Title: Regeneration Energy Dissipation or Store When Using the MX3660 and MX4660

Product(s): MX3660, MX4660

Keywords: MX3660, MX4660, CNC, Emergency Stop, Regeneration

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Summary

The MX3660 and MX4660 are widely used in CNCs, including CNC routers/engravers, CNC mills, CNC cutters, CNC water jets. We got very good feedback because of their high performance, cost-effectiveness and unique design like built-in breakout board and I/O's fits seamlessly in many applications powered by many popular CNC systems such as Mach3, Mach4, EMC, WinCNC, etc..

Problem

We got some customers said their drives (13 pcs of the MX3660 and 4 pcs of MX4660 were returned to our USA office.) failured during using/establishing/building/tuning their machines or systems in these two monthes. And almost all these customers said that it happened when they pushed the E-Stop button.

Investigation

A load (a motor's rotor itself is also a load) traveling at high speed contains significant kinetic energy. When this load is decelerated, this energy needs a place to go. This issue affects not only servo systems, but also stepper motor systems. To understand the issue of regenerative energy, it is important to understand what happens to that energy during a hard deceleration.

Modern pulse-width modulation (PWM) motor drives efficiently transfer energy from the power source into the motor to produce high-performance, high-efficiency motion.

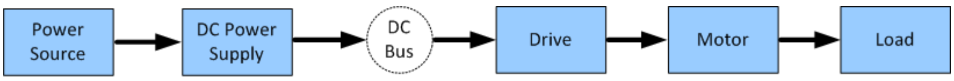

Figure1 Energy flow during normal operation

PWM drives also do a great job returning energy from the motor and load. But where does that energy go? For a DC-powered system, the bus capacitors (including the drive's internal bus caps and the bus caps of the DC power supply) are the main recipient of regenerated energy. That's OK to an extent, but as the recovered energy charges the bus cap, the bus voltage increases. If it goes too high, the drive or power supply will either shut down unexpectedly, or will be damaged.

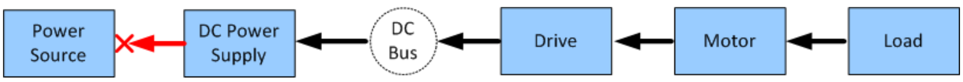

Figure2 Energy flow during regeneration

There are two common approaches to take regenerative energy to a safe place. One is to add a shunt regulator that will dump the power into a resistor. Another is to simply add enough bus capacitance to safely absorb the energy without exceeding the voltage rating of any components like those of the drives and DC power supply.

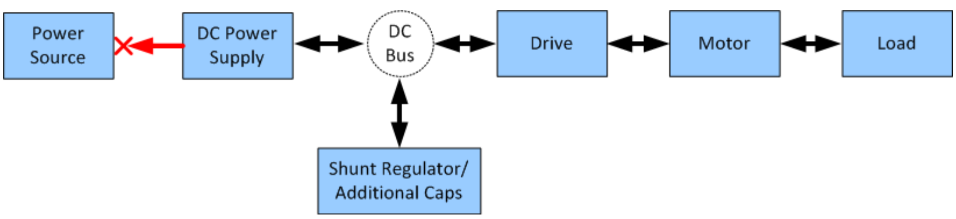

Figure3 Energy flow during normal operation and regeneration with shunt regulator or additional caps

A shunt regulator is a switching device, which uses dissipative elements (resistors) that are switched across the DC bus. The function of the shunt regulator is to regulate the voltage of the DC bus during the period of motor deceleration or emergency stop, whenever the voltage reaches a predetermined level.

On multi-axis systems, if the other axes always take power from the supply when a particular axis is regenerating, then the shunt regulator is probably not required during normal operation. However, when there is an emergency, the user usually has to stop all axes immediately or with an extremely high deceleration, a shunt regulator must be used or additional capacitance should be added to protect the components that may damaged by the regeneration.

Let's consider a 4-axis stepper system using the MX4660 driving four Leadshine 57HS22 (NEMA23 , holding torque 2.0Nm) motors with 5X inertial load on each axis. The rotor inertia of a Leadshine 57HS22 motor is 480 g-cm^2, so the total inertia will be 2,880 g-cm^2 for each axis. For this example, assume the motor speed is 600 rpm (62.8 rad/s) before stop. We can easily calculate the kinetic energy:

$$E = \frac{JW^2}{2} \times 4 = \frac{0.000288 \times (62.8)^2}{2} \times 4 = 2.2717\, j$$

During deceleration/regeneration or emergency stop, some of this energy will be consumed by the motor windings, iron losses and friction. The drive has losses too, but it would not be unusual for 50% of the kinetic energy of the load to return to the bus cap in cases of hard deceleration. The capacitor charging formula:

$$E = \frac{CV_r^2}{2}$$

In order to make the MX4660 and MX3660 small and compact, Leadshine uses a relatively small bus capacitance of **220µF** for each stepper drive module (SDM660), compared to some other one axis stepper drives popular for CNCs like the DM556 (440µF), M542 (440µF), MA860H (660µF) and DMA860H (1360µF). Assuming that 50% of the 2.2717j of kinetic energy makes it to the bus caps (not including bus caps of the DC power supply here), the voltage rise will be:

$$V_r = \sqrt{\frac{2E}{C}} = \sqrt{\frac{2 \times (2.2717j/2)}{4 \times 0.00022F}} = 50.81\, VDC$$

For a MX4660 or MX3660, if using a 48VDC power supply, this kind of voltage rise is certainly enough voltage to damage the drives and/or power supply if no action is taken to direct regenerative energy to a safe place.

Even we consider the bus cap of the DC power supply, the voltage rise still may cause a problem. For example, a popular model 48VDC(@10A) switching power supply RPS4810 has 2350µF internal bus cap. See below for the voltage rise when using the RPS4810 in this situation.

$$V_r = \sqrt{\frac{2E}{C}} = \sqrt{\frac{2 \times (2.2717j/2)}{4 \times 0.00022F + 0.00235F}} = 26.52\, VDC$$

The voltage rise still has 26.52V, which still may damage the drives or power supply.

Here, please note that the maximum operating voltage of the MOSFETs that the MX4660/MX3660 use is 75V, rated voltage of the bus capacitors that the MX4660/MX3660 use is 63V. And rated voltage of the filter/bus capacitors of most 48VDC power supplies on the market is 63V.

As mentioned above, during deceleration/regeneration or emergency stop, some of this energy will be consumed by the motor windings and iron losses. For better motor selection or configuration, let's see another equation that shows more related factors to regeneration. It can be shown that, neglecting friction and other secondary power loss mechanisms, the total energy returned to the power supply during a deceleration period is given by the equation:

$$E_r = 104.7 \times \frac{JN}{K_t}\left(\frac{NK_e}{2} + \frac{I_d^2 R_a^2}{2NK_e} - I_d R_a\right) \quad Jouls$$

Where:

J – Total load inertia (Kgm^2)
K_t – Motor torque constant (Nm/A)
K_e – Motor back EMF constant (V/Krpm)
N – Motor speed at the beginning of the deceleration period (KRPM)
I_d – Magnitude of the deceleration current (A)
R_a – Total armature circuit resistance (Ohm)

Since an 8-lead stepper motor can be operated in parallel connection or series conection to get almost the same maximum output torque at low speeds, but above parameters K_t K_e, I_d, R_a have huge difference in these tow different connections. For example, when we calculated K_e parameters of Leadshine 57HS22-07 in parallel connection and series connection, we got two back EMF response curves below.

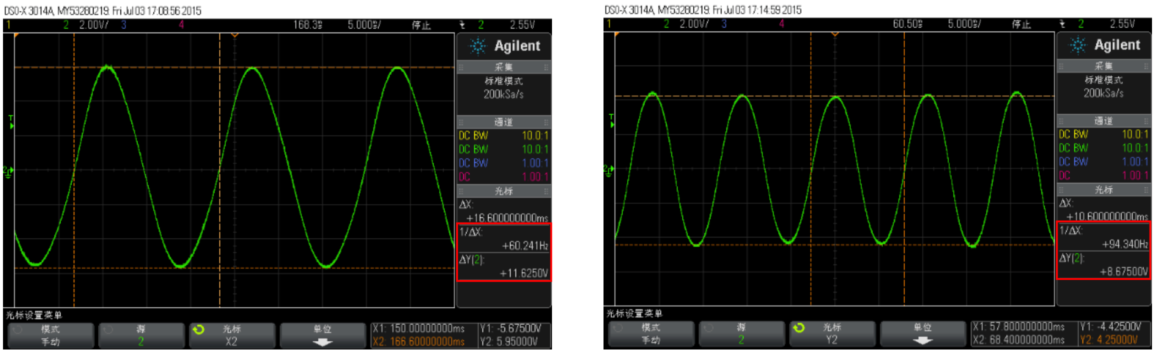

Figure4 Back EMF response of the 57HS22-07 in series connection (left) and parallel connection (right)

And we can calculate the K_{es} in series connection:

$$K_{es} = \frac{\Delta Y/2}{(^1/_{\Delta X})/50} \times 60 \times 1000 = \frac{11.625/2}{(60.241)/50} \times 60 \times 1000 = 290625 \;\; V/Krpm$$

And the K_{ep} in parallel connection:

$$K_{ep} = \frac{\Delta Y/2}{(^1/_{\Delta X})/50} \times 60 \times 1000 = \frac{8.675/2}{(94.34)/50} \times 60 \times 1000 = 137932 \;\; V/Krpm$$

These differece may cause a significant different voltage rise. See below.

Testing1 Conditions:

The MX3660 with three Leadshine 86HS35 motors (no load with their rotors, 8-leads in series connection.). Ran three motors at a constant speed and then press E-STOP button connected on the MX3660, and the voltage rise was monitored by an oscilloscope. The MX3660 has internal bus caps (660µF), the DC power supply RPS4810 (48VDC@10A) has internal bus cap (2350µF), and no additional capacitance. See the testing results below.

Motor speed	Voltage rise in series connection testing results	Voltage rise in parallel connection testing results	Parallel/Series
900RPM	3.625V	0.75V	20.69%
1200RPM	7.625V	1.125V	14.75%
1500RPM	12.375V	4V	32.32%
1800RPM	17.125V	8.375V	48.91%
2100 RPM	22V	13.125V	59.66%

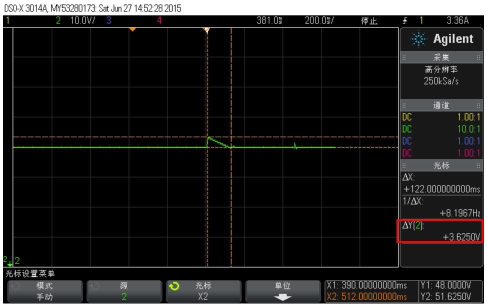

Figure5: 900RPM in series connection

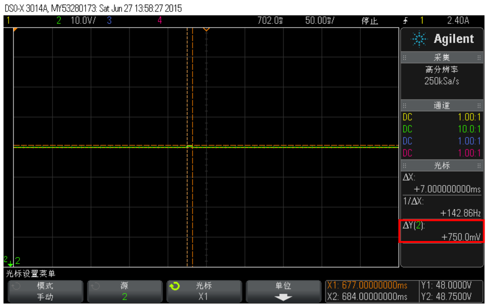

Figure6: 900RPM in parallel connection

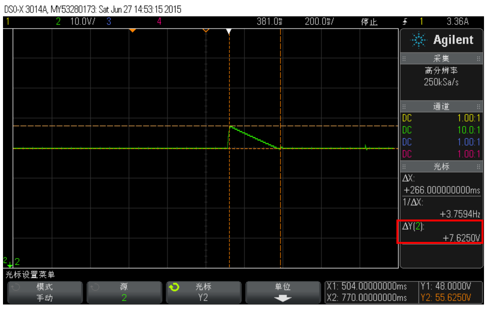

Figure7: 1200RPM in series connection

Figure8: 1200RPM in parallel connection

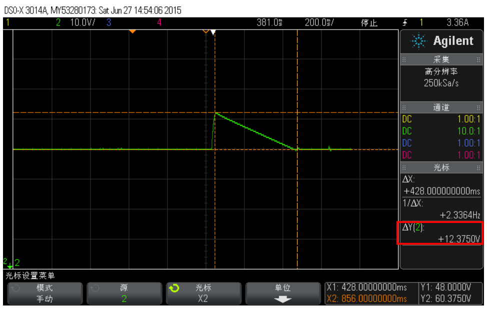

Figure8: 1500RPM in series connection

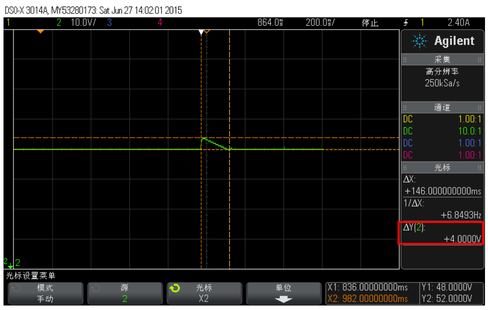

Figure9: 1500RPM in parallel connection

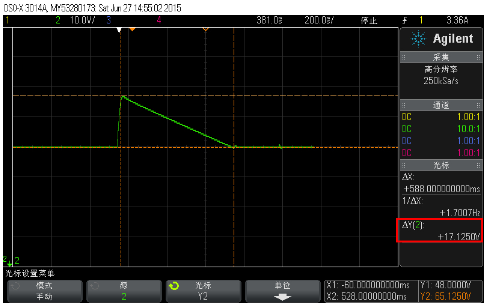

Figure10: 1800RPM in series connection

Figure11: 1800RPM in parallel connection

Figure12: 2100RPM in series connection

Figure13: 2100RPM in parallel connection

We did a lot of testing with different kind of stepper motors, and the testing results show that the voltage rise was much smaller when using a lower K_e or inductance motor. See more testing results in **Appendix** in page 9.

Hereby, for an 8-lead stepper motor, it's suggested to operate the motor in parallel connection if the drive can output enough current. In stead of operate the motor in series connection, which may generate higher voltage rise during a hard deceleration or emergency stop, and that may damage the drives and power supply. And select as lower K_e or inductance motor (with the same holding torque) as possible, if the drive can provide enough current. Then you will get lower regen voltage rise, and better high speed performance.

Solutions

Deciding if a regulator or additional capacitance is required in a particular application is best done empirically, using the actual system as a test-bed. Once you have established your machine/system, you can follow the steps below to evaluate whether a regulator or additional capacitance is required or not in a saft way.

Step1: Prepare a device that can monitor the voltage rise like an oscilloscope or a multimeter. If using a multimeter, it should have a function that can latch the maximum value measured.

Step2: Start from a lower speed and run only one of axes at the beginning, and then monitor the voltage rise or maximum voltage by pushing E-STOP button connected on the MX3660/MX4660.

Step3: If the maximum voltage measured is smaller than **the maximum voltage allowed** (For the MX3660/MX4660, it is 60V, and see the datasheet/manual of the DC power supply for its maximum voltage allowed.), then run the motor of that axis at a speed a little higher than previous speed, and then monitor the voltage rise or maximum voltage by pushing E-STOP button connected on the MX3660/MX4660 again. Repeat Step3 till the maximum voltage measured is smaller than **the maximum voltage allowed** when push the E-STOP button during this axis run at its maximum speed.

Step4: If the maximum voltage measured is higher than the maximum voltage allowed, then add more additional capacitance (recommend step forward about 1000μF each time.) and repeat Step3 till the maximum voltage measured is smaller than **the maximum voltage allowed** when push the E-STOP button during this axis run at its maximum speed.

Step5: Add another axis (Move one axis more) of the machine/system, repeat Step2 to Step4 till the maximum voltage measured is smaller than **the maximum voltage allowed** when push the E-STOP button during all axes run at their maximum speeds.

Step6: Do please to verify there is no any issue like over current protection when the DC power supply powered up with the additional capacitance. This may happen on some switching mode DC power supplies that can not provide enough power required. And if this happen, change to another higher capability DC power supply and continue above testing.

As a design aid, the following information is provided so that one may estimate if a regulator or additional capacitance is required in a particular case, and how much additional capacitance may be needed.

Adding Additional Capacitance Reference

Rated voltage of the bus capacitor(s) added should above 63VDC.

MX4660

MX4660 internal bus cap	RPS4810 (48VDC@10A) internal bus cap (as an example)	Additional capacitance added (above 63VDC)	Voltage rise with additional capacitance **in theory**
220μF ×4 = 880μF @63VDC	470μF ×5 = 2350μF @63VDC	0μF	100%
		1000μF	87.38%
		2200μF	77.13%
		4400μF	65.06%
		…	Based on $V_r = \sqrt{\frac{2E}{C_d+C_p+C_a}}$

Where:

C_d – Internal bus capacitance of the drive

C_p – Internal bus capacitance of the power supply

C_a – Additional capacitance added

Note: The real voltage rise is also related to the motor and load. See more testing results below for referece.

Testing2 conditions:

The MX4660 with four Leadshine 57HS13 motors (no load with their rotors, 8-lead in series connection.). Ran four motors at a constant speed (1800RPM) and then press E-STOP button connected on the MX4660, and the voltage rise was monitored by an oscilloscope.

MX4660 internal bus cap	RPS4810 (48VDC@10A) internal bus cap (as an example)	Additional capacitance added (above 63VDC)	Voltage rise with additional capacitance **testing results**
220μF ×4 = 880μF @63VDC	470μF ×5 = 2350μF @63VDC	0μF	8.75V (100%)
		1000μF	7.25V (82.86%)
		2200μF	6.125V (70%)
		4400μF	4.5625 (52.14%)

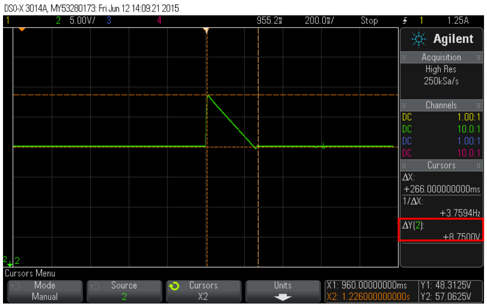

Figure14: 0μF additional cap

Figure15: 1000μF additional cap

Figure16: 2200μF additional cap

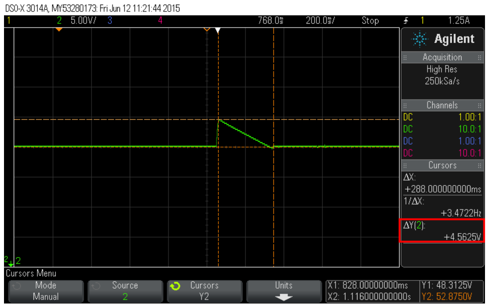

Figure17: 4400μF additional cap

MX3660

MX3660 internal bus cap	RPS4810 (48VDC@10A) internal bus cap (as an example)	Additional capacitance added (above 63VDC)	Voltage rise with additional capacitance **in theory**
220μF ×3 = 660μF @63VDC	470μF ×5 = 2350μF @63VDC	0μF	100%
		1000μF	86.64%
		2200μF	76.01%
		4400μF	63.73%
		…	Based on $V_r = \sqrt{\frac{2E}{C_d+C_p+C_a}}$

Note: The real voltage rise is also related to the motor and load. See more testing results below for referece.

Testing3 conditions:

The MX3660 with three Leadshine 86HS35 motors (no load with their rotors, 8-lead in series connection.). Ran three motors at a constant speed (1800RPM) and then press E-STOP button connected on the MX3660, and voltage rise was monitored by an oscilloscope.

MX3660 internal bus cap	RPS4810 (48VDC@10A) internal bus cap (as an example)	Additional capacitance added (above 63VDC)	Voltage rise with additional capacitance **testing results**
220μF ×3 = 660μF @63VDC	470μF ×5 = 2350μF @63VDC	0μF	17.125V (100%)
		1000μF	14.75V (86.13%)
		2200μF	12.375V (72.26%)
		4400μF	9.625V (56.2%)

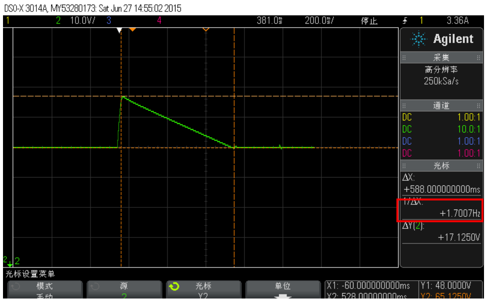

Figure18: 0μF additional cap

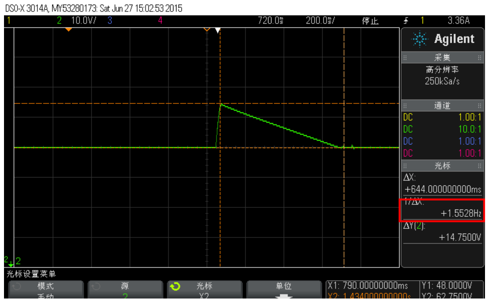

Figure19: 1000μF additional cap

Figure20: 2200μF additional cap

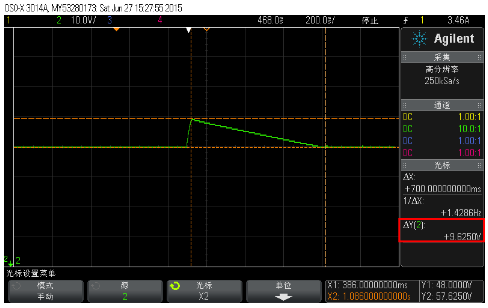

Figure21: 4400μF additional cap

Shunt Regulator Choosing Reference

The following shunt regulators are recommended to work with the stepper systems using the MX4660 and MX3660. See more details in their datasheets or manuals. Parallel connect two or more if one is not enough.

NO.	Model& Brand	Clamping Voltage	Rated Dissipation Capability	More Details
1	SRST50 from Advanced Motion Controls	50VDC	95W	http://www.a-m-c.com/products/shunt-regulators.html
2	DSR70/30 from Maxon Motor AG	12 to 75VDC Adjustable	450W Peak 25W Continuous	http://www.maxonmotor.com
3	SR50W from AMT	20 to 132VDC Adjustable	50W built in Supported external 50W extend	Available time TBD

Appendix

More testing results show the different voltage rise when operated the stepper motors in parallel connection and series connection. For an 8-lead stepper motor, it’s suggested to operate the motor in parallel connection if the drive can output enough current. In stead of operate the motor in series connection, which may generate higher voltage rise during a hard deceleration or emergency stop, and that may damage the drives and power supply. And select as lower K_e or inductance motor (with the same holding torque) as possible, if the drive can provide enough current.

Testing4 conditions:

The MX4660 with four Leadshine 57HS13 motors (no load with their rotors). Ran four motors at a constant speed and then press E-STOP button connected on the MX4660, and the voltage rise was monitored by an oscilloscope.

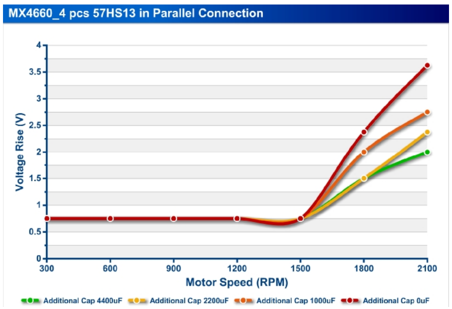

Figure22: In parallel connection

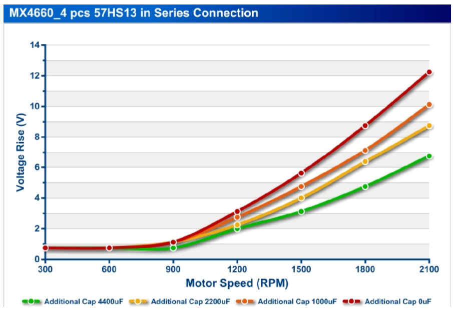

Figure23: In series connectio

Testing5 conditions:

The MX4660 with four Leadshine 86HS45 motors (no load with their rotors). Ran four motors at a constant speed and then press E-STOP button connected on the MX4660, and the voltage rise was monitored by an oscilloscope.

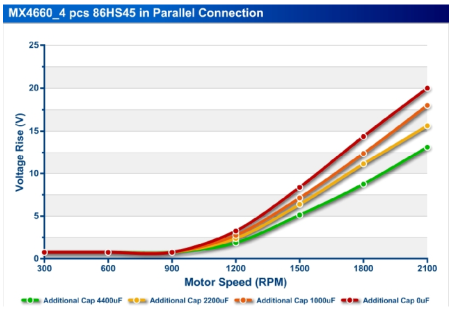

Figure24: In parallel connection

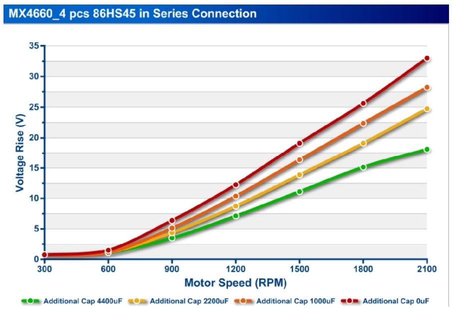

Figure25: In series connection

Testing6 conditions:

The MX3660 with three Leadshine 57HS13 motors (no load with their rotors). Ran four motors at a constant speed and then press E-STOP button connected on the MX3660, and the voltage rise was monitored by an oscilloscope.

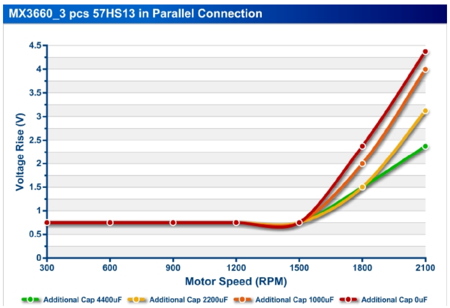

Figure26: In parallel connection

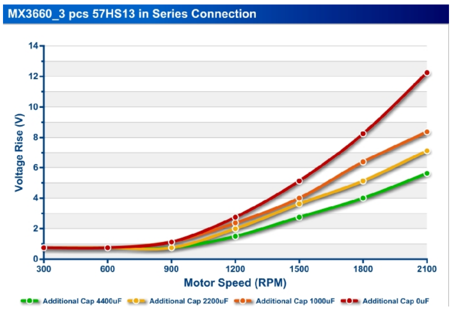

Figure27: In series connection

Testing7 conditions:

The MX3660 with three Leadshine 86HS35 motors (no load with their rotors). Ran four motors at a constant speed and then press E-STOP button connected on the MX3660, and the voltage rise was monitored by an oscilloscope.

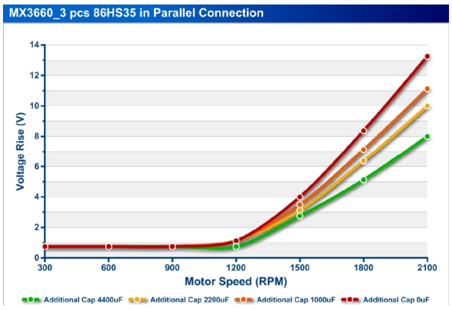

Figure28: In parallel connection

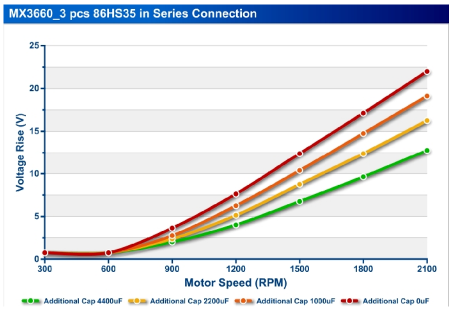

Figure29: In series connection

Leadshine will follow up this issue and do more testing such as testing on different size CNCs to offer more information for our customers to refer. Welcom to contact us if you have any questions about our products, and we appreciate any one who share his testing results or any feedback about their applications or our products!

Reference:

1. http://www.stepperguru.com/
2. http://www.elmomc.com/applications/Design-consideration-for-a-shunt-regulator.htm