**. The two simplest ways to validate a more aggressive choice of current limit on individual units of the MCLV-2 are

- Use a longer filter time constant for R53 and C30 (see next section)
- Check that component tolerances are near their nominal values rather than worst-case
- Determine worst-case PWM current ripple based on the exact model of motor used

4.1.7 How to improve the current-handling capability

When designing a motor drive, for a given power stage, there are ways to improve the current-handling capability by improving the current sense circuitry and overcurrent trip circuitry.

Some of the following steps were included in test case 1 (see section 5.2):

- **Use a filter time constant that is slightly shorter than the required detection time**. For the MCLV-2, we recommend 2µs. This rejects high-frequency errors caused by gate drive current that flows through the shunt resistors, and any parasitic inductance of the shunt resistors, while still allowing detection that is fast enough to protect the transistors. (See section 4.1.5.3 for more details.)
- **Use surface-mount shunt resistors.** This reduces parasitic inductance, compared to through-hole shunt resistors.
- **Use tighter-tolerance gain resistors in current sense circuitry, and in deriving a reference voltage.** We recommend 0.1% resistors. In 2018 these are not particularly expensive: 10K 0603 0.1% resistors are available from Digikey for US $0.08 each in quantity 100, $0.033 in quantity 1000. Their extra cost above normal 1% resistors should be weighed against the cost of power transistors that must be oversized to handle currents that result from looser-tolerance overcurrent circuitry. (The current sense resistors themselves should be 1% resistors; tighter tolerance is too expensive.)
- **Use an ADC reference voltage independent from the power supply.** Whether a reference voltage is used for the VREF in the ADC, or fed in as another channel for manual gain compensation, this improves accuracy while removing the need for the power supply to have tight tolerance. The Diodes Inc AP431I and AP431S 0.5% 2.5V shunt regulators (TL431-type devices with 100µA minimum regulation current) are available from Digikey in quantity 1000 for approximately $0.09-0.11 each.
- **Set the nominal DC link overcurrent threshold higher than the phase current ADC full-scale.** Hardware overcurrent detection is intended to stop catastrophic overcurrents, at a timescale faster than ADC sampling, so there’s no point in trying to keep the threshold below ADC saturation.

4.2 DC link voltage

There are several main limiting factors of DC link voltage. For the most part, these involve maximum voltage (overvoltage detection), but we will include a short discussion of factors that influence minimum voltage (undervoltage detection)

4.2.1 Relevant parameters required for use with motorBench™ Development Suite

Several parameters are required for use with motorBench™ Development Suite:

- Full-scale ADC voltage
- Equivalent time constant of the voltage sense circuitry
- Voltage rating
- Overvoltage threshold

Specific values are given in section 5.1, covering the test cases considered in this document and the unmodified MCLV-2.

Issues involving these parameters are discussed in detail in the following sections.

4.2.2 Full-scale ADC voltage

Full-scale ADC voltage determines the relationship between ADC counts and real-world current level. In the MCLV-2, all test cases considered below are based on the tolerance of the 3.3V AVdd, and on the voltage divider formed by R5 and R6.

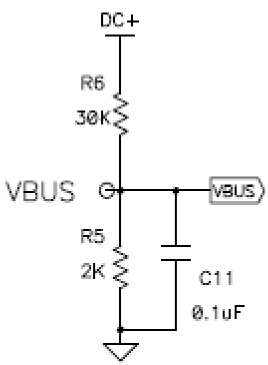

Figure 12: MCLV-2 DC link voltage sensing (excerpt from the dsPICDEM™ MCLV-2 Development Board User's Guide, DS52080A page 37)

- Nominal full-scale voltage is used as a software scaling factor, and is (R6+R5)/R5×AVdd = 16AVdd = 52.8V
- Worst-case tolerance factors include
  - Variation in AVdd: ±5.1% for the LM3940
  - Variation in sense resistors: ±1% resistors cause worst-case full-scale voltage tolerance between 15.7AVdd and 16.3AVdd, or ±1.89% from nominal
  - ADC gain/offset/linearity errors – these are normally much smaller than other sources and can usually be neglected, but read the ADC specs. For the dsPIC33EP256MC506, the worst-case total absolute error is ±4.375 counts or ±0.43% (see section 4.1.6.4.1 for detailed calculation).

Worst-case tolerance of voltage sensing, including full-scale ADC voltage, is therefore ±7.4%, or 48.9V – 56.7V.

Note: Because the analysis above assumes use of the dsPIC33EP256MC506, other devices with different ADC specs may yield slightly wider voltage tolerance.

4.2.3 Equivalent time constant

DC link voltage sensing is modeled by a first-order filter 1/(τs+1) with equivalent time constant τ, and typically consists of a resistor divider with filter capacitance. In this case, the equivalent time constant is the Thevenin equivalent of the resistor divider, multiplied by the filter capacitance. On MCLV-2, this is (R5||R6) × C11 = 1.875KΩ × 0.1uF = 188µs.

In general this time constant should be on the order of 0.1Ts - 1.0Ts where Ts the sampling time; the MCLV-2 time constant for voltage sensing is slightly high for 20kHz switching (Ts = 50us) and C11 would have been better to be a 0.01uF capacitor. Nyquist frequency aliasing of voltage sensing is usually less of an issue than excess phase lag.

4.2.4 Voltage rating

4.2.4.1 Component ratings

Several components of MCLV-2 are affected by DC link voltage Vdc:

Table 10: MCLV-2 components affected by DC link voltage

Ref	Part	Description	Voltage rating	Comments
Q1-Q6	FQB55N10	55A 100V MOSFET, TO263	100V	Little-to-no margin above voltage rating, avalanche failure can be very rapid
U4, U10, U13	IR2181	half-bridge gate drive, SO8	600V	
D5, D7, D9	US1K	ultrafast diode, SMA	800V	
C53	ECA-1JHG471	470uF 63V electrolytic capacitor	63V	Electrolytic capacitors can handle some short overvoltage transients, but repetitive overvoltages reduce component life
C54	CC1206JRNP09BN102	1000pF 50V NP0 1206 capacitor	50V	The schematic suggests using the Panasonic ECJ-2VC2A102J, but the actual part in the MCLV-2 BOM was different.
R6	ERJ-6ENF3002V	30K 125mW 1% 0805 resistor	150V	This is part of a 30K:2K voltage divider; with 48V there is 1.5mA flowing → 68mW dissipation. See section
U9	(dsPIC PIM)		*	The ADC of the microcontroller sees the output of a voltage divider; this is current-limited but can cause input-protection diodes to become forward-biased. See section 4.2.4.2.3.

FIGURE A-3: dsPICDEM™ MCLV-2 DEVELOPMENT BOARD SCHEMATIC (SHEET 3 OF 7)

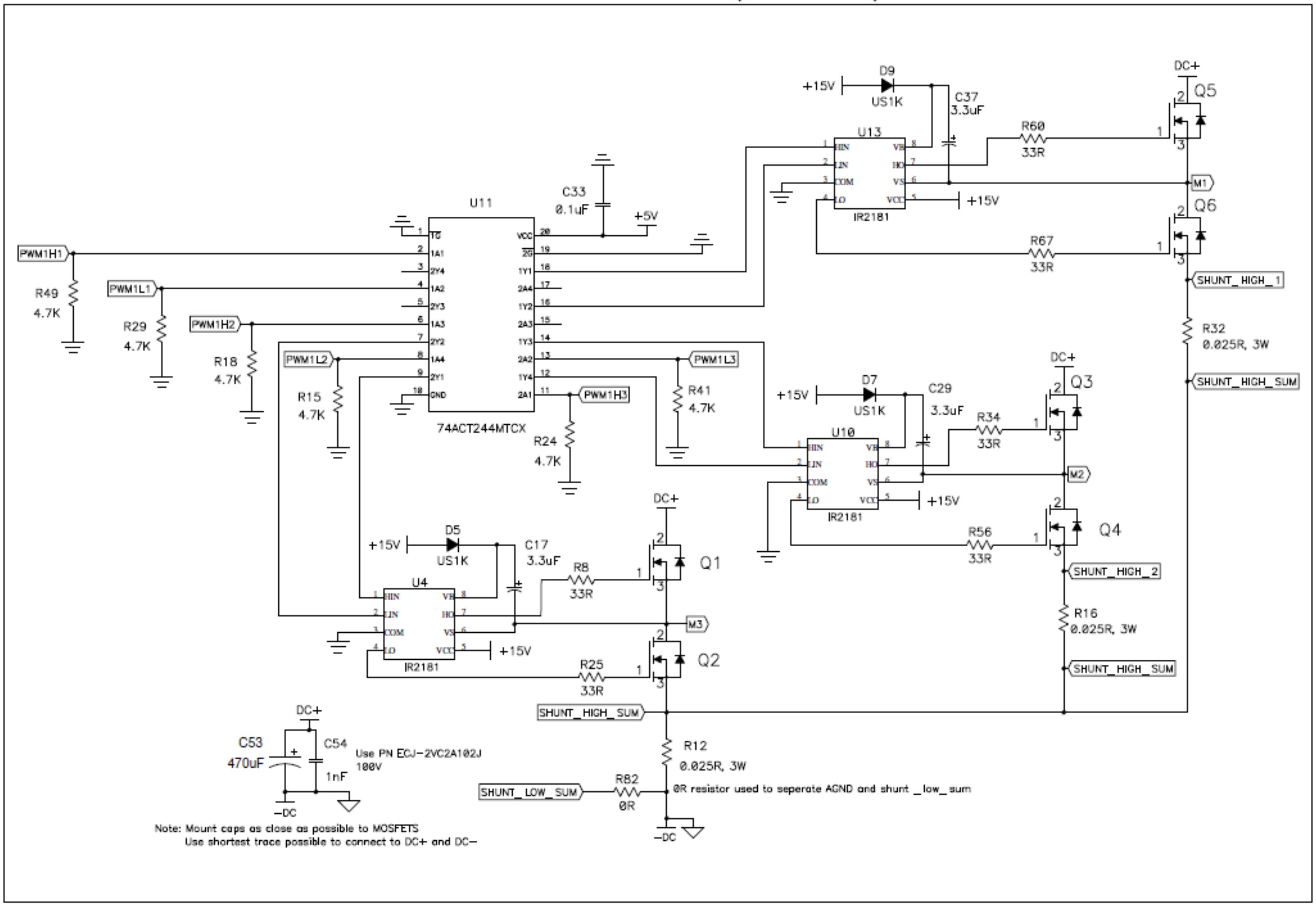

Figure 13: MCLV-2 components affected by Vdc (excerpt from the dsPICDEM™ MCLV-2 Development Board User's Guide, DS52080A page 34)

4.2.4.2 Determining overall voltage rating

At first glance, it looks like the component with the lowest rating determines the rated voltage, namely C54's 50V for the unmodified MCLV-2, or C53's 63V for modified MCLV-2 boards that replace C54 with a 100V ceramic capacitor as in Test Case 2.

Unfortunately, component voltage ratings must be interpreted and are subject to derating guidelines.

Furthermore, nominal DC link voltage and instantaneous voltage present across each component are different – we might be using MCLV-2 with a 48V nominal power supply, but the power supply is 48V ± 2% DC, plus 0.5% worst-case noise spikes, and the MCLV-2 itself produces switching spikes on various components.

Note also that voltage rating and current rating are not independent — in order to keep the transistors within SOA during temporary short-circuit conditions, the value of Vdc must be taken into account when determining a safe current rating.

4.2.4.2.1 Derating guidelines (general)

There are different voltage derating guidelines out there, with varying levels of conservativeness.

- The capacitor vendors may have suggestions: NIC suggests that its aluminum electrolytic capacitors can be operated fully up to the rated voltage (including any ripple voltage)
- Standards such as MIL-STD-975M (NASA) aim to increase reliability by operating components at reduced electrical stress, and have dictated certain guidelines; for example, see Figure 14.

MIL-STD-975M (NASA)

3.1 CAPACITOR DERATING CRITERIA **Capacitors**

Voltage derating is accomplished by multiplying the maximum operating voltage by the appropriate derating factor appearing in the chart below.

Type	Military Style	Voltage Derating Factor (2)	Specification	Maximum Ambient Temperature
Ceramic	CCR (3)	0.60	MIL-C-20	110°C
	CKS	0.60	MIL-C-123	110°C
	CKR (3)	0.60	MIL-C-39014	110°C
	CDR (3)	0.60	MIL-C-55681	110°C
Glass	CYR	0.50	MIL-C-23269	110°C
Plastic film	CRH	0.60	MIL-C-83421	85°C
	CHS	0.60	MIL-C-87217	85°C
Tantalum, foil	CLR25	0.50	MIL-C-39006/1	70°C
	CLR27	0.50	MIL-C-39006/2	70°C
	CLR35	0.50	MIL-C-39006/3	70°C
	CLR37	0.50	MIL-C-39006/4	70°C
Tantalum, wet slug	CLR79	0.60 0.40	MIL-C-39006/22	70°C 110°C
	CLR81	0.60 0.40	MIL-C-39006/25	70°C 110°C
Tantalum, solid	CSR (1)	0.50 0.30	MIL-C-39003/1,2	70°C 110°C
	CSS (1)	0.50 0.30	MIL-C-39003/10	70°C 110°C
	CWR (1)	0.50 0.30	MIL-C-55365	70°C 110°C

(1) For applications where the effective circuit resistance is less than 1 ohm per volt, contact parts specialist.
(2) Applies to the sum of peak AC ripple and DC polarizing voltages.
(3) For low-voltage applications (<10 Vdc), rated voltage shall be at least 100 Vdc.

Figure 14: Capacitor derating criteria, from MIL-STD-975M

Resistor derating guidelines are also variable; some conservative guidelines e.g. US Navy SD-18[2] assume a 50%-70% power derating from the rating specified in the datasheet, with further derating at high ambient temperatures:

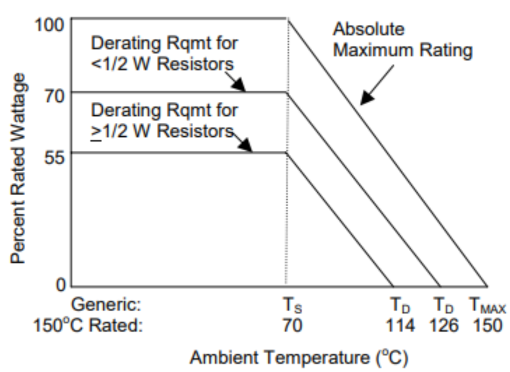

Figure 15: Resistor power derating criteria, for fixed-value film chip resistors, from US Navy SD-18

[2] http://www.navsea.navy.mil/Portals/103/Documents/NSWC_Crane/SD-18/ResistorsDerating.pdf

Other military guidelines are similar, for example RADC-TR-82-172[3] also recommends a 50-70% power derating at low ambient temperatures. NASA's guidelines in MIL-STD-975M are more severe, recommending 60% derating for all types except type RLR metal film resistors, which have a guideline to derate down to 30%.

The datasheet[4] for the Panasonic ERJ-6E series thick-film chip resistor used for R6 contains the derating guidelines shown in Figure 16 (specifically the upper line for 6E parts, connecting 70°C to 155°C), with no derating (100%) for low-temperature ambient environments.

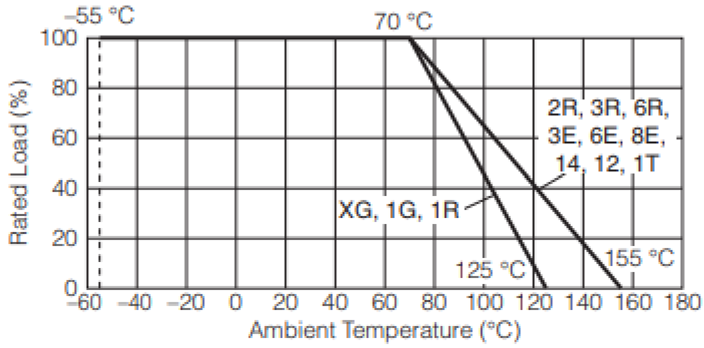

Figure 16: ERJ series chip resistor, power derating

4.2.4.2.2 Methodology used for MCLV-2

We used full voltage rating of the capacitors and resistors, but assumed that the MOSFETs need derating, since they are sensitive to fast transients, and parasitic inductance will cause voltage spikes above what is externally measurable. If capacitor C54 is replaced with a 100V ceramic capacitor, then the DC link voltage should be kept within the limits shown in Table 11.

Table 11: Limits for DC link voltage

Limit	Value	Rationale
Instantaneous	63V	• Stays below electrolytic capacitor (C53) absolute max rating • Leaves comfortable margin for 100V MOSFETs • Leaves sufficient margin for 75V, 80V MOSFETs
Quasistatic (DC / low-frequency)	55V	• Leaves 8V below instantaneous limit for switching spikes • We measured 5.5V switching spikes on MCLV-2 directly across C53 when operated at 48Vdc • Worst-case tolerance of software overvoltage threshold can be kept below this level (see section 4.2.5) • R6, ADC input pin clamp current kept at reasonable levels (see section 4.2.4.2.3)

4.2.4.2.3 Resistor divider and ADC input pin

The choice of 55V maximum quasistatic voltage has implications for resistor R6 and the ADC input. The resistor divider circuit is shown in Figure 12.

Input pins on a dsPIC have input-protection diodes leading to AVdd. The worst-case condition, both for the ADC and R6, is the following:

- AVdd is at its minimum (3.13V for LM3940)
- input protection diodes have low voltage drop – there are no specs on this, but an assumption of 0.3V is extremely conservative. (In reality, voltage drop across the protection diodes is probably in the 0.5-0.8V range,

[3] http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.348.4403&rep=rep1&type=pdf
[4] https://industrial.panasonic.com/cdbs/www-data/pdf/RDA0000/AOA0000C304.pdf

but this leads to less current through R6 and through the ADC pin, so if we can show that 0.3V diode drops still keep conditions below their ratings, then such an assumption is reasonable.)

- R6 is at the low end of its tolerance range = 30K – 1% = 29.7KΩ – this maximizes current through R6 and its power dissipation.
- R5 is at the high end of its tolerance range = 2K + 1% = 2.02KΩ – this minimizes current shunted away from the ADC input pin.

This leads to the assumption that the center of the voltage divider leading into the ADC pin is clamped at around 3.43V. At Vdc = 55V, this implies 51.6V across R6, with a current of 1.737mA through R6, dissipating 89.6mW. Current through R5 is 1.698mA, leaving 39µA to flow through the input protection diode. In general, this current can be calculated as (Vdc/K – Vclamp) / Rth, where K is the voltage divider ratio (16:1 nominal, 15.7:1 worst-case) and Rth is the Thevenin equivalent R6 || R5 = 1.891KΩ for resistors at the end of their tolerance range.

During thermal testing of the MCLV-2 board to determine its current rating, we found that ambient temperature around R6 ranged from 60 - 65°C. (This covers region "Bx9" in the bottom center of the thermal camera image in Figure 7)

Therefore, both R6 power dissipation and the ADC input current are kept at reasonable levels:

- 89.6mW worst-case is 71.7% of the full 125mW power rating; at 65°C ambient, this has a reasonable margin below the derating curve shown in Figure 12.
- 39µA is far below the injection current limit of 5mA per pin, 20mA for all pins of the dsPIC33EP256MC506. (see DS70000657H-page 410)

4.2.5 Software overvoltage threshold selection and response time

We recommend a software overvoltage threshold setting that is at or below 51V, for several reasons:

- It is below the ADC saturation level (52.8V nominal)
- 51V nominal in software translates into 47.2V – 54.8V real-world value (worst-case component tolerance error is ±7.4%; see section 4.2.2), which can be used with high confidence to detect voltages above the 55V quasistatic rating we recommended in section 4.2.4.2.2

MCLV-2 does not contain a hardware overvoltage detection circuit. There is a software undervoltage and overvoltage detection routine that executes each PWM cycle to disable MOSFETs; delay before detection is caused primarily by the 188µs equivalent time constant RC filter.

4.2.6 Overvoltage threshold and response time

Some applications may require a hardware overvoltage detection circuit. Although MCLV-2 does not contain one, this section provides some guidance on hardware overvoltage detection.

4.2.6.1 Overview

The intent of hardware overvoltage sensing is to protect the transistors from an overvoltage condition. There should be enough design margin between each of the following voltages, in descending order:

- Voltage rating of the transistor
- Switching spikes within the transistor package itself
- Hardware overvoltage threshold
- DC link voltage switching spikes
- Voltage rating of the power stage (quasistatic operation)

MOSFETs and IGBTs can fail very rapidly and must be protected from voltage surges by disabling the gate drive.

In a 220VAC nominal system there is often power factor correction to boost the DC link, and the relevant voltages are usually around the following:

- 600V IGBTs
- Switching spikes within the transistor package in the 400-600V range

- 400-420V hardware overvoltage rating
- DC link voltage switching spikes somewhere in the middle of the preceding and following voltages
- 350-380V DC link voltage
- Rectified AC input varies by country[5]; the highest standard AC mains voltage is 240Vrms and is used in several island nations and in Kenya, Malaysia, and Uganda. Typical input voltage ratings on electrical equipment intended for standard AC mains are 85-264Vrms = 120-373V rectified DC.

The switching spikes on the transistors are caused by parasitic inductance (L di/dt voltage) in the transistor package itself. The large safety factor between transistor voltage rating and the operating DC link voltage is due to very fast changes in current during switching; L di/dt in the transistor itself is essentially impossible to measure, so this tends to be very conservative.

4.2.6.2 What causes an overvoltage condition?

There are three main causes of overvoltage:

- Direct: voltage source itself has an overvoltage, e.g. AC mains surge or battery overvoltage
- PFC control failure: the feedback loop controlling Vdc goes out of range
- Regeneration: energy generated back onto the DC link during regenerative operation has nowhere to go and pushes the DC link up

In MCLV-2, as long as laboratory power supplies are used, regeneration is the only possibility. There is no regenerative brake to dissipate extra energy, and the bulk capacitor C53 will be charged up enough until the drive is disabled or one of the components on Vdc fails.

4.2.7 Is it important to detect an undervoltage condition?

There are four main reasons to detect Vdc below an undervoltage threshold:

- Gate drive operation — sensing of Vdc itself isn't usually done; most gate drives with undervoltage lockout usually rely on sensing the gate drive supply directly.
- Power source collapse — battery-powered motor drives have an interesting failure mode caused by the interaction of battery resistance and the constant-power behavior of motor control loads. If a motor drive is used to maintain a given torque-speed operating point, then the power drawn from Vdc is essentially constant. With a battery supplying Vdc having some internal open-circuit voltage Vbat and resistance Rbat, the maximum power delivery is at Idc = Vbat / 2Rbat, so that half the power is dissipated in Rbat and half is drawn by the motor drive. At this point the power drawn by the DC link is $(Vbat)^2/4Rbat$, and any attempt to draw more power from Vdc will essentially collapse the DC link, drawing high currents until equilibrium is met or the power load from the battery decreases. Note that this can happen regardless of the battery's state of charge, but since Vbat decreases and Rbat increases with decreasing state of charge, it is more likely to occur when a battery is empty.
- Battery end-of-discharge — batteries should never be discharged below some characteristic voltage.
- Valid design range — the control software has been designed to meet a certain valid Vdc range based on assumptions that voltage will be within this range; operation outside that range violates these assumptions and may cause decreases in performance or failure. MCAF R3 is designed to operate down to 1/8 of full-scale voltage sensing range (6.6V for the nominal 52.8V full-scale) but may have additional vulnerabilities at low voltage which we aim to uncover during testing.

4.2.8 Can Q1-Q6 be replaced with 75V or 80V MOSFETs to achieve lower Rdson?

MOSFETs with 75V or 80V rating can be used, and will have sufficient margin if Vdc is kept below 55V quasistatic, 63V instantaneous.

Proper thermal analysis and testing are required to determine the resulting current rating. (See section 4.1.)

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[5] Reputable lists and standards of AC mains voltage by country are notoriously hard to find. See http://www.iec.ch/worldplugs/list_bylocation.htm

4.2.9 What components should be modified to allow increased DC link voltage above 55V?

Section 4.2.4.2.2 discusses 55V quasistatic and 63V instantaneous ratings (and the replacement of C54 to achieve these ratings). Tolerance in the ADC sense circuitry, however, limits these values further, depending on actual component values; the nominal software overvoltage threshold of 51.0 discussed in section 4.2.5 may translate to an actual Vdc of 47.2V.

To increase these values, we suggest two possible modifications of Test Case 2, as shown in Table 12.

Table 12: Increasing DC link voltage

Vdc limit	Parameter [1]	TC2	TC2A	TC2B	Comments
Instantaneous	V02	63.0V	80.0V	100.0V	Measured at DC link capacitor
Quasistatic		55.0V	70.0V	88.0V	Measured taking into account RC time constant (see section 4.2.3)
Maximum overvoltage	V03	54.8V	[2]	[2]	Must be below the quasistatic limit
Nominal overvoltage	V04	51.0V	[2]	[2]	
Minimum overvoltage	V05	47.2V	[2]	[2]	

Note [1]: Parameters in the table above refer to Table 13 in section 5.1.

Note [2]: Overvoltage thresholds subject to good engineering judgement and component tolerances.

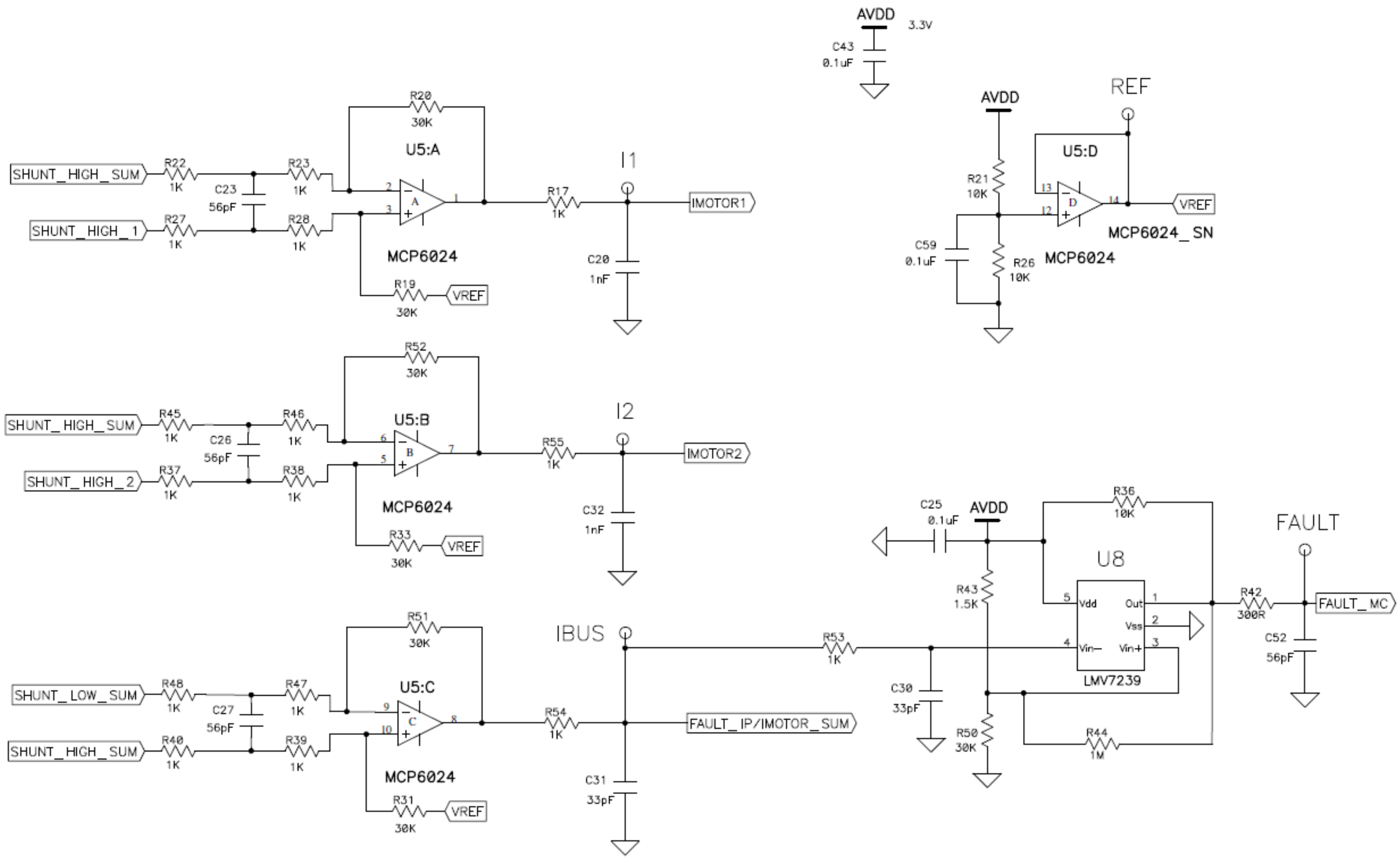
- TC2A = quasistatic operation rated no higher than 70.0V:
  - Replace C53 with an electrolytic capacitor rated at least 80Vdc.
  - Replace R6 with a higher-value resistor, so that the following requirements are met:
    - Full-scale voltage range should be increased to cover the intended operating range
    - ADC input pin injection current is kept low – this should follow from proper choice of full-scale voltage range, but please verify this through analysis as in section 4.2.4.2.3.
    - Power ratings leave sufficient design margin – consider a 1/4W 0805 resistor such as the Stackpole RNCP series
  - Determine appropriate overvoltage threshold to keep below quasistatic limit and above intended operating voltage range.
- TC2B = quasistatic operation rated no higher than 88.0V:
  - Replace C53 with an electrolytic capacitor rated at least 100Vdc.
  - Replace Q1-Q6 with MOSFETs rated at least 120V. (There are 120V-rated MOSFETs available, but selection is limited compared to 150V-rated devices.)
  - Replace R6 with a higher-value resistor per the same requirements as in TC2A
  - Determine appropriate overvoltage threshold to keep below quasistatic limit and above intended operating voltage range.

Note: Neither of these cases have been tested.

We do not recommend usage of MCLV-2 above 88.0V quasistatic / 100.0V instantaneous. Creepage and clearance distances on this board were not designed for high voltage.

5 Test cases

The following circuitry is reproduced from page 30 of the dsPICDEM™ MCLV-2 Development Board User's Guide (document DS52080A).



Note 1: All resistors on this page must be 1%.

2: Supply Voltage should be AVDD for MCP6024.

Figure 17: MCLV-2 current sense circuitry

5.1 Intended ratings of each test case

The column “Base” refers to unmodified MCLV-2; test cases 1-4 are given in the columns labeled TC1 – TC4. Highlighted cells are differences from the unmodified MCLV-2.

Background for calculations of each of these cases is given in section 4, or where noted in the “Comments” column.

Table 13: Parameters contributing to voltage and current ratings

#	Parameter	Base	TC1	TC2	TC3	TC4	Comments
R01	Hardware overcurrent trip threshold, tolerance	8.05%	3.55%	8.05%	8.05%	8.05%	See sections 4.1.6.4.1, 5.2.2; relates OC trip to software command limit
R02	Software current tolerance	8.47%	6.67%	8.47%	8.47%	8.47%	See section 5.2.2
R03	Design margin for avoiding overcurrent trip	25%	25%	25%	25%	25%	Intended to cover control overshoot and PWM current ripple
I01	Full-scale current, nominal	4.40A	11.00A	4.40A	4.40A	2.20A	
I02	Maximum current for thermal limitations	8.68A	8.68A	8.68A	8.68A	8.68A	
I03	Current command limit, nominal, for thermal limitations	7.94A	8.10A	7.94A	7.94A	7.94A	I02 × (1-R02)
I04	Hardware overcurrent trip threshold, nominal	3.98A	9.95A	3.98A	3.98A	1.99A	
I05	Hardware overcurrent trip threshold, minimum	3.66A	9.60A	3.66A	3.66A	1.83A	I04 × (1-R01)
I06	False current transients	0.8A	0	0.8A	0.8A	0.4A	Affected by OC filtering
I07	Current command limit, nominal, to avoid overcurrent trip	2.29A	7.68A	2.29A	2.29A	1.14A	Set to (I05-I06)/(1+R03)
I08	Current command limit	2.29A	7.68A	2.29A	2.29A	1.14A	Set to min(I03, I07)
V01	Full-scale voltage, nominal	52.8V	52.8V	52.8V	52.8V	52.8V	
V02	Maximum instantaneous DC link voltage	50.0V	50.0V	63.0V	50.0V	50.0V	Determined by C53 and C54
V03	Overvoltage threshold, maximum	30.1V	30.1V	54.8V	30.1V	30.1V	7.4% above V04 (due to tolerance)
V04	Overvoltage threshold, nominal	28.0V	28.0V	51.0V	28.0V	28.0V	
V05	Overvoltage threshold, minimum	25.9V	25.9V	47.2V	25.9V	25.9V	7.4% below V04 (due to tolerance)
V06	Maximum normal operating voltage	26.0V	26.0V	48.5V	26.0V	26.0V	See section 5.3.1. Individual boards at the edge of their tolerance may be limited to V05.
V07	Nominal operating voltage	24.0V	24.0V	48.0V	12.0V	24.0V	
V08	Minimum normal operating voltage	16.0V	16.0V	16.0V	11.0V	16.0V	
V09	Undervoltage threshold, nominal	14.0V	14.0V	14.0V	10.0V	14.0V	
V10	Maximum operating voltage, UI	26.0V	26.0V	49.0V	26.0V	26.0V	MCAF R3: V04 = V10 + 2V
V11	Minimum operating voltage, UI	16.0V	16.0V	16.0V	12.0V	16.0V	MCAF R3: V09 = V11 – 2V
T01	Equivalent time constant, current sense	1.0μs	1.0μs	1.0μs	1.0μs	1.0μs	R17 × C20 and R55 × C32; see section 4.1.3

Currents cited refer either to dq-frame amplitude |Idq| (I01, I02, I03, I07, I08) or hardware overcurrent limit (I01, I04, I05, I06), or both, as in I01 (since phase current and DC link current use the same signal conditioning gains). As discussed in section 6.1.1, |Idq| = 1.0A at constant frequency describes 3-phase currents of 1.0A amplitude, 120° apart.

5.2 Test case 1: Increased current capability at 24Vdc

5.2.1 Rework description

Table 14: Bill of Materials for TC1

Qty	Specification	Manufacturer	Part # (Digikey part #)	Comments
1	capacitor, low ESR 63V electrolytic	United Chemi-Con	EGPD630ELL242MM40H (565-3816-ND)	Do not second-source; ripple current specification is important.
6	resistor, 12K 0.1% 0805	Panasonic	ERA-6AEB123V (P12KDACT-ND)	2nd-sourcing ok
2	resistor, 10K 0.1% 0805	Panasonic	ERA-6AEB103V (P10KDACT-ND)	2nd-sourcing ok
12	resistor, 1K 0.1% 0805	Panasonic	ERA-6AEB102V (P1KDACT-ND)	2nd-sourcing ok
1	resistor, 100Ω 1% 0805	Yageo	RC0805FR-07100RL (311-100CRCT-ND)	2nd-sourcing ok
1	resistor, 2K 1% 0805	Yageo	RC0805FR-072KL (311-2.00KCRCT-ND)	2nd-sourcing ok
1	capacitor, 1000pF 50V NP0 0805	Murata	GRM2165C1H102JA01J (490-8285-1-ND)	2nd-sourcing ok

1. **Power supply**
   Remove jumper J6
2. **Current sense gain resistors**
   Change R19, R20, R33, R52, R51, R31 from 30K 1% 0805 to 12K 0.1% 0805.
   This reduces current sense gain from 15 to 6.
3. **Current sense gain resistors**
   Change R22, R23, R27, R28, R45, R46, R37, R38, R48, R47, R40, R39 from 1K 1% 0805 to 1K 0.1% 0805.
4. **Vref divider**
   Change R21, R26 from 10K 1% 0805 to 10K 0.1% 0805
5. **Overcurrent trip dynamics**
   Change R54 from 1K to 100Ω 1%
   Change R53 from 1K to 2K 1%
   Change C30 from 33pF NP0 0805 to 1000pF 5% NP0 0805
6. **Increasing ripple current capability**
   Change C53 from 470uF 63V to United Chemi-con EGPD630ELL242MM40H (2400uF 63V 5.66Arms) – note: this requires manual lead-bending to fit in the MCLV-2 board, which has approx 5mm hole spacing but the capacitor is 7.5mm lead spacing.

5.2.2 Recalculated current tolerances

The use of 0.1% resistors tightens up the range of current tolerances. This changes the calculation done in sections 4.1.6.4.1 and 4.1.6.4.2 as follows:

Table 15: Error analysis for TC1 modifications

#	Source of error	Unmodified MCLV-2	Rework for test case 1
A	Sense resistor gain tolerance, nominal vs. actual current	±1%	same
B	Sense resistor gain tolerance, worst-case phase current vs. DC link current	±2%	same
C	Current sense gain tolerance, nominal vs. actual current	±2%	±0.2%
D	Current sense gain tolerance, worst-case phase current vs. DC link current	±4%	±0.4%
E	Overcurrent threshold resistor divider tolerance	±0.2%	same
F	Tolerance of AVdd 3.3V regulator	±5.1%	same
G	Absolute error of ADC after offset compensation (no offset error, twice INL; assumes dsPIC33EP256MC506, 10-bit operation)	±0.37%	same
H	Vref offset of 1:1 voltage divider	±1% of center-to-edge = ±16.5mV	±0.1% of center-to-edge = ±1.65mV
I	Vos of comparator	±8mV	same
	Total worst-case error, nominal vs. actual overcurrent threshold (A+C+E+F+H+I)	±9.78% =1%+2%+0.2%+5.1% +(24.5mV/1.65V)	±7.08% =1%+0.2%+0.2%+5.1% +(9.65mV/1.65V)
	Total worst-case error, software phase current vs. actual overcurrent threshold (B+D+E+G+H+I)	±8.05% =2%+4%+0.2%+0.37% +(24.5mV/1.65V)	±3.55% =2%+0.4%+0.2%+0.37% +(9.65mV/1.65V)
	Total worst-case error, software phase current accuracy after offset compensation (A+C+F+G)	±8.47% =1%+2%+5.1%+0.37%	±6.67% =1%+0.2%+5.1%+0.37%

5.3 Test case 2: Nominal current capability at 48Vdc

5.3.1 Detailed comments on intended rating

Rating V05 for test case TC2 of 48.5V refers to the absolute maximum voltage applied at input terminals on J7 – applications that require a higher (looser) upper limit will need to verify that the voltage on the terminals of capacitor C53 does not exceed its rating.

5.3.2 Rework description

Table 16: Bill of Materials for TC2

Qty	Specification	Manufacturer	Part # (Digikey part #)	Comments
1	capacitor, 1000pF 100V NP0 1206	AVX	12061A102JAT2A (478-1450-1-ND)	2nd-sourcing OK

1. **Power supply**
   Remove jumper J6
2. **DC link ceramic capacitor**
   Change C54 to 1000pF 100V NP0 1206 – this is presently a 50V part (User's guide says it's 100V but the BOM for MCLV-2 used a different part). This is located near the electrolytic capacitors.

5.4 Test case 3: Nominal current capability at 12Vdc

5.4.1 Rework description

1. **Power supply**
   Remove jumper J6

5.5 Test case 4: Decreased current capability at 24Vdc

5.5.1 Rework description

Table 17: Bill of Materials for TC4

Qty	Specification	Manufacturer	Part # (Digikey part #)	Comments
3	50 milliohm ±1% 3W through-hole sense resistor	Ohmite	13FR050E (13FR050E)	Do not second-source

1. **Sense resistors**
   Replace R12, R16, R32 with Ohmite 13FR050E

6 Motor ratings

6.1 Rated current

The rated current of a motor can be notoriously confusing to identify. It cannot be measured, except through destructive or intrusive experiments on a population of motors. This is a parameter that should be provided in a clear manner by the motor manufacturer, but many motor manufacturers are not clear about what they mean when they list "rated current" in the datasheet.

As a result, it is necessary to interpret the motor datasheet very carefully. Furthermore, the interpretation of rated current depends somewhat on how it is used: duty cycle[6] and ambient temperature can affect the actual current rating in any given application.

6.1.1 Definition of rated current for MCAF and motorBench™ Development Suite

The Motor Control Application Framework and motorBench™ Development Suite use the following definition of rated current:

> Continuous dq-frame amplitude of current in field-oriented control, under all conditions, including stall

- Current is measured as an amplitude, not RMS. A value of 1.0A amplitude under constant-frequency commutation (*not* including stall) translates into sine-wave currents on each of the motor phases, of 1.0A amplitude (0.7071Arms), 120° apart.
- Stall behavior is the limiting case as frequency decreases to zero, where commutation angle is fixed. This tends to concentrate thermal dissipation in whichever phase has the highest current flowing, and as a result, one winding of the motor will run hotter than the other two. This means that the current rating of the motor needs to be lower at stall, in order to keep the windings from exceeding their rated insulation temperature. The total power dissipation of the windings does not change significantly, however: even if the commutation frequency changes, the value of $Ia^2 + Ib^2 + Ic^2 = {}^3/_2|Idq|^2$ remains constant under field-oriented control with constant current amplitude.[7]
- MCAF R3 does not provide any transient capability higher than continuous current capability, so peak current rating of a motor is not appropriate to use.

With proper verification, rated current can be decreased to accommodate operation at stall, or increased to accommodate applications of low duty cycle. This type of verification is outside the scope of this document, and usually involves measuring stator winding temperature rise by installing thermocouples or thermistors in very close thermal

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[6] "Duty cycle" in this section refers to its traditional definition, namely the fraction of time a machine is in use, over seconds or minutes or hours, rather than in the sense of pulse-width modulation where modulation frequency is at 10-20kHz.

[7] Technically the sum of I^2R over all three windings *does* change, since winding resistance changes as a function of temperature, but the effect is very small. Consider a hypothetical motor that has been running for a long time, at a moderate commutation frequency with 4.0A amplitude, with the windings reaching 80°C for an ambient temperature of 20°C, and nominal resistance of 1.0 ohm in all 3 windings under this condition. (If the current in the motor were turned off and the motor were allowed to cool, the resistance would drop.) The average I2R dissipation in each winding over a commutation cycle is 8W, or 24W total. Now suppose the motor stalls suddenly, but maintains amplitude of current: Ia = 4A, Ib = -2A, Ic = -2A. Immediately after stall, phase A sees 16W dissipation (an increase of 8W) and the B and C phases see 4W dissipation (decrease of 4W). The total power dissipation is still 24W, but this causes phase A to heat up and phases B and C to cool down, redistributing the heat. For every two degrees that the phase A winding increases, phase B and phase C windings each decrease by one degree. Perhaps the A-phase winding increases to 100°C and the B- and C-phase windings decrease to 70°C. Copper wire has a linear resistance dependence on temperature, with a temperature coefficient of 0.00393 per degree C relative to 20°C. Running through the proper calculations, phase A resistance will increase to 1.064 ohms and phase B resistance will decrease to 0.968 ohms, leading to a total power dissipation of 24.768W: this is only a 3.2% increase for a 30-degree difference between the "hot" phase and the two "cool" phases. This is an unusually large thermal gradient in a motor; usually the stator is constructed so that the windings overlap and there is good thermal coupling between phases, leading to relatively small differences between motor windings at stall. In extreme cases, measure temperature to be certain.

proximity of the windings. Also note that peak current in a motor is dependent on other factors besides wire insulation rating, namely demagnetization and stator iron saturation level.

For many applications, operation at low duty cycles with high current, or at stall, is not necessary, and the continuous current rating of the motor can be used directly.

6.1.2 Effect of low commutation frequencies on transistors

Operation at or near stall affects the rated current of the motor drive power stage, as well as the rated current of the motor itself.

At very low frequencies, power dissipation will tend to concentrate in whichever of the three phases carries the largest instantaneous current, in whichever of the transistors (upper or lower) has the largest duty cycle at the PWM frequency. This produces slightly greater thermal rise in that transistor, than at commutation frequencies of even a modest value[8], where heating is permitted to equalize among the transistors.

6.1.3 Reading and interpreting motor datasheets

The following sections provide some guidelines and sample calculations for interpreting motor current ratings.

6.1.3.1 Relation between RMS current, six-step current and FOC current

Many PMSM datasheets seem to assume the use of six-step current for BLDC applications, rather than sine-drive current for FOC. Current ratings for these two cases are slightly different.

With six-step operation, at any given instant, some current I_6 flows through two of the phases, and no current flows through the third. (Transients at the instant of commutation are short, and can be neglected except in certain high-speed applications.) If the motor commutates smoothly through each of the six possible sectors, then for four of these sectors, phase current is $\pm I_6$, and during the other two sectors, it is zero.

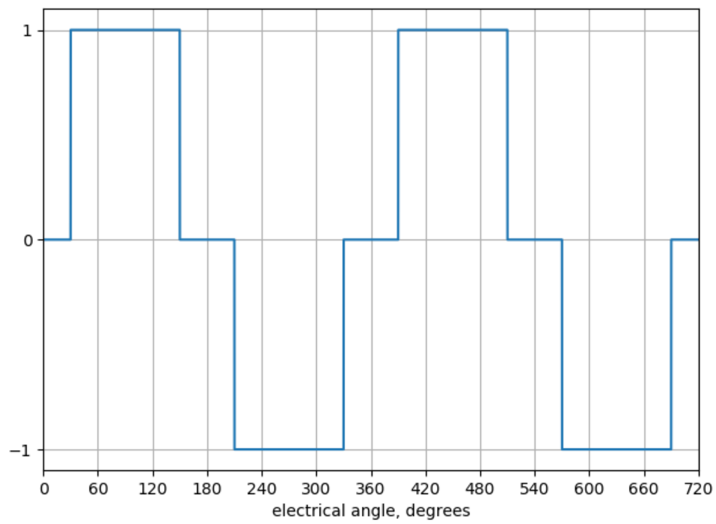

Figure 18: Typical six-step current waveform

The RMS value of this current is $I_{RMS} = \sqrt{\frac{2}{3}} I_6$.

For sine-drive operation, currents during smooth commutation are sinusoidal, and in this case $I_{RMS} = \sqrt{\frac{1}{2}} \left| I_{dq} \right|$.

The conversion factor between I_6 and I_{dq} amplitude for equal I^2R thermal dissipation is therefore $\left| I_{dq} \right| = \sqrt{\frac{4}{3}} I_6 \approx 1.155 I_6$.

[8] This behavior depends on thermal capacitance in the case and any heatsink element closely coupled to the case. For thermal testing of MCLV-2 performed in section 4.1.5, a commutation frequency of roughly 0.08Hz was used, and the resulting temperature swings were approximately 2°C peak-to-peak. MCLV-2 uses TO-263 transistors soldered directly to a copper pour.

6.1.3.2 The perils of using published torque constants

Although the topic of this section is motor current rating, sometimes it needs to be inferred from other datasheet values, such as torque constant. In general, use of the torque constant should be avoided. This is why:

Under FOC, torque is ideally constant and equal to $T_{em} = \frac{3}{2}K_e I_q$, with K_e expressed in V/(rad/s) line-neutral, zero-peak.

Under six-step operation with perfect commutation, average torque $\langle T_{em}\rangle = \frac{3}{2}K_e\langle I_q\rangle = \frac{3}{2}K_e \cdot \frac{3}{\pi} \cdot \sqrt{\frac{4}{3}}I_6 = \frac{3\sqrt{3}}{\pi}K_e I_6 \approx 1.654 K_e I_6$. The constant $\frac{3}{\pi} \approx 0.9549$ comes from the average value of $\cos\theta$ over a perfectly-commutated sector (-30° to +30°), and represents the “torque inefficiency” of six-step operation relative to field-oriented control. Errors in the commutation angle, at which one sector is switched to the next, will lower this value.

The “torque constant” published in the datasheet only rarely includes usage information. It usually refers to a constant of proportionality between motor current and torque. But without knowing whether the datasheet authors meant six-step or sine-drive operation, or how they measure current, it is impossible to determine how to apply it.

6.1.3.3 Other strategies for interpreting motor datasheets

- In the event of ambiguity, contact the motor manufacturer and ask for clarification in writing.
- When conflicting information arises, and all possibilities appear reasonable, choose the one that is most conservative. Both of the examples below make use of this principle.

6.1.3.4 Example 1: BLY342D-24V-3000

The Anaheim Automation BLY342D-24V-3000 is one of the motors we tested with the high-current MCLV-2 (Test case 1).

Item	Rated Voltage (V)	Rated Power (Watts)	Rated Torque (oz-in)	Rated Speed (rpm)	Torque Constant (oz-in/A)	Back EMF Voltage (V/kRPM)	Line-to-Line Resistance (ohm)	Line-to-Line Inductance (mH)	Rotor Inertia (oz-in-sec^2)	"L" Length (in)	Shaft	Weight (lbs)
BLY341S-12V-3000	12	94	42.5	3000	4.15	2.17	0.08	0.16	0.005664	2.28	Single	3.51
BLY341S-24V-3000	24	110	50.0	3000	7.50	6.15	0.15	0.17	0.005660	2.28	Single	3.31
BLY341S-48V-3200	48	110	50.0	3200	13.30	10.50	0.45	0.63	0.005660	2.28	Single	3.31
BLY341D-24V-3000	24	110	50.0	3000	7.71	5.70	0.15	0.17	0.005664	2.28	Double	3.30
BLY341D-48V-3200	48	110	50.0	3200	13.30	10.50	0.40	0.63	0.005664	2.28	Double	3.30
BLY342S-12V-3000	12	189	85.0	3000	4.08	2.13	0.02	0.06	0.005664	2.80	Single	3.53
BLY342S-24V-3000	24	220	100.0	3000	7.93	6.00	0.07	0.08	0.011330	2.79	Single	4.08
BLY342S-30V-3000	30	220	100.0	3000	9.91	7.22	0.12	0.11	0.011330	2.79	Single	4.08
BLY342S-48V-1000	48	147	198.0	1000	43.90	22.20	0.80	2.00	0.011328	2.80	Single	4.10
BLY342S-48V-3200	48	220	100.0	3200	17.00	12.20	0.18	0.35	0.011330	2.79	Single	4.08
BLY342S-160V-3000	160	220	100.0	3000	53.80	40.50	3.26	9.50	0.011330	2.79	Single	4.08
BLY342D-48V-1000	48	147	198.0	1000	43.90	22.20	0.80	2.00	0.011328	2.80	Double	4.12
BLY342D-24V-3000	24	220	100.0	3000	7.93	6.48	0.07	0.08	0.011328	2.80	Double	4.10
BLY342D-30V-3000	30	220	100.0	3000	9.90	7.22	0.12	0.11	0.011328	2.80	Double	4.10

Figure 19: BLY34 series motor parameters

This datasheet does not include rated current, unfortunately. There are three ways of inferring rated current, all assuming six-step operation to determine current I_6 and then compute $|I_{dq}| = \sqrt{\frac{4}{3}}I_6$

1. From rated power and voltage: current $I_6 = P_{rated}/V_{rated}$
2. From rated torque and torque constant: $I_6 = T_{rated}/K_T$
3. From rated torque and back-emf constant: $I_6 = T_{rated}/\left(\frac{3\sqrt{3}}{\pi}K_e\right)$ as per section 6.1.3.2
    - Torque needs to converted[9] from oz-in to Nm; 100 oz-in = 0.706Nm.
    - Back-emf constant needs to be in Nm/(rad/s) line-neutral zero-peak (l-n 0-p); 1 V/KRPM l-l 0-p[10] = $\frac{\sqrt{3}}{100\pi}$ = 0.005513V/(rad/s) l-n 0-p. So 6.48V/KRPM l-l 0-p ≈ 0.0357V/(rad/s) l-n 0-p.

[9] The reputable reference NIST SP811 (https://www.nist.gov/pml/special-publication-811) lists 1 oz-in = 7.061552 × 10^{-3} Nm.

[10] Note that the datasheet does not specify whether back-EMF constant is expressed line-to-line or line-to-neutral, or in RMS or zero-peak. We have found, through independent measurements of several motors, that Anaheim Automation datasheets appear to

Table 18: Calculations for rated current of BLY342D-24V-3000

Method	Calculation for rated I_6	Rated I_6	Rated $\lvert I_{dq} \rvert$
Rated power and voltage	220W / 24V	9.17A	10.6A
Rated torque and torque constant	100oz-in / 7.94 oz-in/A	12.59A	14.54A
Rated torque and back-emf constant	0.706Nm / ($\frac{3\sqrt{3}}{\pi}$·0.0357V/(rad/s))	11.96A	13.81A

Anaheim's torque constant values are unfortunately suspect — the torque constant and back-EMF constant should be exactly proportional, but in the BLY34 series the ratio ranges from 1.2 to 2.0 — so to be conservative, we recommend using the minimum value of these methods, or 10.6A, for rated current $\lvert I_{dq} \rvert$.

6.1.3.5 Example 2: Hurst DMA0204024B101

The Hurst DMA0204024B101 (MicrochipDirect AC300022) has a datasheet that is more complete, and easier to interpret. An excerpt indicating motor parameters is shown in Figure 20.

hurst — ***Sample Motor Data Sheet***

Date: 11/18/2010

Model# **DMA0204024B101**	L-L Resistance (R_{tm}) Ohms : **0.57**	Electrical Time Constant (τ_e) mSec. : **1.123**
Serial #	L-L Inductance (L_{tm}) mH at 1Khz : **0.64**	Mechanical Time Constant (τ_m) mSec. : **2.882**
Model Description: **10P 12 slot Y - connected**	Torque Constant (K_t) oz.in./Amp : **8.38**	Thermal Resistance (R_{th}) °C/watt:
Controller Type: **AMC #BE15A8B**	Voltage Constant (K_e) V_{peak}/K_{RPM}: **6.2**	Thermal Time Constant (τ_{th}) min. :
Amb. Temp. (°C): **21.5**	Stack Length: **3.00**	Rotor Inertia *(Jr)* oz-in-s² : **0.00251**

NOTE: Motor is Y - connected; 12 Slot 10 Pole

Speed / Torque Test Data - Control set at 100% duty cycle.

System Input			Motor Data											Motor Losses
Volts *(DC)*	Amps *(DC)*	Watts *(DC)*	Volts *(RMS)*	Amps *(RMS)*	Watts *(RMS)*	LOAD	TORQUE *(oz.in.)*	SPEED *(RPM)*	Output *(watts)*	Output *(HP)*	Sys. EFF. *(%)*	M-EFF. (%)	Inv. EFF. *(%)*	*(watts)*
24.06	0.23	4.55	20.19	0.24	2.28	1	0.00	3644	0.00	0.00	0.00	0.00	50.15	2.28
24.05	1.07	24.90	20.20	1.01	22.57	2	8.00	3426	20.27	0.03	81.40	89.80	90.65	2.30
24.05	1.92	45.28	20.19	1.82	43.03	3	16.00	3209	37.97	0.05	83.86	88.24	95.03	5.06
24.04	2.76	65.03	20.16	2.61	62.15	4	24.00	3002	53.28	0.07	81.93	85.73	95.58	8.87
24.03	3.59	84.51	20.12	3.42	80.79	5	32.00	2804	66.34	0.09	78.51	82.12	95.60	14.44
24.03	4.42	103.85	20.07	4.22	99.27	6	40.00	2615	77.36	0.10	74.49	77.93	95.59	21.91
24.02	5.26	123.06	20.03	5.04	117.00	7	48.00	2436	86.48	0.12	70.27	73.91	95.08	30.52
24.02	6.10	142.51	19.99	5.86	135.80	8	56.00	2266	93.84	0.13	65.85	69.10	95.29	41.96
24.01	6.94	161.61	19.95	6.67	153.46	9	64.00	2107	99.73	0.13	61.71	64.98	94.96	53.74
24.00	7.81	181.58	19.86	7.47	171.10	10	72.00	1956	104.17	0.14	57.37	60.88	94.23	66.93

Figure 20: Excerpt from Hurst DMA0204024B101 datasheet

Here the yellow highlight most likely indicates the continuous current rating. (The Hurst DMB0224C10002 is similar, but explicitly states "Max Continuous Rating" next to the yellow highlight.)

Note that the peak current/torque ratings are much higher, and therefore the continuous current rating must be due to thermal limits. A sine-drive output current of 4.837A amplitude also has 3.42Arms, so the rated |Idq| for this motor would be 4.837A.

There is one additional piece of conflicting information, however:

The part number, as indicated on the manufacturer's website http://www.hurst-motors.com/ntdynamo.html, represents the following:

- DM – this series of motors (NT Dynamo)
- A0 – externally controlled commutation

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be consistent with measuring back-EMF constant as V/KRPM line-to-line, zero-to-peak. Most vendors use Vrms/KRPM line-to-line: measure RMS voltage between motor terminals, measure speed, compute the ratio.

- 2 – 250ppr encoder
- 0 – no thermal protection
- 4 – 30 oz-in rated torque
- 024 – 24V
- B – winding type
- 101 – size 17 with cables

The 30 oz-in rated torque conflicts with the 32 oz-in listed in the datasheet.

To be conservative, scale down 4.837A rating linearly by 30/32 = 4.53A, for rated |Idq|.

7 Testing

This section summarizes test efforts. Further detailed information is available separately from MCU16 Applications.

7.1 Test motors

We chose motors that were easily available. The Hurst motors can be obtained from MicrochipDirect; Anaheim Automation sells their motors directly, and the Quanum motor we obtained from hobbyking.com.

Table 19: Motors used with test cases TC1-TC4

							Comments
Manufacturer	Nidec Hurst	Nidec Hurst	Anaheim Automation	Anaheim Automation	Anaheim Automation	DongYang Smart Technology Co. Ltd. (DYS)	
Part number	DMA0204 024B101	DMB0224 C10002	BLY342D-24V-3000	BLY342D-48V-3200	BLY171D-24V-4000	Quanum MT4012	
ID	hurst300	hurst075	bly342d-24v-3000	bly342d-48v-3200	bly171d	quanum-mt4012	used by MC team for internal development
Test cases	1, 3	2, 4	1	2	4	3	1: high current 2: 48V 3: 12V 4: low current
Rated current, A	4.53	1.16	10.6	5.29	2.08	15.8	
Rated speed, RPM	3600	3125	3000	3200	4000	8750	
Pole count	10	10	8	8	8	14	
R, line-line, Ω	0.74	5.66	0.24	0.54	1.83	0.28	From self-commissioning
L, line-line, µH	718	4750	226	1080	2530	62	From self-commissioning
Ke, V/KRPM line-line, zero-peak	6.74	7.57	6.42	13.5	3.82	2.42	From self-commissioning
J, µNm/(rad/s²)	18.1	5.5	105	93.1	2.3	19.3	From self-commissioning
B, µNm/(rad/s)	32.2	15.3	62.5	107	4.8	8.3	From self-commissioning
Tf, mNm	4.8	1.7	39.6	43.6	1.6	5.7	From self-commissioning

7.2 Test procedure

MCAF and motorBench™ Development Suite were tested in three ways, two using test hardware and the test motors in Table 19, and one using simulations.

7.2.1 Development build tests

These tests used MCLV-2 boards modified for test cases TC1-TC4, with each of the above motors (four pairs of test cases total), and involve extensive testing using development builds of MCAF outside of motorBench™ Development Suite. Loads vary by test, but include

- No load (motor shaft allowed to spin freely)
- Abrupt disturbances ("hand grab" for small motors) to test stall detection

- Dynamometer loads

The purpose of development build tests is to exercise various edge cases of MCAF, and identify issues relating to various operating points that may be dependent on test cases TC1-TC4 and on different motors. MCAF development builds help to streamline and automate testing, reducing test time and chances of human error.

7.2.2 Abbreviated testing using motorBench™ Development Suite

These tests used the same hardware as development build tests (one pair of motors for each of test cases TC1-TC4, with MCLV-2 boards modified appropriately), following the instructions in section 3.

The purpose of abbreviated testing is to ensure that motorBench™ Development Suite operates as expected for these cases, and interacts correctly with MCAF in each case.

7.2.3 Monte Carlo analysis

Monte Carlo analysis tests were performed for these test cases, using MCAF. These tests ensure that code generation can complete successfully, by running the same calculations used to create the parameters files (parameters/foc_params.h, parameters/fault_detect_params.h, etc.) over a large number of samples distributed near the edges of a nonlinear multivariate sample space.

For computation efficiency, this bypasses motorBench™ Development Suite and most of code generation, but does use the same exact Python calculations to compute configurable parameters.

7.3 Summary of test results

Brief summaries of test results are given below. If more information is needed, please contact the local Microchip office.

7.3.1 Development build tests

During the first quarter of 2018, development build tests were performed on MCAF R2, which has minor differences from the more recent MCAF R3.

Most of the issues found fell into the following categories:

- False trip of stall detection with the torque angle method – this method is disabled by default in MCAF R3
- Oscillation or marginal stability in velocity or current loops in edge cases
- Motor startup failure

These issues have been identified as areas of improvement in MCAF.

7.3.2 Abbreviated testing using motorBench™ Development Suite

In April 2018, all motors in Table 19 were tested on an internal version of motorBench™ Development Suite containing MCAF R2. The only issues found were

- False trip of stall detection with the torque angle method in two motors, at low commanded speed – this method is disabled by default in MCAF R3
- The Quanum motor could not complete the test due to problems in self-commissioning and code generation. Self-commissioning now supports operation at other voltages and this issue has been resolved.

In November 2018, the following motors were tested on a preliminary version of motorBench™ Development Suite 2.0 containing MCAF R3.

Test case	Vdc	Motor	Status
TC1 (high current)	24V	Hurst300	Passed test.
TC2 (48V)	48V	Hurst075	Passed test.
TC3 (12V)	12V	Quanum MT4012	Passed test.
TC4 (low current)	24V	Hurst075	Passed test.

7.3.3 Monte Carlo analysis

A total of 2 million (2×10^6) sample points were used for test cases, according to the following; two minor issues were found that affect particular ranges of motor parameters

- Base case (unmodified MCLV-2 used at 24V): parameter ranges shown below in Table 20.
- TC1 (high current)
  - I01: Fullscale current 11A
  - I08: maximum command current 7.68A
  - Reduced values of R and L (line-neutral):
    - $0.004\Omega \le R \le 8\Omega$
    - $4\mu H \le L \le 12.5mH$
- TC2 (48V)
  - V10: Maximum operating voltage 49V
  - V11: Minimum operating voltage 16V
  - Increased values of magnet flux ψ_m between 1.2mV·s and 60mV·s line-neutral (since $K_e = \psi_m N_p$ with N_p the number of pole pairs, this corresponds to increased values of K_e)
  - Back-emf voltage at rated speed is left unchanged; it already covers roughly 6-52V line-line
- TC3 (12V)
  - Not executed; the base case already includes ranges of motors with low rated voltage, and aside from the overvoltage and undervoltage thresholds, configuration parameter generation is not dependent on operating voltage range

- TC4 (low current)
  - I01: Fullscale current 2.2A
  - I08: maximum command current 1.14A
  - Increased values of R and L (line-neutral):
    - $0.02\Omega \le R \le 60\Omega$
    - $20\mu H \le L \le 60mH$

Table 20: Ranges for base case of Monte Carlo analysis

Metric	Units	Lower range	Upper range	Description
ω_{e1}	rad/s electrical	400	7000	electrical frequency at rated speed
ω_{m1}	rad/s mechanical	36.364	7000	mechanical frequency at rated speed
V_1	V line-neutral 0-p	3.5	40	$K_e\ \omega_{m1}$ = back-emf voltage at rated speed
I_1	A	0.8	20	rated current
P_1	W	1.0	10000	$= I_1\ V_1$
N_p	—	1	11	number of pole pairs
R	Ω line-neutral	0.01	30	stator resistance
L	H line-neutral	10^{-6}	30×10^{-3}	stator inductance
K_e	V/(rad/s) line-neutral 0-p	0.001	1.0	back-emf constant
B	N·m/(rad/s)	10^{-9}	0.01	viscous damping
T_f	N·m	10^{-5}	1.0	Coulomb friction
J	N·m/(rad/s^2)	10^{-9}	0.1	inertia
K_m	N·m/√W	0.002	0.5	$K_e\sqrt{3/(2R)}$ = motor constant
τ_e	s	10^{-4}	0.01	L/R = electrical time constant
τ_m	s	0.0005	0.1	J/K_m^2 = mechanical time constant
ψ_m	V·s line-neutral 0-p	0.0006	0.04	rotor magnet flux
ξ	—	0.9	2.0	Lq/Ld = saliency
$\bar{\tau}_e$(τ_e bar)	—	0.3	6.0	$\tau_e\ \omega_{e1}$ = normalized electrical time constant
$\bar{\tau}_m$(τ_m bar)	—	0.1	500.0	$\tau_m\ \omega_{m1}$ = normalized mechanical time constant
α_J	—	0.1	1000.0	τ_m / τ_e = normalized inertia
α_B	—	0.0005	0.1	B/K_m^2 = normalized viscous damping
α_ψ	—	0.01	1.5	LI_1/ψ_m = normalized magnetic flux utilization
α_{Tf}	—	0.0005	0.5	$T_f/1.5K_eI_1$ = normalized Coulomb friction
α_R	—	0.01	0.5	I_1R/V_1 = normalized stator resistance
$\phi_{m\omega}$	degrees	65	85	Velocity loop phase margin
$\phi_{z\omega}$	degrees	5	15	Velocity loop PI phase lag at crossover

7.3.3.1 High-inertia motors

Use of high-inertia motors with particular settings may cause code generation failures due to an out-of-range error for the parameter `stall_detect.group.timerCountsVarianceDetect`. This parameter is determined based on the crossover frequency of the velocity control loop, and if this crossover frequency is too low, the value of `timerCountsVarianceDetect` exceeds a representable value.

Range errors were observed only when all of the following conditions were true:

- Velocity loop phase margin ≥ 82°
- Velocity loop PI phase at crossover ≥ 13°

- Mechanical time constant $\tau_m = J/K_m^2 \geq 70$ milliseconds
- Normalized viscous damping $\alpha_B = B/K_m^2 \leq 0.0007$

In these conditions, consider reducing phase margin or PI phase at crossover so the velocity loop crossover frequency is slightly greater.

7.3.3.2 High-resistance motors

Use of high-resistance motors may cause code generation failures due to an out-of-range error for the parameter `pll.normRs`. Specifically, a range error is caused when $R_s I_U/V_U \geq 4.0$ where Rs is the line-neutral resistance, I_U is the software fullscale current, and V_U is the software fullscale voltage.

For an unmodified MCLV2, I_U = 8.8A (twice the nominal phase current at ADC fullscale) and V_U = 52.8V (nominal DC link voltage at ADC fullscale), so the maximum value of Rs supported is 24Ω. Motors with resistance this high are likely to be ill-matched to the MCLV-2 board anyway, either because they have low rated current compared to I_U or high nominal voltage compared to V_U (or both).

8 Determining current sense compensation gains

8.1 Overview

The MCLV-2 board has a layout error in the current sense traces that shorts together the Kelvin connections, shown in green in Figure 21, and schematically in Figure 22, where resistors Rp1-Rp6 represent parasitic trace resistance.

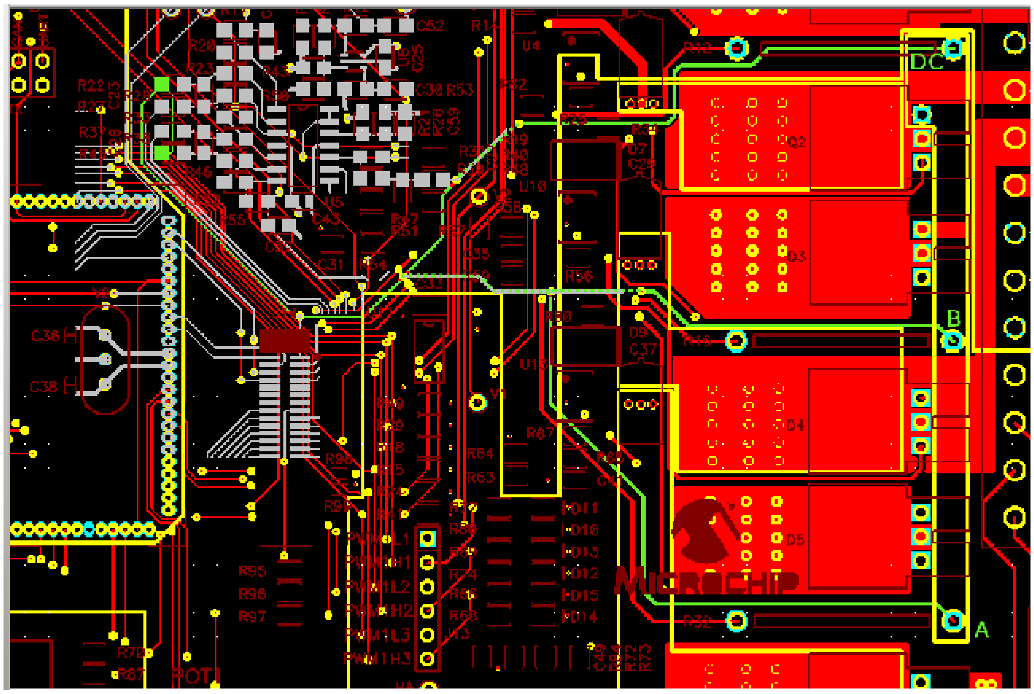

Figure 21: MCLV-2 current sense layout error

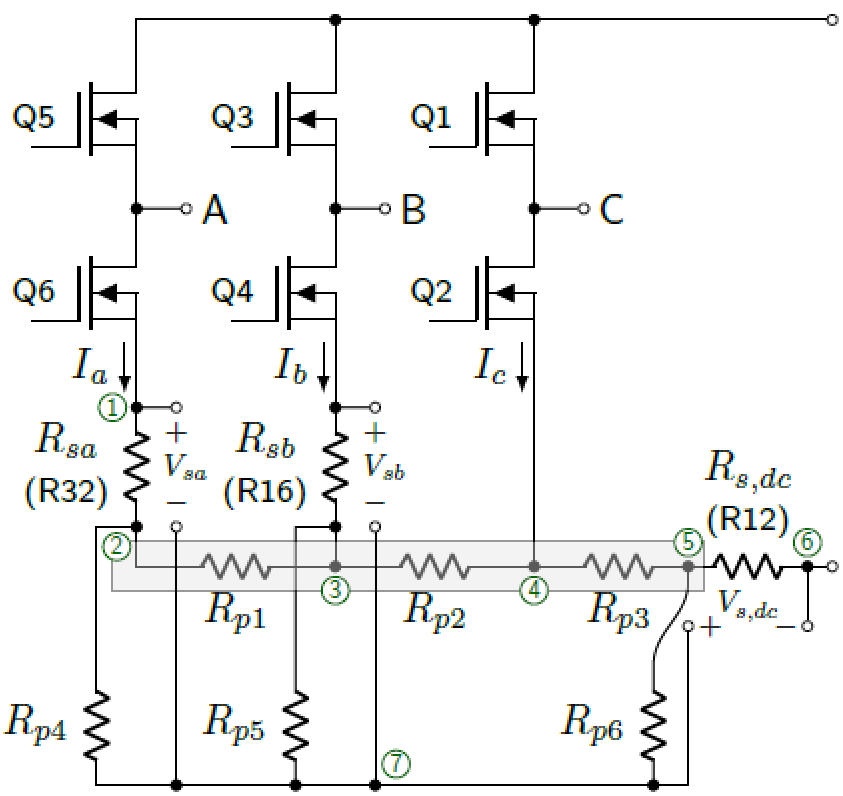

Figure 22: MCLV-2 current sense layout error (schematic equivalent)

The implications of this error are

- Gains of the current sense channels depend on both the sense resistors and parasitic trace resistance
- There is cross-coupling between channels A and B

In matrix algebra, there is some gain K that relates ADC input readings with actual current values:

$$\begin{bmatrix} I_A \\ I_B \end{bmatrix} = \begin{bmatrix} K_{AA} & K_{AB} \\ K_{BA} & K_{BB} \end{bmatrix} \begin{bmatrix} I_{A,ADC} \\ I_{B,ADC} \end{bmatrix}$$

Equivalent scalar equations are

$$I_A = K_{AA} I_{A,ADC} + K_{AB} I_{B,ADC}$$

$$I_B = K_{BA} I_{A,ADC} + K_{BB} I_{B,ADC}$$

The current gain compensation code in MCAF_ADCApplyCurrentCompensation() implements this matrix multiplication.

We have measured several MCLV-2 boards, some with the unmodified 25mΩ sense resistors, and some for Test Case 4 with 50mΩ sense resistors, and determined best-fit gains for KAA, KAB, KBA, and KBB, as mentioned in section 3.5.1.1.

To determine appropriate compensation gains for other sense resistor values, follow the steps described in section 8.2.

8.2 Current sense measurement

This section requires measurements of actual current and of the voltages on the "I1", "I2", and "IBUS" test points of the MCLV-2 board. The approach is with the software disabled, use a laboratory power supply to apply a known test current I_T to one of the current sense paths and measure the amplified voltages on the ADC inputs. The power supply should not be connected directly to the sense resistor, but rather to nearby components (source of Q2/Q4/Q6 on one side; on the other, the negative DC link input to J7 or the tab terminal BP1)

8.2.1 Selection of test current

The test current I_T should be between 50-90% of full-scale, in order to have sufficiently large amplitude but avoid both of the following situations:

- Ensure that the hardware overcurrent of the MCLV-2 does not trip
- Ensure that current sense amplifiers of the MCLV-2 do not saturate: output voltages should be between 5% and 95% of AVdd.

8.2.2 Equipment needed

- One power supply capable of delivering constant test current I_T across the MCLV-2 sense resistor circuitry and any connecting wires (1V load voltage should be sufficient)
- Two accurate, calibrated DMMs, one to measure DC current and the other DC voltage. The DC current measurement is usually the one requiring more expensive equipment, using either of the following techniques:
    - DMM "A": capable of 0.5% accuracy or better, for the DC current I_T
    - DMM "B": capable of 0.25% accuracy or better to measure the current I_{T0} through a laboratory current shunt of 0.25% accuracy or better (for example: the 10A 100mV 0.25% Murata 3020-01107-0), at a test current such that the voltage across the sense leads of the shunt can be measured at 0.5% accuracy or better with a second DMM (DMM "C") Compute the value of the laboratory shunt by dividing measured voltage by measured current, and use the same DMM (DMM "C") for subsequent measurements of the voltage across the laboratory shunt sense leads. (This is a ratiometric approach, and the absolute accuracy of the shunt resistor and DMM "C" don't matter as much as their stability and linearity. DMM "B" accuracy is important.)

We used the DMM "B" approach, with an Amprobe AM-140-A to measure I_{T0} = 499mA; at this range its accuracy is 0.1% + 30 counts.

The DMM for measuring voltage on the MCLV-2 test points should be 0.1% accuracy or better. (Amprobe AM-140-A voltage accuracy is 0.03% + 2 counts at the 5V range.)

- Test cables (for example, banana-to-alligator, banana-to-banana, or banana-to-test-clip) as necessary

If the power supply has a calibrated meter to measure current, with 0.5% or better accuracy, then it can be used rather than a DMM.

8.2.3 Measurement procedure

1. Apply 24V control power to MCLV-2, with no motor connected.
2. **Make sure the drive is disabled.** (If jumper J6 is disconnected, do not apply voltage across Vdc. It is ok for lower transistors to be on or switching at a low duty cycle, but the upper transistors must be turned off.)
3. Measure the voltage between the "AVdd" and "AVss" test points of the MCLV-2. (This isn't used in calculation of compensation gains, but it is used during the verification step, since it affects ADC measurements.)
4. For each of the following cases, measure and record the current applied, and measure and record the voltages on the test points "I1", "I2", and "IBUS" relative to the "AVss" test point.
    a. No current
    b. Current I_T through phase A only: Lab power supply, current shunt, and current-measuring DMM connected between MCLV-2 DC- (J7, 2nd terminal) and Q6 source pin, current set to I_T
    c. Current I_T through phase B only: Lab power supply, current shunt, and current-measuring DMM connected between MCLV-2 DC- (J7, 2nd terminal) and Q4 source pin, current set to I_T
    d. Current I_T through phase C only: Lab power supply, current shunt, and current-measuring DMM connected between MCLV-2 DC- (J7, 2nd terminal) and Q2 source pin, current set to I_T
5. Repeat 4b, 4c, 4d with opposite polarity current

8.2.4 Estimation of gain matrix K

Perform a least-squares fit of the voltage at I1, I2, and IBUS test points to the applied currents. With a two-measurement system (Ia, Ib) the two basis vectors are [Ia=1, Ib=0, Ic=–1] and [Ia=0, Ib=1, Ic=-1]; multiplication of the 2x3 matrix of least-squares estimated gains from [Ia, Ib, Ic] to measurements of Ia and Ib, by the 3x2 basis vectors, gives a 2x2 matrix from actual Ia and Ib to raw measured Ia and Ib. Inverting this matrix gives a compensation gain matrix.

The Python script shown in Listing 1 can be used, with appropriate substitution of measurements for program variables:

- I: measurements of applied current
- V: measurements of the voltage on MCLV-2 test points
- Knominal: nominal sense resistor voltage, times current sense amplifier gain

Its only dependency is the numpy module.

Listing 1: Python script for determining current sense correction factors

```
"""
Gain estimation and compensation

This script is a standalone script (only dependency is numpy)

You will need to edit the I, V, and Knominal values to cover
your measurements and nominal current sense gains
"""

import numpy as np

# Each row is 1 followed by the A, B, and C applied currents
I = np.array(
    [[1,0,0,0],       # no current
     [1,1.787,0,0],   # phase A
     [1,-1.786,0,0],  # phase A
     [1,0,1.786,0],   # phase B
     [1,0,-1.786,0],  # phase B
     [1,0,0,1.786],   # phase C
     [1,0,0,-1.786]]  # phase C
)


# Each row is the voltage measured on MCLV-2 board
# for "I1", "I2", and "IBUS" test points, relative to AVss
V = np.array(
    [[1.6523, 1.6480, 1.6564],
     [3.0781, 1.6532, 3.0596],
     [0.2259, 1.6428, 0.2526],
     [1.6772, 3.0196, 3.0451],
     [1.6275, 0.2766, 0.2680],
     [1.6544, 1.6505, 3.0119],
     [1.6502, 1.6455, 0.3010]]
)
K = np.linalg.lstsq(I,V)[0]
K0 = K[0,:]
KA = K[1,:]
KB = K[2,:]
KC = K[3,:]
print "offset:              ", K0
print "3-phase gains from IA:", KA
print "3-phase gains from IB:", KB
print "3-phase gains from IC:", KC

# Knominal = Rs (ohms) times the current sense gain
Knominal = 50e-3 * 15
rKab = np.dot(K[1:,:2].T,
              np.array([[1,0,-1],[0,1,-1]]).T)/Knominal
print "Relative gains from IA, IB (IC=-IA-IB) to measured I1: ", rKab[0,:]
print "Relative gains from IA, IB (IC=-IA-IB) to measured I2: ", rKab[1,:]
cKab = np.linalg.inv(rKab)
print "[Kaa Kab] = %s (%s counts)" % (cKab[0,:], np.round(cKab[0,:]*16384).astype(int))
Kaa, Kab = cKab[0,:]
print "[Kba Kbb] = %s (%s counts)" % (cKab[1,:], np.round(cKab[1,:]*16384).astype(int))
Kba, Kbb = cKab[0,:]
```

8.3 Application and verification of current sense compensation gains

The resulting values KAA, KAB, KBA, and KBB need to be applied as in section 3.5.1.1.

To make sure the measurements and calculations are correct, follow the steps in section 3.6.1.1.

9 Revision History

Revision	Date	Summary
1	2018 Apr 6	Initial release
2	2018 Nov 20	Update for motorBench 2.0, MCAF R3