APPLICATION NOTE
QuickStick 100 Power Cable Sizing and Selection

Purpose

This document will provide an introduction to power supply cables and selecting a power cabling architecture for a QuickStick 100 system. This document provides a limited selection of background knowledge required for this analysis. Following the instructions in the document is not a replacement for analysis of your system's power wiring by a qualified electrical engineer.

Introduction

When designing a power transmission system, it is important to take into consideration that the voltage experienced at the supply may not be the same as the voltage at the QuickStick end of the power wiring. Voltage drop or regeneration of power can drive the voltage at the QuickStick higher or lower than what the supply provides.

Like any other electrical component, the QuickStick 100 motors have a defined operating voltage range. Operating below or above this range can result in the motor turning off or being damaged. While the motor has protections in place to prevent this damage, the power supply system should be designed so that the voltage limits are not exceeded during normal operating conditions.

The allowable standing (non-operational) voltage input range to the QuickStick 100 motor is 48V ± 5%.

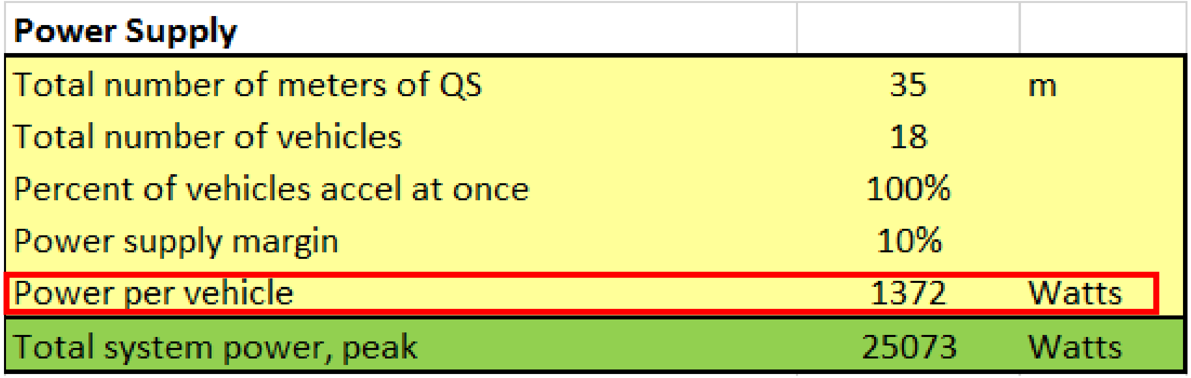
The allowable voltage input range during operation on a QuickStick 100 motor is 42.5-57V, with a nominal voltage of 48V. MagneMotion recommends allowing for a minimum tolerance of 0.5V from these values when designing power supply wiring.

The limits and curves expressed in this document are valid for software
- Node Controller version 2.2.23
- Master version 1.4.31
- Slave version 2.2.7

or newer.

Determining Vehicle Power Draw

During the quoting process for a QuickStick system, MagneMotion provides a sizing estimate sheet. The sizing sheet will generate a movement profile and a corresponding peak propulsion power draw per vehicle.



Power Supply		
Total number of meters of QS	35	m
Total number of vehicles	18	
Percent of vehicles accel at once	100%	
Power supply margin	10%	
Power per vehicle	1372	Watts
Total system power, peak	25073	Watts

Figure 1: Power Estimate from a Sample Sizing Sheet

Logic Power

Logic power is used to operate the controls portion of a motor and can be provided separately or though the propulsion power pins. Logic power draws a constant 10W.

If logic power is provided separately, ensure that logic power remains above 45V.

If logic power is provided through the propulsion power feed, the 10W should be added to the peak vehicle power draw when calculating power per motor.

For the purposes of our examples below, we will consider logic power as being provided separately and disregard it.

Propulsion Power

Propulsion power refers to the power used to accelerate and decelerate a vehicle. This is the main function that consumes power and will vary based on the activity of the motor.

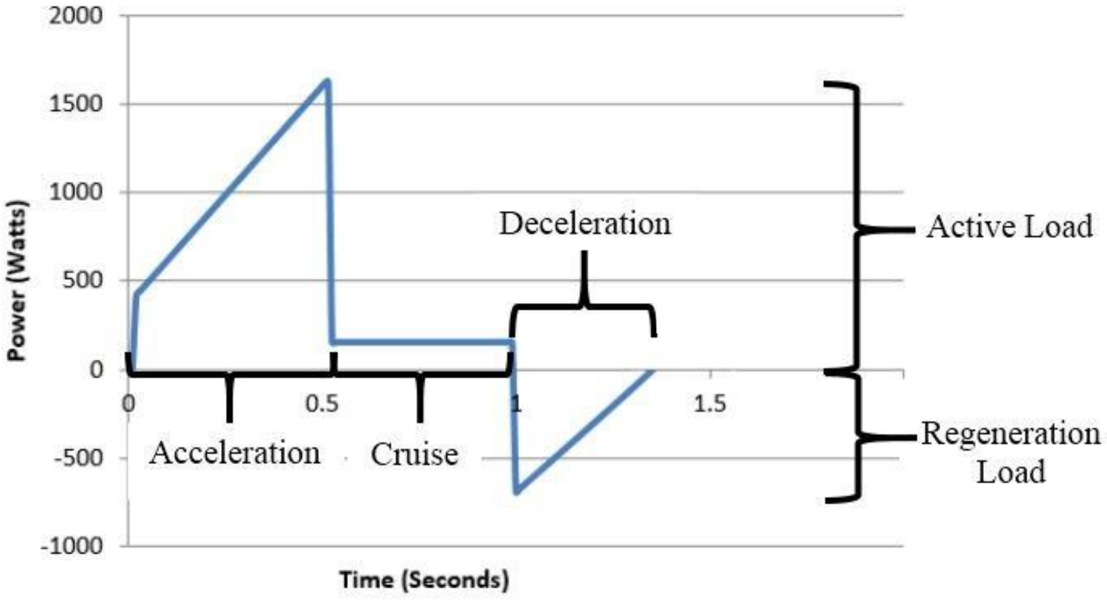


Figure 2: Example of Power Consumption for a Single Movement from Sizing Sheet

The vehicle motion will consume power when it accelerates and regenerate power when it decelerates. The locations on the system where peak power and regeneration are reached will depend on the move profile being used.

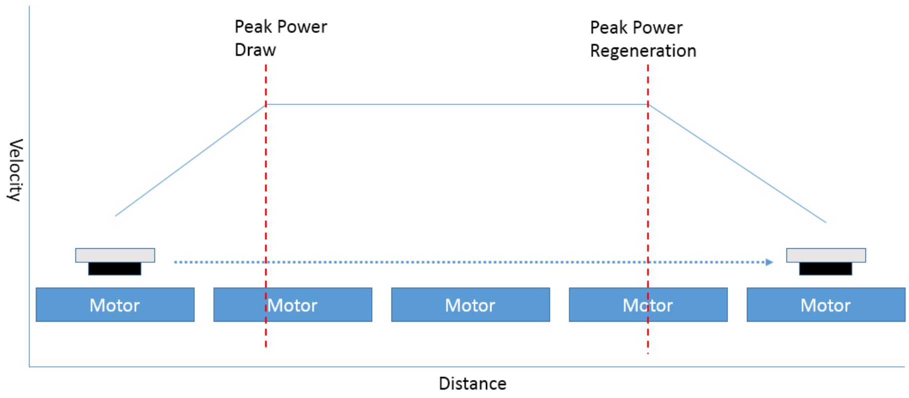


Figure 3: Location of Power Peaks During Motion

Transfer of Propulsion Power within a System

The power system driving the QuickStick Motors must be designed to provide power to individual motors while the vehicle is accelerating and to transfer power between motors when the vehicle is decelerating.

While accelerating, power is drawn from the power supply and into the motors that are accelerating vehicles. This power is then converted into mechanical energy to move the vehicle.

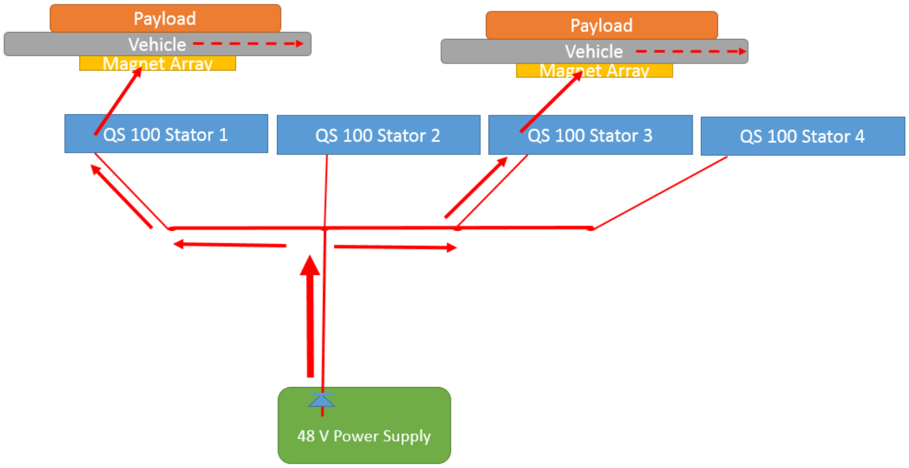


Figure 4: Power Transfer, Acceleration Case

While decelerating, the mechanical energy of the vehicle is converted into electrical power. This power is then passed to the other motors in the system to be dissipated or used. In these examples, it is assumed that the power supply cannot dissipate power.

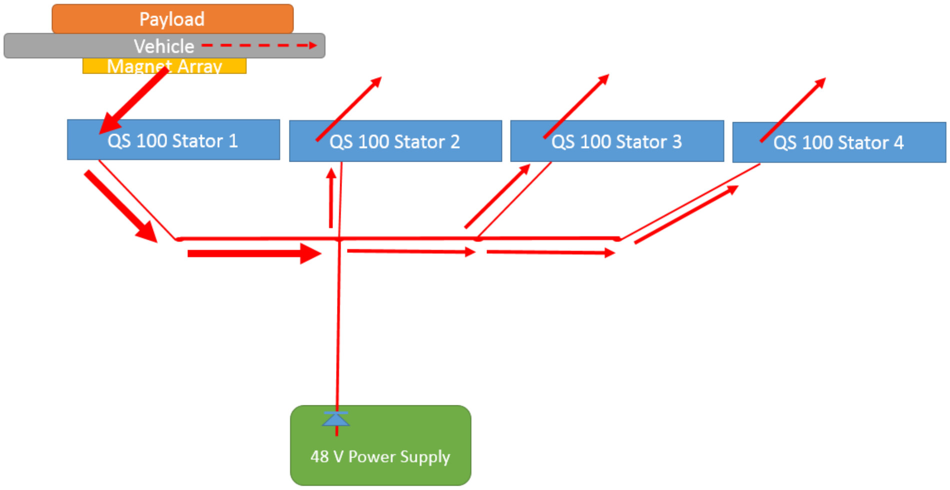


Figure 5: Power Transfer, Deceleration Case

Acceleration

While the vehicle is accelerating, the motor is drawing power from the power supply system. In the worst case, a single motor can draw up to the value for peak power per vehicle shown in the sizing estimate sheet while the vehicle is finishing its acceleration.

The current to each motor in a system at a given time will depend on system behavior and vehicle size. When sizing cables, the worst case power draw, current, and vehicle movements should always be used.

Example – Single Motor

The first case that we will consider is a single motor connected directly to the power supply.

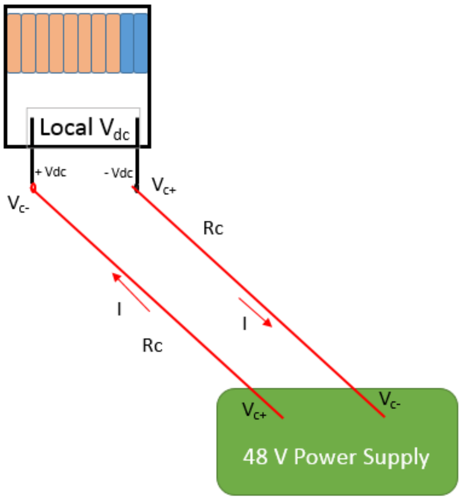


Figure 6: Example of a Power System for Single Motor

In the figure above:

- Local V_{dc} is the voltage at QuickStick
- I is the current in the cable
- Rc is the resistance of the cable (1 way)

Note that half of the total cable resistance is on one conductor and the other half of the total resistance is on the return conductor.

By Kirchhoff's Voltage Law, all of the voltages in the loop must sum to zero. V_C refers to the voltage drop within a cable.

$$48V - V_C - Local\ V_{dc} - V_C = 0$$

$$48V - Local\ V_{dc} = 2V_C$$

By Ohm's Law, the voltage across a component is equal to the resistance of that component multiplied by the current through that component.

$$48V - Local\ V_{dc} = 2IR_C$$

The term $48V - Local\ V_{dc}$ is referred to as "voltage drop" as this is the deviation from the nominal 48V power supply voltage experienced at the load end of the power system.

Based on Kirchhoff's Current Law, the currents through each element of the system are the same. Using the Power Law, divide the peak power draw from the motor by the local voltage at the motor to determine what this current is. For these examples, use the peak power draw identified in Figure 1 of 1372W.

As MagneMotion recommends sizing cables so that the voltage drop is not within 0.5V of the low voltage limit, a Local V_{dc} of 43V will be used for this example.

$$I = \frac{P}{V} = \frac{1372W}{43V} = 31.9A$$

$$48V - Local\ V_{dc} = 2IR_C$$

$$48V - 43V = 2\ (31.9A)R_c$$

$$R_C = \frac{48V - 43V}{2\ (31.9A)} = 0.078\Omega$$

So in this case, a cable resistance of less than 0.078Ω would be required. If minimum allowable local voltage of 42.5V is used, the calculations are as follows.

$$I = \frac{P}{V} = \frac{1372W}{42.5V} = 32.28A$$

$$48V - Local\ V_{dc} = 2IR_C$$

$$48V - 42.5V = 2\ (32.28A)R_c$$

$$R_C = \frac{48V - 42.5V}{2\ (32.28A)} = 0.085\Omega$$

As shown, the cable resistance must be selected based on the desired voltage at the QuickStick. This calculated cable resistance can then be used to select appropriate sized cabling for the system.

Example – Series Bus

The preferred architecture for a QuickStick power bus is a number of junction boxes (shown in green in Figure 7) connected in series to form a single, low resistance, power bus. Each junction box (terminals shown in green below) supplies a certain number of motors. Both logic and propulsion power connections are shown below, but only propulsion power is used for the calculations.

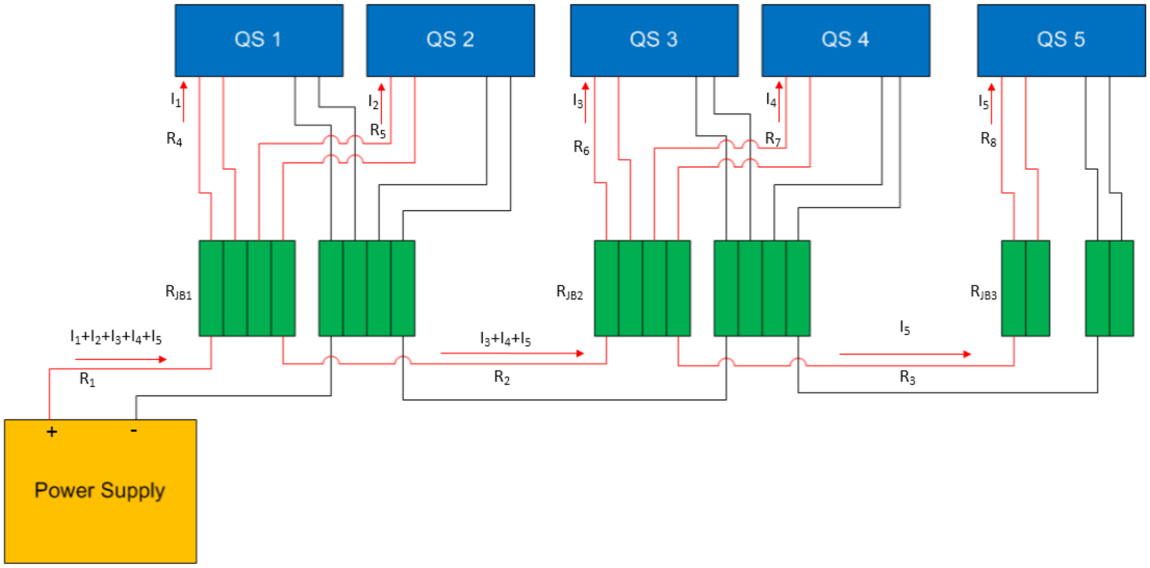


Figure 7: Example Power System for Series Bus Architecture

Kirchhoff's Current Law must be applied in order to determine which current must be used when evaluating voltage drop across a particular component. In this case, application of Kirchhoff's Current Law shows that the current in the single main bus line will decrease the further from the bus the motor is located. The current to each motor will depend on system behavior and vehicle size. When sizing cables, the worst case power draw and current should always be used.

The equation for modeling the cable resistance and voltage at motor 1 (V_1) would be as follows:

$$48V - V_1 = \left[2(I_1 + I_2 + I_3 + I_4 + I_5)(R_1 + R_{JB1})\right] + \left[2I_1R_4\right]$$

The equation for modeling the cable resistance and voltage at motor 5 (V_5) would be as follows:

$$48V - V_5 = \left[2(I_1 + I_2 + I_3 + I_4 + I_5)(R_1 + R_{JB1})\right] + \left[2(I_3 + I_4 + I_5)(R_2 + R_{JB2})\right] + \left[2(I_5)(R_3 + R_{JB3} + R_8)\right]$$

Example – Central Bus

One type of power architecture that has been used for certain systems is the central bus architecture. A number of QuickSticks are attached to a local junction box supplying propulsion power (Junction box terminals shown in green in Figure 8). Each junction box is then routed back to a central power cabinet, where they are connected to a central bus line connected to the power supply.

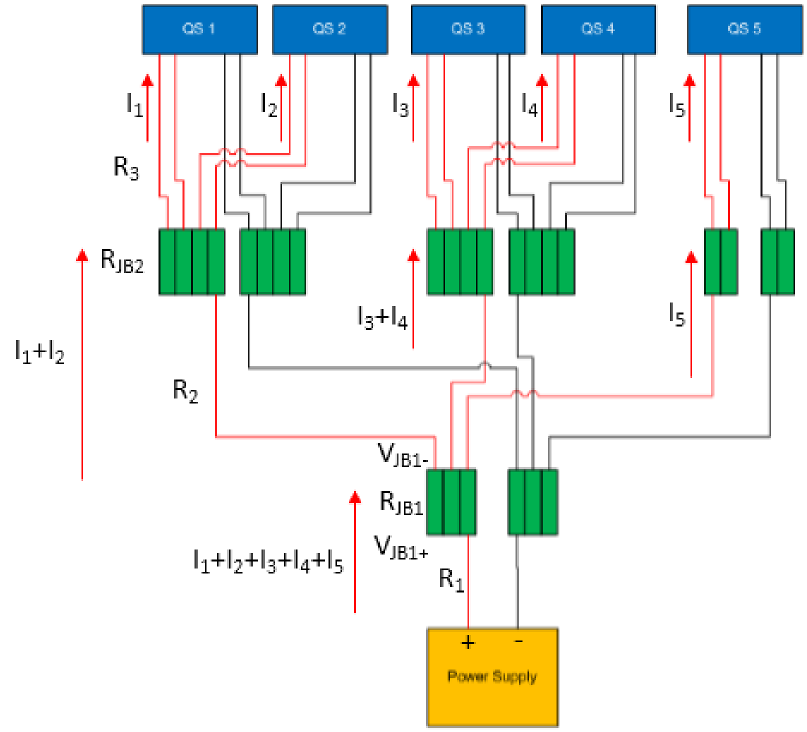


Figure 8: Example Power System for Central Bus Architecture

In this case, Kirchhoff's Current Law shows that the currents become smaller as the single bus splits into multiple cables. In this example, the equation by Ohm's Law for voltage across the first junction box (JB1) would be

$$V_{JB1} = (I_1 + I_2 + I_3 + I_4 + I_5)R_{JB1}$$

The equation for modeling the cable resistance and voltage at motor 1 (V_1) would be as follows:

$$48V - V_1 = \left[2(I_1 + I_2 + I_3 + I_4 + I_5)\left(R_1 + R_{JB1}\right)\right] + \left[2(I_1 + I_2)\left(R_2 + R_{JB2}\right)\right] + [2I_1R_3]$$

Deceleration (Regeneration)

In addition to providing the power used to accelerate a vehicle, the wiring must also be designed to manage power regenerated by a vehicle as it stops. In general, if a system is designed to support supplying power during acceleration, it will also support the deceleration case.

Power Regenerated by a Vehicle

When a vehicle slows to a stop, the mechanical energy of the vehicle is converted to electrical energy on the power bus. This energy must then be dissipated to avoid raising the voltage of the bus beyond the acceptable limit of 57V.

Power is being provided to the stator coils to actively slow down the vehicle so the net "effective" regeneration power is lower than the power required to accelerate the vehicle. The reduction is based on a number of factors, but a conservative first estimate is that the net effective regeneration power is about 75% of the acceleration power. For the example power draw used in Example – Single Motor (page 5):

$$P_{regen} = P_{acc} * 0.75 = 1372W * 0.75 = 1029W$$

Note that as the vehicle slows down under constant deceleration, the regeneration power will drop linearly with speed. The power found above is the peak regeneration power.

Power Dissipation within MMI Systems

The QuickStick motors will work to dissipate the extra power generated as the vehicle slows and prevent the bus voltage from rising. This is done using two different types of over voltage (OV) protection features in the motor.

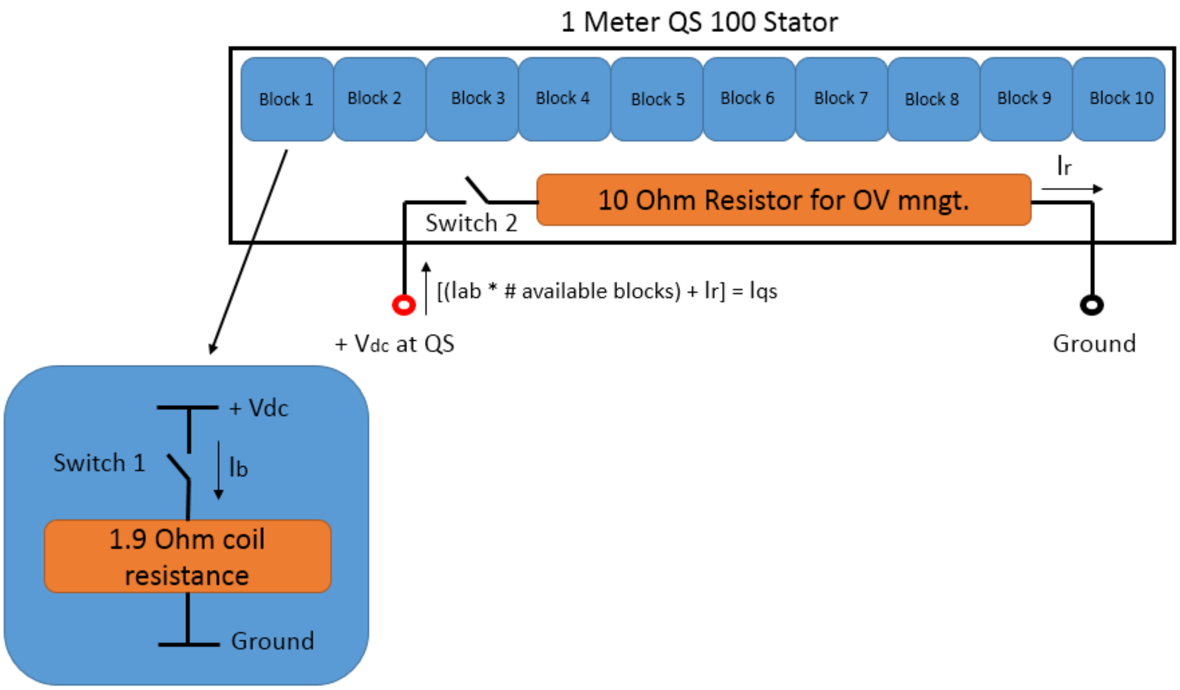


Figure 9: QS100 Over-Voltage Protection Features

The over voltage protection activates in two stages:

1. When V_{DC} is greater than 51.5V, Switch one will close if a block is available to dissipate power
2. When V_{DC} is greater than 59V, Switch 2 will close and begin dissipating power though the 10 ohm resistor. Switch 1 opens to protect the blocks and inverters and an Over Voltage Fault will be declared. Inverter shut down will eliminate regeneration, and will also lead to uncontrolled vehicle motion.

Switch 2 should not close during normal operation. It is for protection of the motors in the event of an unusual event, not something that should be used on a regular basis during normal operation. Continuously activating and deactivating Switch 2, can lead to damage to the motors and premature failure.

In order to identify blocks that are unavailable to regenerate power, the software determines which blocks are occupied or soon will be occupied by a vehicle. Only blocks occupied by a magnet array or next to a block occupied by a magnet array are considered busy and unavailable to absorb power.

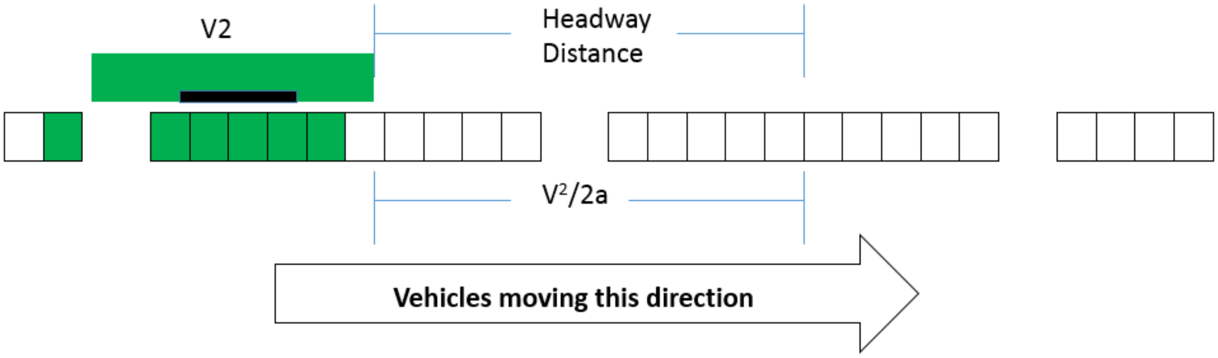


Figure 10: Blocks Unavailable to Dissipate Power

Once Switch 1 is closed, the motor will begin dissipating power. The power dissipated will vary with voltage per Figure 11. A detailed version of the figure is available in Appendix A: Power Dissipated per Block.

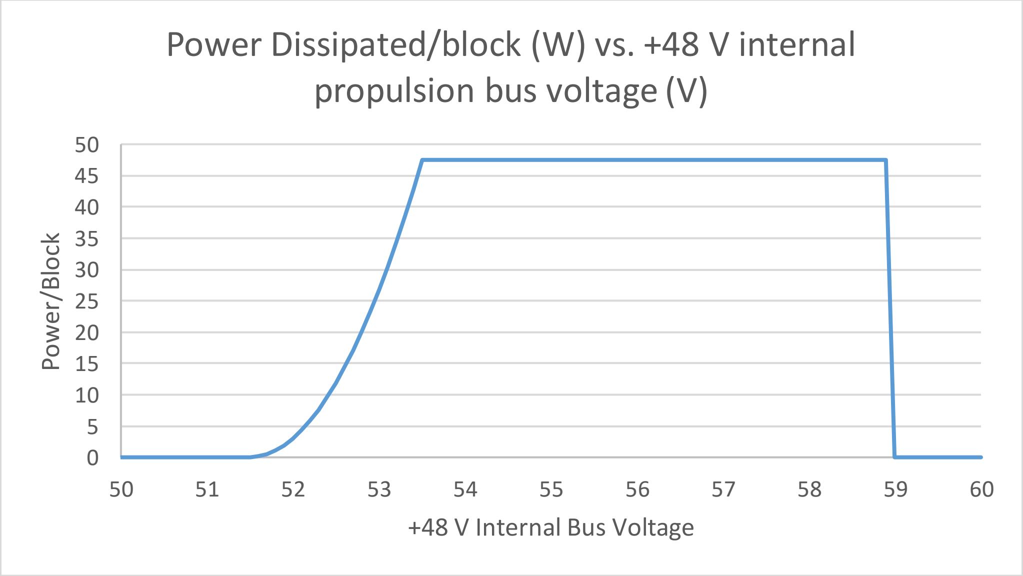


Figure 11: Power Dissipation per Block

Example – Two Motors

The first example to be considered is a single motor dissipating power and a single motor inputting power. To simplify the analysis, the following assumptions were made for this example:

- All cable resistances are identical
- The magnet array and its adjacent blocks occupy exactly (1) 1-meter motor (10 motor blocks per motor)
- The vehicle is just beginning to decelerate at that location
- The power supply has a diode and is not capable of absorbing power

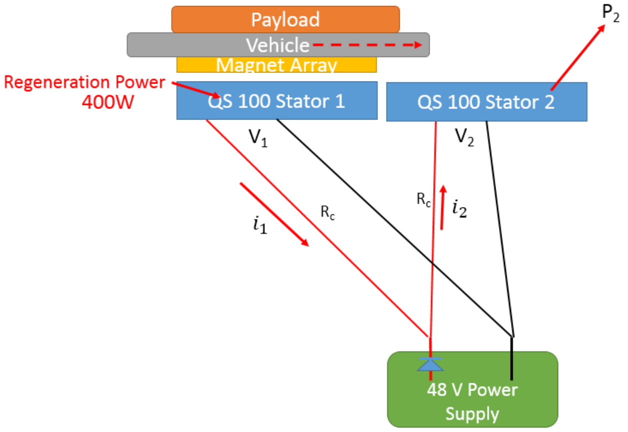


Figure 12: Single Vehicle Decelerating with Two Motors

V_1 can be set to 57V, the maximum allowable voltage for the system during normal operation. Based on this, the Power Law can be used to find the current i_1.

$$i_1 = \frac{P_1}{V_1} = \frac{400W}{57V} = 7.02A$$

By Kirchhoff's Current Law, the sum of the currents entering and leaving the junction near the power supply must be zero.

$$i_1 - i_2 = 0$$

$$i_1 = i_2$$

Motor 2 has no magnet array over it, so all 10 blocks are available to dissipate power. Assuming that power loss in the cables is considered to be negligible, this means that the power dissipated per block is

$$\frac{400W}{10\ blocks} = 40\ \ W/block$$

Using Figure 17: Power Dissipated per Block, this puts V_2 at 53.3V. Using Ohm's Law, the maximum allowable resistance in the cables can be found.

$$V_1 - V_2 = i_1 R_c + i_2 R_c = 2 i_1 R_c$$

$$57V - 53.3V = 2(7.02A) R_c$$

$$R_c = \frac{57V - 53.3V}{2(7.02A)} = 0.26\Omega$$

Example – Central Bus with One Vehicle

Another example to be considered is a single vehicle decelerating on a path. Use the same assumptions as in the previous example and the example sizing for regeneration power.

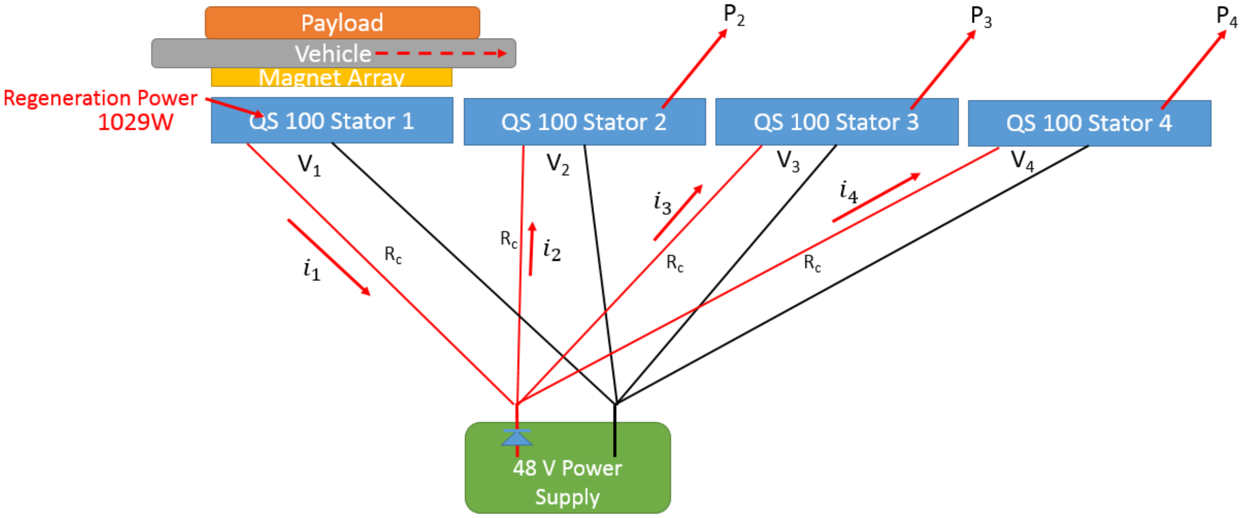


Figure 13: Single Vehicle Decelerating with Four Motors

V_1 can be set to 57V, the maximum allowable voltage for the system during normal operation. Based on this, the Power Law can be used to find the current i_1.

$$i_1 = \frac{P_1}{V_1} = \frac{1029W}{57V} = 18.05A$$

By Kirchhoff's Current Law, the sum of the currents entering and leaving the junction near the power supply must be zero.

$$i_1 - i_2 - i_3 - i_4 = 0$$

$$i_1 = i_2 + i_3 + i_4$$

Additionally, the voltage at each motor is related by the voltage at the connection point near the power supply. The voltage drop from the motor to the supply must bring the motor voltage to the same level as the power supply.

$$V_{PS} = V_1 - i_1 R_C = V_2 + i_2 R_C = V_3 + i_3 R_C = V_4 + i_4 R_C$$

All of the power into the system must also be dissipated by the system.

$$P_1 = {i_1}^2 R_C + P_2 + {i_2}^2 R_C + P_3 + {i_3}^2 R_C + P_4 + {i_4}^2 R_C$$

If there were any partially covered motors or differing cable resistances in this example, a model would be required in order to balance the current, voltage, and power dissipation in each block. In this simple example, because there are no partially covered motors and all cable resistances are the same, power dissipation in each motor can be assumed to be identical.

$$P_2 = P_3 = P_4$$

Since all of the cable resistances are the same, this also makes the current and voltage at each motor identical.

$$V_2 = V_3 = V_4$$

$$i_1 = 3i_2$$

On this basis, the power required to be dissipated can be divided by the number of available blocks. This assumes that the power loss in the cables (the $i^2 R_C$ term) is negligible. In this case there are 3 empty motors, so there are 30 available blocks.

$$\frac{1029W}{30\ blocks} = 34.3\ W/block$$

From Figure 17: Power Dissipated per Block, the voltage at motors 2 through 4 is 53.2V. If the value produced by this calculation cannot be found in Figure 17: Power Dissipated per Block, not enough blocks are available to dissipate the regenerated power.

Examining the voltage drop between V_1 and V_2, the cable resistance can be determined.

$$V_1 - V_2 = i_1 R_c + i_2 R_c = \frac{4}{3} i_1 R_c$$

$$57V - 53.2V = \frac{4}{3}(18.05A) R_c$$

$$R_c = \frac{57V - 53.2V}{\frac{4}{3}(18.05A)} = 0.158\Omega$$

Example – Central Bus with Two Vehicles

Consider the previous example, but with a second vehicle stopped on the path.

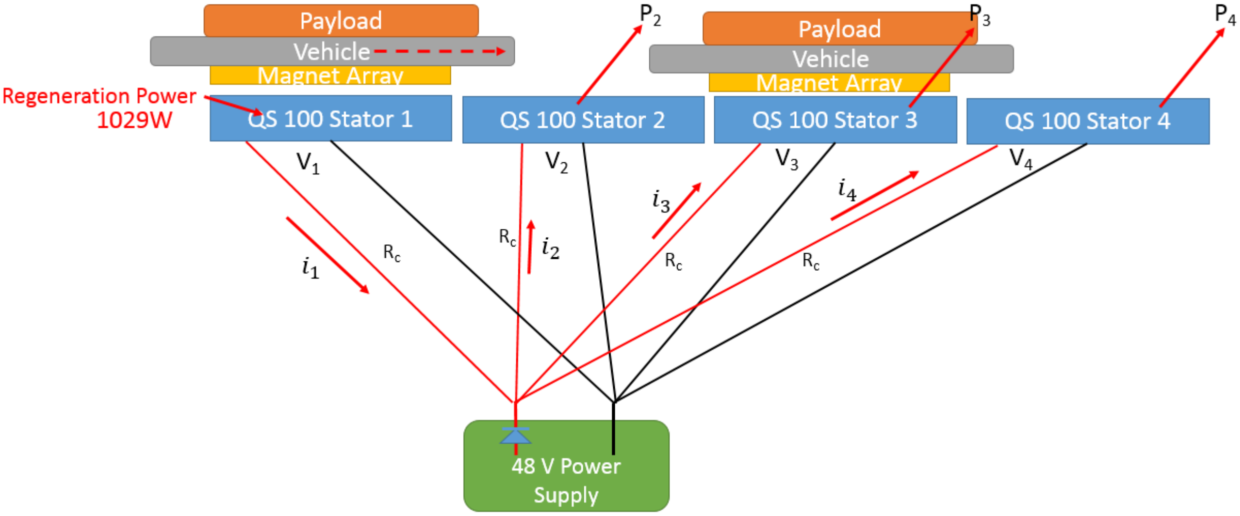


Figure 14: Single Vehicle Decelerating with Four Motors and Parked Vehicle

In this case, the same assumptions and equations apply, however there are 20 blocks to dissipate power because motor 3 is occupied and unavailable.

$$P_3 = 0$$

$$i_3 = 0, i_1 = 2i_2$$

$$V_3 = V_{PS}$$

$$\frac{1029W}{20\ blocks} = 51.45\ W/block$$

Appendix A: Power Dissipated per Block shows a maximum power dissipation per block of 47.5W. There are not enough free blocks in this system to dissipate the power being regenerated. To prevent over voltage faults more motors must be added to the power bus, the velocity or acceleration (and thus regenerated power) must be decreased, or a voltage clamp must be installed.

Methods to Reduce Voltage Increase through Hardware Changes

There are two methods that can be used to reduce the increase of voltage in the system during deceleration through hardware changes. The first method is to decrease the cable resistance between motors. This will reduce the voltage difference between the motor regenerating power and the motors dissipating power and allow the voltage at the regenerating motor to be lower.

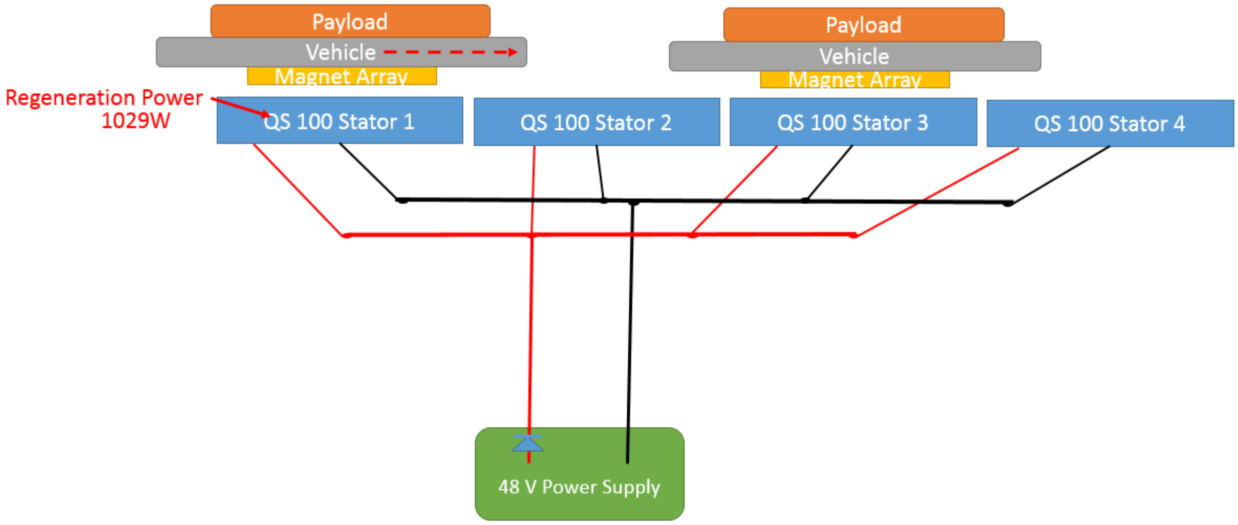


Figure 15: Central Bus with Reduced Cable Resistance between Motors

The second method is to install a voltage clamp in your power supply circuit. A voltage clamp is a circuit that will begin dissipating power if the voltage on the bus goes above a certain level.

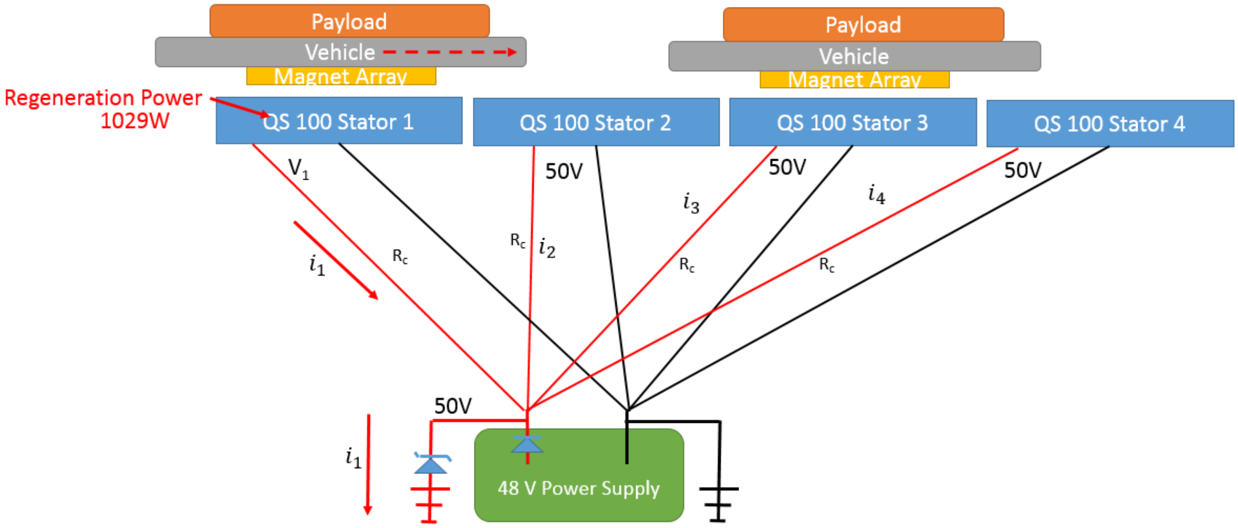


Figure 16: Four Motor System with a 50V Clamp at the Power Supply

If the clamp is set at less than 51.5 volts, no power will be sent to other motors to be dissipated.

$$0 = i_2 = i_3 = i_4$$

The voltage at the regenerating motor will equal to the clamp voltage plus the voltage drop in the cable leading to the clamp. This can be represented as a combination of the Power Law and Ohm's Law.

$$V_1 = \frac{P_1}{i_1} = 50V + i_1 R_c$$

This method will have no effect on the under voltage case directly, but may allow the power supply to be set to a higher voltage to compensate for voltage drop in longer cables without risking exceeding the high voltage limit of the motor.

If a clamp voltage below 51.5V is selected as shown here, ensure that the circuit is rated for the total regenerated power. This is because below 51.5V, no power will be dissipated by the other motors.

Summary

In larger systems, the sizing of the power cabling can have a significant effect on system performance. Incorrectly sized cables can lead to:

- Soft Start Not Complete Faults resulting in the motor losing propulsion power
- Over Voltage Faults results in the motor shutting down
- Damage to motors
    - Soft start resistor failure due to repeated under voltage
    - Protection resistor failure due to repeated over voltage
- Reduced motor life due to increased component stress
- Possible uncontrolled vehicle motion due to loss of propulsion or control power leading to collisions

The electrical design of the power system for the QuickStick motors is the responsibility of the system integrator. MagneMotion strongly recommends that all power systems be reviewed by an electrical engineer prior to installation. The examples in this document are simplifications of an actual electrical system and apply only to the specific circumstances described.

Appendix

Appendix A: Power Dissipated per Block

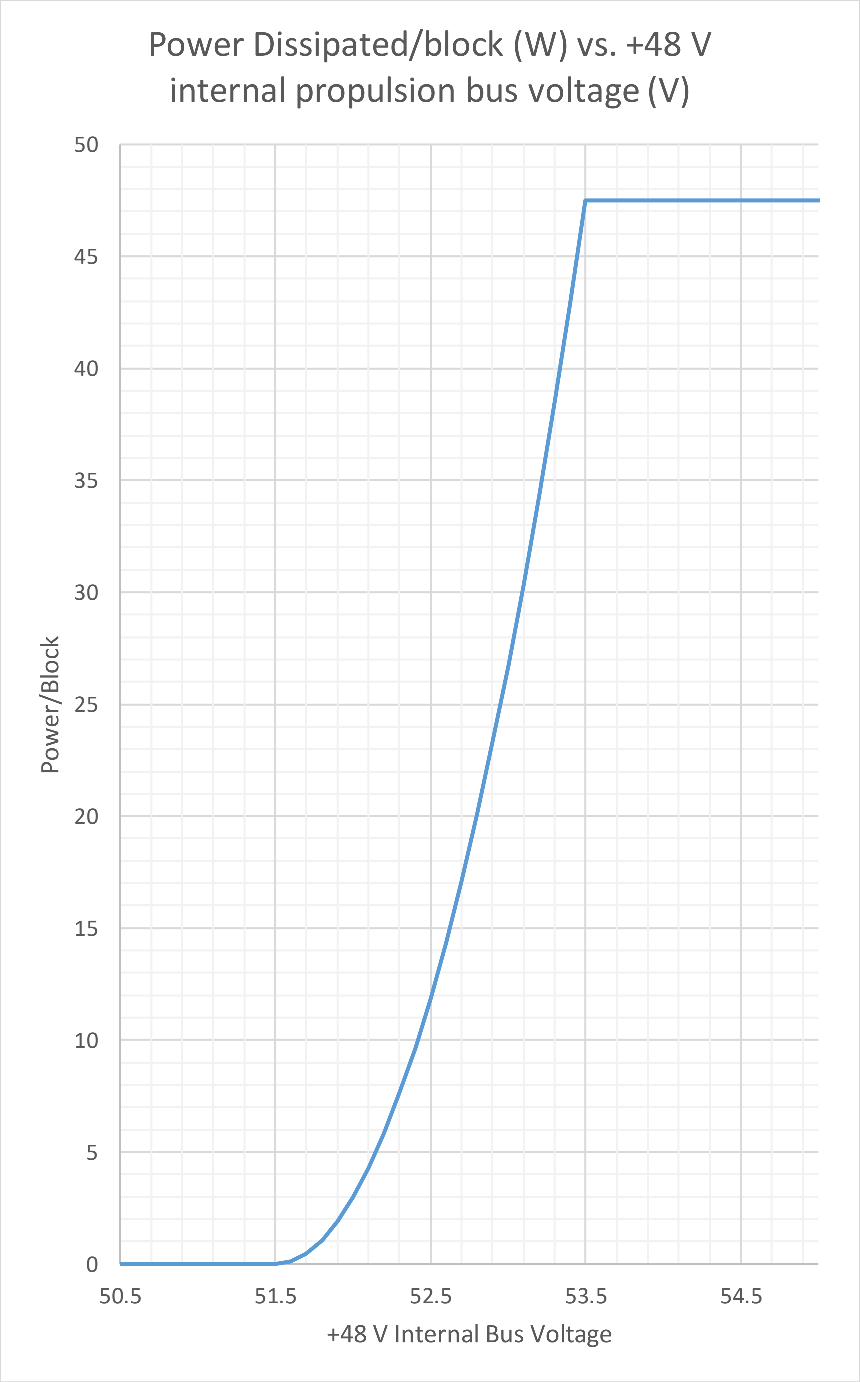


Figure 17: Power Dissipated per Block

For any questions related to the content of this document, please contact MagneMotion Customer Support.
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Email: customersupport@magnemotion.com

More Information

MagneMotion Website: www.magnemotion.com

Questions & Comments: www.magnemotion.com/about-magnemotion/contact.cfm

Revision History

Rev.	Change Description
A	Initial release
B	Fixes Formatting Errors
C	Updated for new software versions. Removed background equations section.