Application Note

understanding the role of shunt resistors and bus capacitors in regenerative systems

properly sizing bus capacitance reduces failure rates and shunt resistors and decreases power consumption

Introduction

Multi-axis production machines such as packagers, labelers, and equipment with assembly robots tend to perform the same sequence of moves repeatedly, often over extended time periods. In some cases, the motion profile results in the axes generating regenerative energy. In the extreme, this regenerative energy increases bus voltage to potentially damaging levels. To protect the equipment, systems typically include shunt resistors designed to dissipate the excess energy. When properly sized, shunt resistors can be effective. When improperly sized or applied, they can at best trigger frequent faults and at worst go into early failure. In either case, the effect is increased downtime and reduced productivity. Adding capacitor banks to the power bus enables the system to absorb the excess energy. The technique reduces stress on the shunt resistor and the system as a whole to enable faster operation and increased productivity while storing excess energy for later reuse. In this application note we will review the relationships between shunt resistors, bus capacitance, and regenerative energy with an emphasis on techniques for proper sizing to optimize system performance, increase productivity, and minimize cost of operations.

What is regenerative energy?

A motor is designed to convert electrical energy into mechanical energy as torque. As the motor rotates, the coils moving through the magnetic field also generate a back EMF in the windings that increase relatively to the motor speed. the magnitude of the back EMF is smaller than the applied voltage. As a result, the axis generates a net positive torque to drive the load.

Under certain conditions, such as when a heavy load is rapidly decelerating, the load inertia applies a torque to the motor that opposes motor speed. The change in rotation increases the back EMF until it becomes larger than the applied voltage. The direction of voltage changes so that the axis increases the bus voltage. At this point, the motor is no longer converting electrical energy into mechanical energy. It is doing the opposite – acting as a generator. It is producing regenerative energy.

Part of the regenerated energy will be dissipated in the motor windings due to internal resistance, which is known as copper loss. The rest of the regenerated energy will be sourced through the drive toward the power supply (see figure 1).

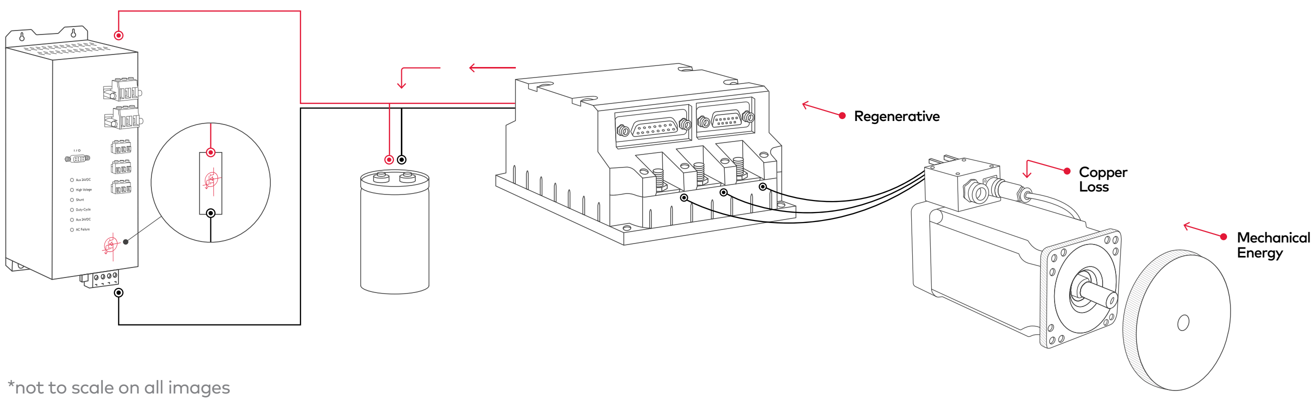

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Figure 1: In a decelerating system, the mechanical energy of the load is converted into regenerative energy.

Although most servo axes will regenerate energy during deceleration, few of them will do it at a level high enough to interfere with normal operation. Regenerative energy does become a problem when high-inertia, low-friction axes undergo fast deceleration from high speeds (see figure 2). Examples include large gantry axes, heavy rotating carousels, rotating antennas that are required to stop, elevation axes that work against gravity, and other systems that involve high dynamics with high inertia. The problem might be exaggerated in a multi-axis machine when several axes are decelerating simultaneously, causing a sum of regenerated power to source back to the power supply.

Quadrant II forward deceleration net negative torque back EMF>Ve (voltage flows into bus)	Quadrant I forward motoring net positive torque back EMF<Ve (voltage flows into motor)
Quadrant III reverse motoring net positive torque back EMF<Ve (voltage flows into motor)	Quadrant IV reverse deceleration net negative torque back EMF>Ve (voltage flows into bus)

Figure 2: Four-quadrant plot shows the operating modes of a DC motor that produce regenerative energy (Quadrant II and Quadrant IV).

The power supply and drives can be designed to prevent the voltage increase from damaging the bus electronics.
A better solution is to use a capacitor bank to store the regenerated energy for future use. The approach can prevent overvoltage faults and equipment damage, which increases uptime and productivity. It also makes the regenerative energy available for future use, cutting power consumption and reducing cost of ownership.

Bus capacitance

Bus capacitance is the total capacitance of the main DC bus. The primary contributors are the built-in capacitors of the power supply and the VP+ capacitance in the drives (see figure 3). The power supply includes an output capacitance that smooths the harmonics of the AC rectification bridge. The built-in capacitors of the drives are designed to support the fast and powerful PWM switching with an immediate, resistance capacitance.

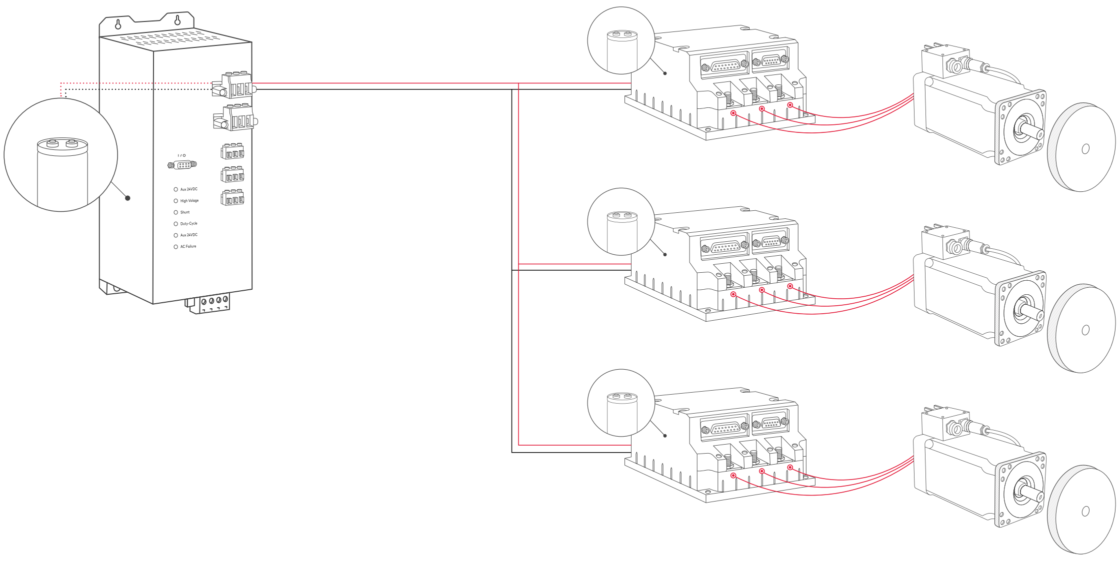


Figure 3: The primary contributors to bus capacitance are the built-in capacitors of the power supply and the capacitance in the drives.

An insufficient capacitor on a power supply will reflect in a poor rectification of the AC power, resulting in large voltage variations of the DC bus voltage under load (see figure 4).

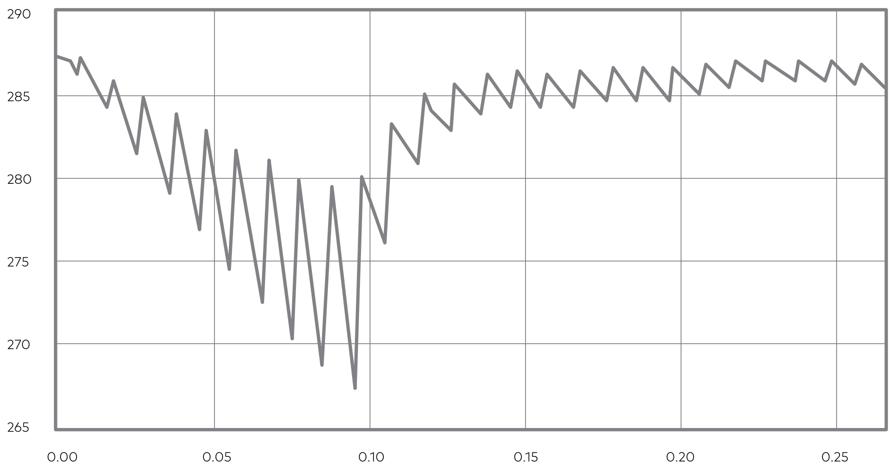


Figure 4: Plot of voltage versus time for the DC bus voltage shows a volt P-P ripple at 100 Hz during acceleration as a result of an undersized capacitor.

A shunt resistor can be used to protect the bus from a surge of regenerative power. Elmo power supplies include built-in shunt resistors control electronics to dissipate the power and clamp the voltage just below the maximum permissible level (see figure 5). When bus voltage rises above that level, known as the shunt trimming level, the shunt is turned on.

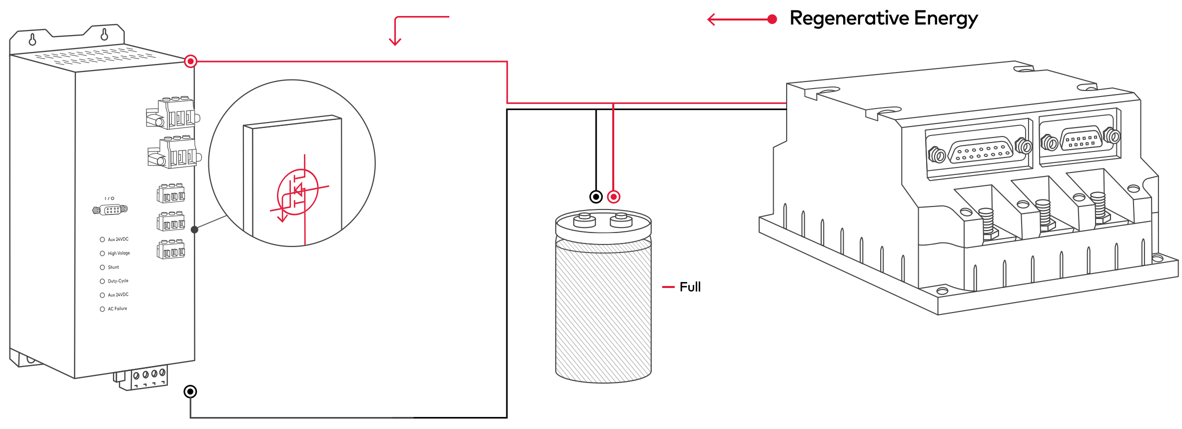


Figure 5

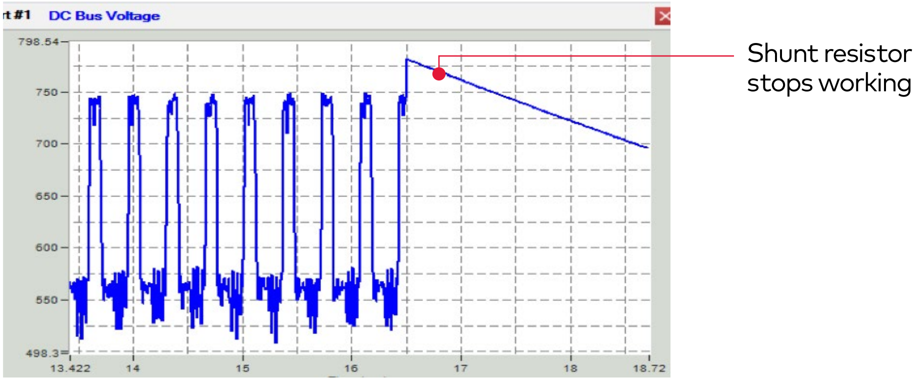


Figure 6: The shunt resistor effectively clamps the voltage at a certain level. When heat builds up beyond a certain threshold, the shunt resistor will fault out (red arrow).

The solution is to increase bus capacitance to enable the bus to absorb more energy before reaching the shunt resistor trimming voltage (see figure 7). This reduces the load on the shunt resistor and the heat generated. Increasing bus capacitance serves another role in a servo system: the capacitor bank can store the regenerative power for reuse, cutting power consumption and reducing cost of ownership.

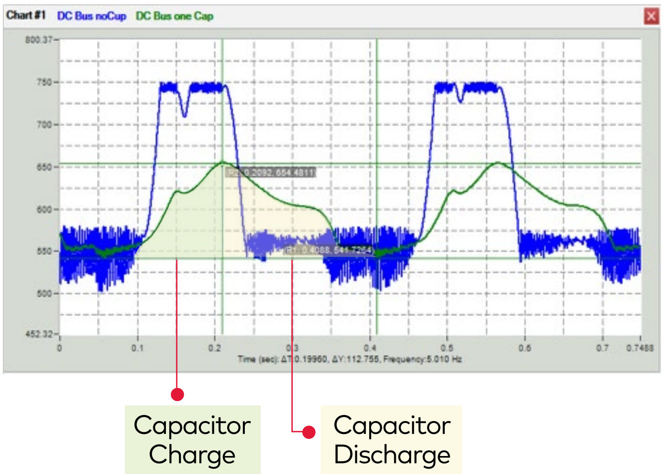
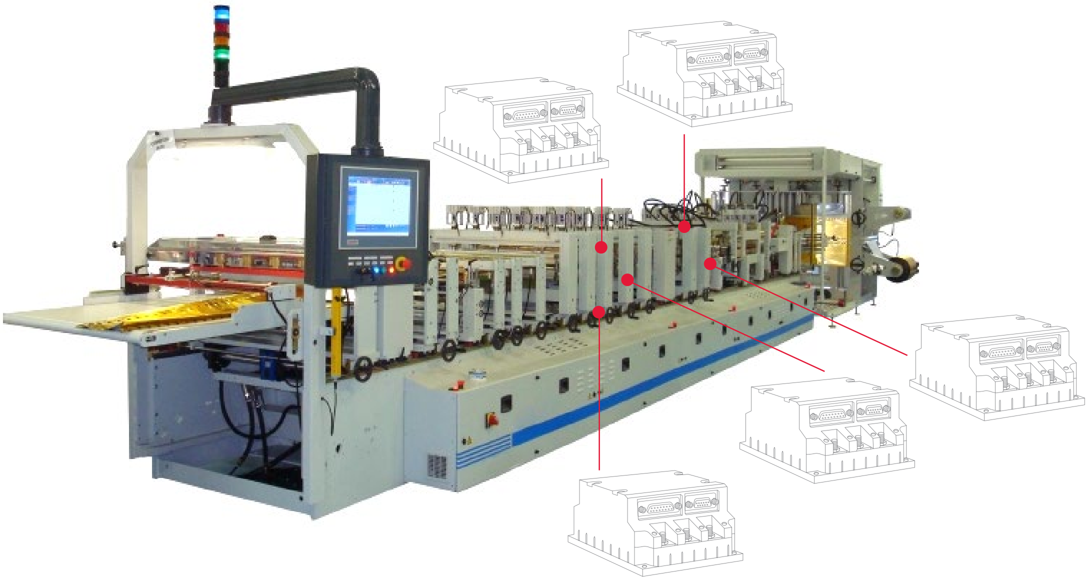


Figure 7: In a packaging machine with low capacitance, the bus voltage ramps quite fast and activates the shunt resistor. If we add an additional 5000uF bus capacitor, the capacitor bank will charge during regenerative power surges and then discharge when appropriate. The capacitor bank enables the energy to be reused while preventing the bus voltage from ever reaching the shunt resistor trimming threshold.

Bus capacitance case study

Consider a pouch making machine that incorporates up to 20 sealing stations. The stations operate simultaneously and continuously with the same profile. During the "release" phase the axes are regenerating power.



Due to the enormous regenerative energy, the machine uses two Elmo TAM100/480VAC power supplies, each one equipped with a shunt resistor sized to dissipate peak powers of 23 kW shunt resistor peak power. This would be an effective solution if the machine generated these peak powers only occasionally. Unfortunately, with the simultaneous operation of the sealing stations, the shunt resistors were activated several times per second. As a result, they stopped working after a few minutes of operation, resulting in an immediate over-voltage protection that caused the machine to fault out.

Sampling the bus voltage during operation demonstrates the high duty cycle of the shunt resistor (see figure 8). The DC bus voltage rises to 750 VDC on every cycle for approximately 70 ms. Once the bus voltage reaches 750 VDC, which is the shunt trimming voltage, the shunt resistor starts to act and the regenerated power is dissipated as heat.

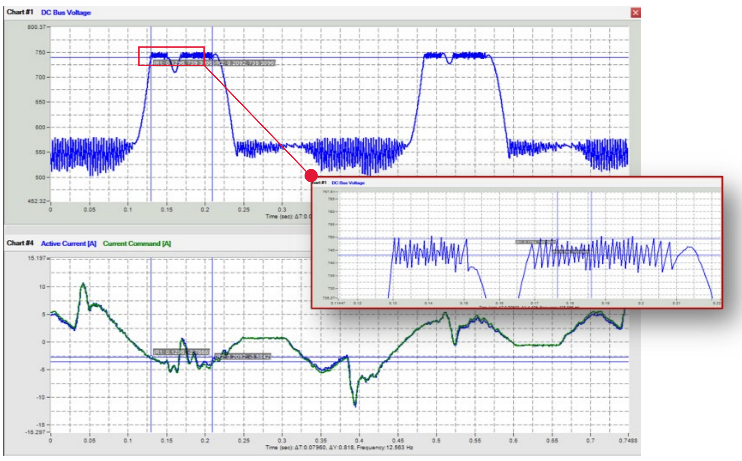


Figure 8: ceiling scene machine pouch sealing machine increases DC bus voltage to 750 V DC every 70 ms, activating the shunt resistor. He buildup from the high duty cycle caused the axes to fault repeatedly, stopping production.

The solution to the problem is sizing a capacitor to capture and store the regenerative energy. Let's run through the calculation. We start by calculating the regenerative energy produced. By viewing the voltage mean at its peak, we can estimate a 50% average activation rate, meaning that the shunt resistor only dissipates half of its peak power (23KW for this model). (Note: an alternative approach to determining activation rate is to measure the voltage and the reversing current with an external scope and estimate accordingly how much energy is being dissipated.)

On every cycle, the regenerative energy Eregen being dissipated through the shunt resistor is:

Eregen =P*t

Where P is power and t is time. In our case, the dissipated energy is 50% of 23KW over a duration of 0.06 s for a total of approximately 690 J.

Although the shunt resistor provides protection during occasional power spikes, it is not appropriate to deal with continual regeneration. Adding a capacitor bank to the bus to absorb the regenerated energy reduces energy consumption of the machine as a whole while increasing the lifetime of the shunt resistor and reducing downtime. Let's take a look at sizing.

$$E_{cap} = \frac{C(V^2_{max} - V^2_{min})}{2}$$

where Vmax is the maximum allowable voltage (750VDC, in our case) and Vmin is the nominal bus voltage before the regenerative energy (560VDC, in our case).

According to the above, the required capacitance should be:

$$C = \frac{2 * E_{cap}}{(V^2_{max} - V^2_{min})} = \frac{2 * 690}{(750^2 - 560^2)} = \sim 5540\ \mu f$$

If we add 5000uF additional capacitance to the system, and it absorbs and stores the additional voltage. The bus voltage never reaches 750 VDC; the shunt resistor is never activated.

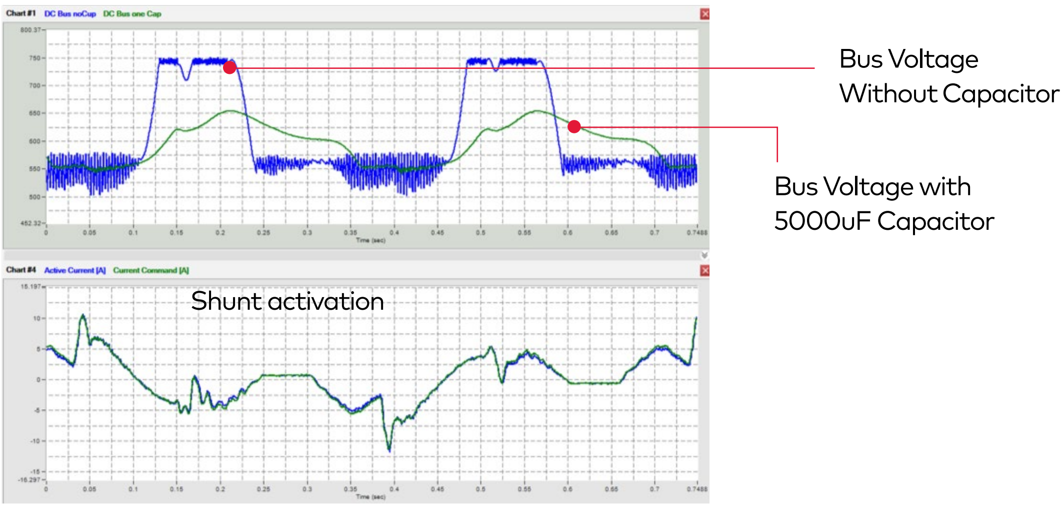


Figure 9: Regenerative energy repeatedly drives the bus voltage of the pouch sealing machine above threshold (blue line), overheating the shunt resistor and triggering unnecess nuisance ary faults. With the addition of the 5000 μF capacitor bank, the bus voltage (greenline) never reaches threshold.

Because the machine no longer faults out at high speeds because of the shunt resistor, the user is able to run the machine at a much faster rate (see figure 10).

Without Extra Capacitor | With Extra 5000uF Capacitor

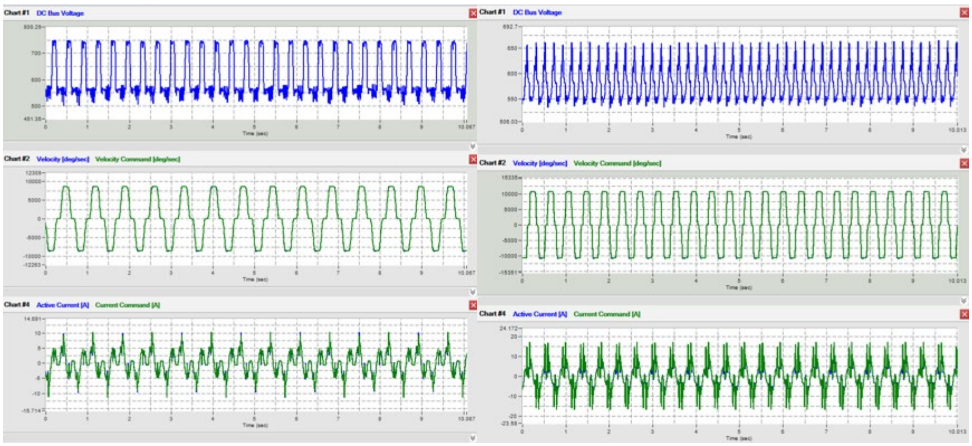


Figure 10: Headingley capacitor bank eliminated nuisance faults from the overheated shunt resistor. As a result, it could run successfully at significantly higher speeds.

Sizing Bus Capacitance

The linear motors market is constantly growing and brings direct, accurate, high performance motion systems to more and more applications. Although linear motors can be effective solutions for many cases, they also can introduce challenges. Linear motors are typically equipped with low-friction rails. Minimal friction is good for precision positioning but most of the kinetic energy flows back to the power supply, and stress on the shunt resistor is high. Here, a regenerative drive can help, but only if it is properly sized.

Consider a linear axis with 40kg payload that goes forth and back in a triangle profile: maximum acceleration, maximum deceleration. It rests for 500ms and then repeats the sequence for the entire time the machine is in operation. The key operating parameters are:

Travel:	1m
Acceleration:	6m/s²
Deceleration:	6m/s²
Mass:	40kg
Cycle Period:	1.23s
Deceleration time:	0.365s
Bus Voltage:	220VAC
Kt:	57.2N/A
Resistance:	3.4Ω

We start by calculating the regenerative energy produced. Assuming zero frictional force, E deceleration is given by:

$$E_{deceleration} = \frac{m\,(V_{max}^2 - V_{min}^2)}{2} = \frac{40\,(2.19^2 - 0^2)}{2} = \sim 96J$$

We can calculate the motor's "Copper Loss"

$$P_{core} = I^2R = R\left(\frac{F}{Kt}\right)^2 = R\left(\frac{ma}{Kt}\right)^2 = 3.4\left(\frac{40 * 6}{57.2}\right)^2 = \sim 60W$$

And the corresponding copper loss is:

$$P_{core} = pmot * Tdecel = 60 * 0.365 = \sim 20J$$

We can express regenerative energy Eregeneration as:

$$E_{regeneration} = E_{deceleration} - P_{core} = 96 - 22 = 74J$$

This axis will regenerate 74j every cycle, meaning every 1.23s
The bus voltage is 311 VDC. Elmo has two regenerative drives that could potentially work:

- **G-OBO10/230FE**
  - charge voltage level: 380 VDC
  - total energy storage: ~57.7J
  - internal capacitor size: 800uF
- **G-OBO10/480FE**
  - charge voltage level: 750 VDC
  - total energy storage: ~56.2J
  - internal capacitor size: 200uF

Explanation

Both drives are the same physical size and have similar energy storage capacity. At first consideration, the G-OBO10/230FE seems like a good fit. It's charge voltage level is high enough to exceed the level for the system by a comfortable margin. It also has sufficient energy storage capabilities. Ultimately, however, it was not the best choice. The G-OBO10/480FE was finally chosen due to its better energy absorption when running at 220VAC

Even though G-OBO10/480FE capacitor absorbs 46.6 Joules it is still not enough to store all of the regenerative energy, the axis regenerates 74 J every cycle. We still need to dissipate ~28J every cycle.

We need to determine what size shunt resistor we need. We need to know the power generated from the system:

and the average power can be calculated accordingly:

$$Pcontinuous = \frac{E_{regeneration}}{Cycle\ Period} = \frac{28\ Joules}{1.23\ sec} = \sim 22.8.W$$

This continuous power can be dissipated through the driver's built shunt resistor, which has a maximum allowed continuous power of.

Conclusions

When working with large capacitors, users should take some key precautions. Users should be cautious. A large capacitor will increase the inrush current at power up. Care should be taken in choosing the machine's circuit breaker. Elmo recommends circuit breaker type C. Dangerous power can still exist on the bus voltage even after shut down due to charge on the capacitor. The user must protect the hot lines and take care for discharging the capacitor at Power Off.

Although increasing bus capacitance can be very effective when properly sized and applied, it is not the perfect solution for all applications. It's all a matter of numbers. If the regenerative energy is too large it is not practical to solve by a capacitor and other solutions should be used. It is most effective for production machines with an ongoing cycle of fast acceleration and decelerations such as packaging machines, AOI machines, etc.