The Demystifying of the Servomotor and Servo-drive

Power Supply matching for CNC applications.

Note: This document is targeted for customers with basic electrical knowledge. To keep it handy for these users, many minor aspects are omitted and oversimplified. There are in depth publications that describe this subject in great detail. The purpose of this document is not to repeat them, but to highlight a few important facts in plain English in order to ensure the reliable, failure-free, long term operation of Rutex servo drives for all users.

1. Servomotors:

1.1. Torque-wise, there are usually two ratings associated with the servomotors: Peak and Continuous. The Peak rating is the torque the motor can actually deliver for brief periods of time (limited duty-cycle). The Continuous rating reflects the heat dissipation limits of the motor at 100% duty-cycle. Usually the ratio between peak and continuous ratings is about 5:1 for brush motors and 5:2 for brush-less motors. In Brush-less motors the motor windings are mounted to inside of the motor's case, and the heat can thus dissipate faster. Continuous rating must be considered for applications such as conveyer belts etc. where the duty-cycle is expected to be 100%.

In CNC applications there is a need for plenty of torque only during acceleration/deceleration. There is also usually plenty of stand-by time for a motor to cool down. For most CNC applications it is quite safe to consider the peak rating of the torque or current. Torque is directly proportional to the motor current (Amps) and speed (RPM) is proportional to the voltage (Volts).

1.2. **How much torque do I need?** There are ways to precisely calculate the required torque based on the mass, friction, required acceleration, pitch of the lead screw, gear ration, etc., but these calculations are beyond the scope of this document. A simple way to estimate required torque is to mount a large hand wheel or pully/string/weight configuration on the end of the lead-screw and determine by experimentation the weight or force needed to rotate the lead screw . Then multiply the required "force" in pounds (lb) or newtons(N) by the radius of the hand-wheel to get the lb-in or Nm rating. You can also use a torque wrench to determine the torque if you have access to one. Then you can match this value to the torque specification in the prospective servomotor's datasheet in the motor selection process.

1.3. **How do I select a motor?** Begin by examining the graphs that normally accompany motor specifications. Match the motor's specified peak torque rating (paragraph 1.1.) and the torque that we estimated that is needed (par. 1.2.) for the specific application. Now you will need to select the required speed of the motor. Motor manufacturers quite often specify maximum speed at maximum terminal voltage with no load. This parameter is quite easy to measure but rather useless. You will have to look at the graphs that show the torque and speed relationship to determine the maximum practical speed of the motor at the required torque. For example, to obtain a motion of 200 Inches per minute (IPM), using a 5 TPI lead-screw, you will need to rotate the lead screw at 1000 RPM. You will find out that most servomotors, especially small motors, are useable to several thousand RPMs. It is good idea to use the full available speed range of the motor and install a speed reduction mechanism between the motor and the lead-screw. This is often done with pulleys and a timing belt. There are several advantages of using speed reduction if the maximum motor speed will allow for it. You will get more precise control from the servo motor/drive and the torque at the lead screw will also be multiplied by the speed reduction ratio. Considering the above factors, you might come to the conclusion that the size of the required motor is way too small in comparison to the physical size of the motors found on other commercial CNCs. It is important to do the calculations, and then provide a safety factor. As an analogy, let's have look at automobiles. The manufacturer's specification of the power of the car is specified at about 6000 RPM but we hardly ever drive a car at 6000 RPM. Nobody would like to buy a car which had to be revved up to 6000 RPM just to get it out of the driveway. A Car like this would not last long either. Back to CNC. It depends on your application, but usually doubling the required torque or providing a 100% safety factor is satisfactory. Keep in mind, however, that it may not always be a good idea to significantly to oversize the motor because a big motor also works as a big generator while braking and the servo drive has to handle the regenerated energy (BEMF) generated by the motor. More on that later.

1.4. **How do I select the servo-drive?** A Servo motor datasheet may include graphs for torque in relation to current and speed in relation to voltage, but quite often a motor specification will show only the Kt constant in Nm/Amp or oz-in/Amp and Kv constant in Volts/kRPM. To properly size the drive needed, you need to determine the current and voltage required to produce the desired motion.

The calculation of the current required using the Kt parameter is very straightforward: divide the required torque by Kt to get the current. For example, if the required torque is 20 lb-in (320 oz-in) and the Kt = 32 oz-in/Amp, then 320/32 = 10 Amps. This value is the current that the servo drive has to be able to provide.

Every servo motor is also inherently a generator, and the voltage that is generated when the motor is turned by some external rotary machine provides a valuable parameter (Kv) that can also be used to determine how fast the motor will turn for any given voltage applied to the motor when the motor is serving as a servo motor. The Kv parameter is therefore a measure of the back electromotive force (BEMF) constant and it is given as a regenerated voltage produced per each 1000 RPM (kRPM). If the motor was 100% efficient you could just multiply the Kv by required speed in kRPM to get the required voltage. In reality, however, the voltage required must be scaled up by typically 1.2 to 1.4 to make up for losses in the motor. Additionally, the servo drive output is pulse width modulated (PWM) meaning that it is never "on" 100% of the time and this must be taken into account. The scale factor of 1.5 should cover all the losses. For example, if the desired speed is 5000 RPM and the Kt = 10 Volts/kRPM, then the Vm should be 75 Volts (1.5 * 5 kRPM * 10 Volts/kRPM).

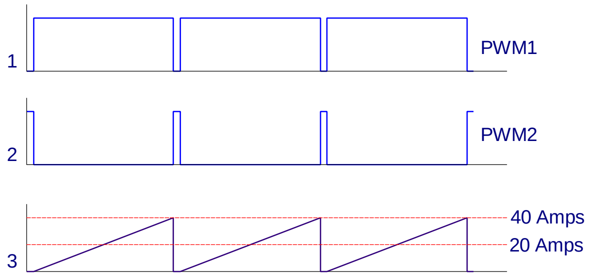
2. Servo Drives:

As previously mentioned, the output power provided by the Rutex drives is pulse width modulated (PWM). This means that the energy going to the motor is not modulated in voltage, but in time. For full power to the drive the voltage pulse is "on" most of the time. The motor voltage applied (Vm) is always the same whenever the drive transistors are turned on. The length of time the voltage is "on" (is sent to the motor) is varied, thus the term PWM.

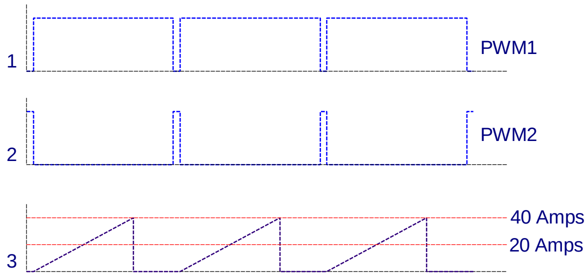
2.1. **Voltage rating:** The maximum voltage rating of a servo drive is determined by the maximum Vds specification of the output MOSFETs transistors used to switch or pulse the output of the servo drive. The semiconductor manufacturers guarantee that their devices will work at specified Vds as long as the users will keep the transistor Vds within the specified maximum. In a servo motor application, the Vds will be a combination of the Vm calculated above (1.4) and other factors mentioned here. This Vds is a specification that must not be exceeded, or else drive failure will eventually occur. Therefore it is important to consider the factors that could contribute to the voltage that these output transistors may be required to control in operation. Factors such as motor BEMF, the ESR (equivalent series resistance) of the power supply capacitor, wiring resistance, parasitic inductance, and power mains voltage fluctuations, etc. can easily be overlooked, but these factors will all add to the motor supply voltage (Vm) and if not considered, the Vm can easily exceed the Vds rating of the MOSFET transistors. The BEMF factor is especially significant during braking when the kinetic energy of a moving axis and motor is converted back into current and voltage that increase the servo drive voltage Vm.

Considering the above factors, and from a practical point of view, the Vm should be kept below 80% of the drive rating for a simple transformer+bridge+capacitor type power supply. Alternatively, If a shunt regulator is included in the motor power supply, the Vm can be as high as 95% of the rated Vm. See paragraph 4.7 below for a description of a shunt regulated motor power circuit.

2.2. **Current rating:** The Rutex R2010 brush motor drive and the R2030 brushless motor drives can both deliver a current of 20 Amps to the motor. The R2020 brush motor drive can deliver 40 Amps. Due to the inductance of the motor, the maximum average current that a motor can draw out of the servo drive is about a half of what you might think it could draw if you were calculating the motor current by simply taking the motor voltage(Vm) divided by the motor's specified resistance. See the graphs below for a 40 Amp servo drive operated at close to 100% PWM duty-cycle – its maximum output.



The first two lines of this illustration (PWM1 and PWM2) show the voltage across the motor terminals. The third line shows the actual current in the motor. The above example shows the motor current reaching just below peak current limiting point. The average current (a sum of surface area under the graph) is close to 20 Amps. The servo drive sees the motor as an inductive load that changes its resistance to current flow depending on the load. In the idle condition the inductance of motor is as per the motor's datasheet. At full load, however, the servo drive sees the motor as very small inductor (L) and the current (i) increases very quickly (i = t / L). The Graph below shows the motor with a large load. Note that it reaches the current limiting point in time before the end of full PWM cycle.



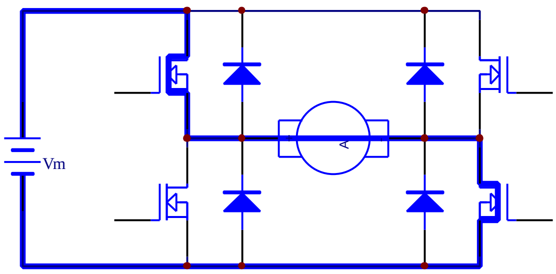
This relationship between average and peak applies to all servo drives (including 3rd party) that employ the typical 4-quadrant PWM H bridge output.

There are techniques that can be used to get the full 40 Amps motor current out of the 40 Amp servo drive but many are application specific. Low pass filters can be used to filter out the ripple current, but designs using this method are complex, and depending on the CNC application, they may not work well. Low pass filters work only where there are constant loads, and thus constant ratios between the motor's Voltage and current. Other methods are beyond the scope of this document.

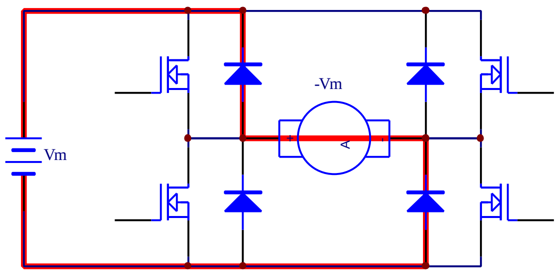
3. Driving an oversized motor with undersized drive:

Q: *"I have a large motor on a machine. When I drive the motor directly from the power supply it draws only few Amps. Can I use the smaller servo drive (R2010) to drive it? I do not need a lot of torque from the motor."*

3.1. The answer is Yes and No. A general understanding of factors contributing to current in a servo system is helpful to the servo system builder and is provided in the following two paragraphs. The small drive can drive a large size motor as long as the user (or CNC control) can guarantee that the system will always decelerate at the same or lower rate in which it was accelerated. The forward current into the servomotor is limited by the drive MOSFETS – during acceleration. However, during deceleration, the regenerated current (BEMF) is not controlled by the drive MOSFET transistors themselves. Rather, it is passed directly through the protection diodes that are an integral part of the MOSFET transistor components. The MOSFET transistor manufacturers include a high power, fast schottky diode inside each MOSFET transistor component, with a rating higher than the MOSFET itself to protect the MOSFET from high reverse currents. If the deceleration time is same as acceleration, then the regenerated current is the same as the forward current and the drive transistor components have no problem handling the BEMF from the motor. No additional protection is needed. For an explanation of this, see the illustration below. Note that this only illustrates a two-quadrant operation. In a four-quadrant operation the braking current can flow via the diode and the opposite MOSFET as well.



Forward current flow



Regenerated BEMF current flow

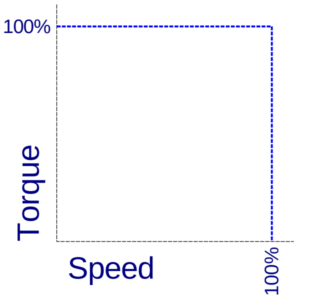
The motor *draws* most of the current during rapid acceleration and *generates* most of its current during rapid deceleration. As noted above, the BEMF generated in rapid deceleration or braking needs to be considered when driving an oversized motor. The worst conditions to be considered are when the motor hits the end of the axis travel (metal on metal) at full speed as would occur during the failure of a limit switch or when the motor violently oscillates due to incorrect tuning. The theoretical regenerated current can even momentarily be high enough to begin to demagnetize the permanent magnets in the servo motor or it can exceed the ratings of the schottky diodes in the servo drive, so a conservative approach needs to be taken to limit it. Most of the motor manufacturers do not specify the exact demagnetizing current, and the peak torque motor specification (Tp) may or may not be less than the demagnetizing current. For our calculations, consider the regenerated voltage to be equal to –Vm and the maximum regenerated current to be equal to Vm/Rsum. The Rsum includes, in addition to the motor's specified armature resistance (terminal resistance), resistance from wiring, the ESR of the power supply, and other minor contributors. The inductance of the motor's winding, however, is not a factor of the Rsum, because during deceleration, the current is DC – it is not pulsed by the PWM as the forward current is when the servo motor is accelerating or being driven.

3.2. **What is the minimum armature resistance (motor winding plus wiring resistance)?** The Rutex 20 Amp drives (R2010/R2030) are fitted with 37 Amps continuous and 110 Amps peak current MOSFETS. The 40 Amp drive (R2020) is fitted with 65 Amps continuous and 220 Amps peak current MOSFETS. A conservative approach is to take in account the continuous current rating, rather than the peak rating. In this situation, the minimum armature resistance calculates out to be about 0.03 Ohms/Volt for 20 Amp drives (100V/37A/100V = 0.03) and 0.015 Ohms/Volt for the 40 Amp drive (200V/65A/200V= .015). This is an important motor characteristic to be used to determine whether a braking resistor is needed. See paragraph 3.3 below.

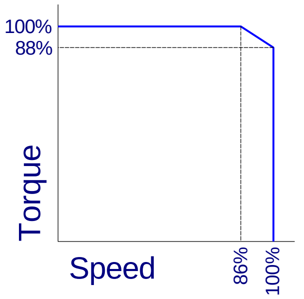
3.3. **How do I know if I need a braking resistor?** For a correctly matched motor / servo drive combination you will not need any external braking resistor or any other protection. Although, if the motor is "too big" for the drive you will need a braking resistor. Consider, for example, using a R2010 drive and a Vm of 75 Volts. The minimum recommended armature resistance would be 2.25 Ohms (0.03 Ohms/V * 75V). You can subtract about one quarter of an Ohm for the wiring resistance, leaving about 2 Ohms for the motor. In this situation, since the motor winding resistance is less than 2 ohms, you should add a resistor in series with this motor to get the required 2 Ohms to limit the BEMF generated by the motor during deceleration.

3.4. **How do I calculate the value of the braking resistor?** Let's use the example from paragraph 3.3. A R2010 is being operated with a Vm of 75VDC and to get full torque, the required current (I) is 10 Amps (see paragraph 1.4). Let's assume that the motor manufacturer specified the motor armature resistance to be 1.0 Ohms. You should use the motor's datasheet value because the typical hand-held multimeter is very inaccurate for measuring small values of resistance – the typical error is +/-1 Ohms. The calculated value of the braking resistor would be 1.0 Ohms or more - connected in series with the motor winding. The resistor will also have to be able dissipate 100 Watts ($R * I^2$) at a 100% duty-cycle. A 100% duty cycle should be considered, because these braking resistors can get very hot. The resistor should also be wire-wound to be able to handle the short-term overload produced by the braking current.

3.5 **How much power will I loose on this braking resistor?** In the above example, having a motor winding resistance 1 Ohm and a braking resistance 1 Ohms, would lead us to believe that 50% of the power will be lost on the resistor, but this is a very incorrect assumption. The motor represents 7.5 Ohms at full speed and load (75 Volts / 10 Amps). A braking resistor of 1 Ohms at 10 Amps represents only a 10 Volt drop, so that up to 65 Volts (86% of speed) is provided to the motor. In this configuration, at top speed, 8.8 Amps or 88% of the torque is available (75 Volts / (7.5 + 1) Ohms). The graphs below show the available torque versus speed without and with the braking resistor in the circuit.



Without braking resistor



With braking resistor

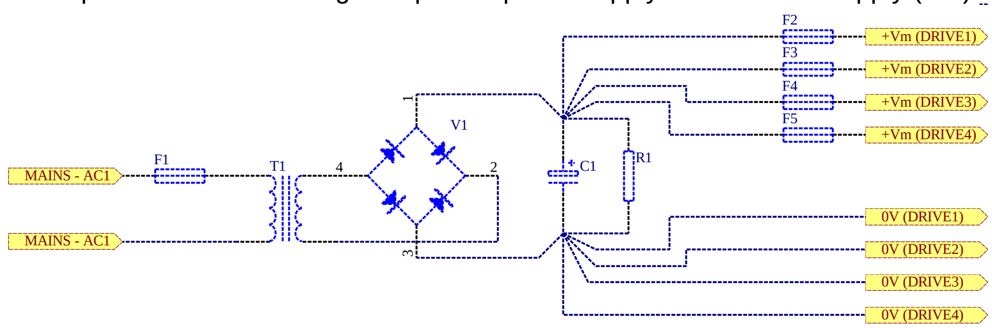
One side benefit of providing a braking resistor is the extended brush life of the motors. The braking resistor tends to suppress the arcing of the brushes and commutators.

3.6 **Cooling and Heat Sinking:** Because of the wide range of applications where Rutex drives are used, it is difficult for us to specify cooling requirements. Many users simply mount the anodized aluminum heat sink on the back of the drives to the backplane of an electrical cabinet. Others mount them to finned aluminum heat sinks. MOSFET transisitor manufacturers have published statistics that show that for each 10 degrees Celcious decrease in temperature at which their components are operated, a year of life can be gained. Keeping the servo drive cool enough that you can hold your finger on the black anodized aluminum heat sink /mounting plate for each drive would be a minimum. An impressive amount of heat can be dissipated with a small fan directing a flow of air across the drive assembly.

4. Power supply to Servo System matching:

4.1. The 24 Volt logic power supply needed for the Rutex drives (Vc) can be a standard off the shelf switching or linear power supply. You can even use DC 24V/1A wall plug modular power supply. Each Rutex drive draws less than 50 mA. A separate 5 volt voltage regulator is provided in each Rutex drive just for the encoder but driving an encoder that draws as much as 200 ma can contribute significantly to the heat the drive has to dissipate. US Digital encoders typically draw less than 50 ma and are recommended. If your encoder draws more than 150 ma, you should supply the encoder with its own supply voltage or provide extra (forced air) cooling for the drive.

4.2. A Simple Transformer+Bridge+Capacitor power supply for the motor supply (Vm):



To minimize ground loops, the Vm voltage should be distributed in star configuration directly from the terminals of the capacitor and individually fused.

4.3. **Transformer:** The secondary AC voltage of the transformer should be 0.7 * Vm. For example, to get a Vm of 75 VDC, you will need a transformer with secondary output of 53 VAC (0.7 * 75). You may use standard 48V or 55V transformer. The VA rating of the transformer depends on the load. Consider this example: If we need to supply a 3-axis machine running in 2 ½ axis mode and the calculated drive for each axis is 75 Volts and 10 Amps maximum current. Each drive is 750 VA maximum and in 2 ½ axis mode only 2 axes run at the same time - making 1500 VA total. This is the peak power, or the maximum that the machine is going to need, but the average power is going to be only fraction of this (see paragraph 1.1.). The typical transformer can deliver a current or power about 5 to 10 times more than it is rated at for short periods of time before it heats up and cooks itself. Therefore the transformer should be at least 300VA – assuming a 20% duty-cycle.

4.4. **Bridge**: For a Vm up to DC 100 Volts use at least a 400 Volt bridge rectifier. For a Vm up to DC 200 Volts a 600 V bridge rating would be the minimum recommended. Do not use anything smaller than a 35 Amp bridge even if the required current is relatively small. Bridge rectifiers are inexpensive. The most critical parameter is the I_{FSM} (maximum surge current). The most common failure of the bridge occurs at power up time while the power supply charges up its capacitors. Large bridges (35 or more Amps) have the I_{FSM} in 400+ Amps range and that's usually enough to charge several 10's of thousands of microfarad capacitors.

4.5. **Capacitor**: The size of the motor power supply capacitor should be 1000uF / Amp, where the total current (Amps) is the sum of the estimated current needed by all of the drives. A 20,000 uF Capacitor is needed for a 20 Amps power supply. Two or more smaller capacitors can be connected in parallel to get the required capacitance. Do not skimp on the size of ths capacitor. For safety, you should also install a bleeder resistor (R1) across the capacitor to discharge it when power is turned off. At 75 Volts, a 10 kilo-ohms resistor will discharge a 10,000uF to half voltage in about 70 seconds; a 1 kilo-ohm discharges this capacitor in about 7 seconds. The 10 k resistor will dissipate 0.6 Watts (75*75/10000); whereas a 1 k resistor will dissipate nearly 6 Watts. The bleeder must also be rated at a power (watts) sufficient to dissipate this amount of power. It is good idea to over-rate the power (Watts) rating of the bleeder resistor several times to minimimize the temperature rise.

4.6. **Fuses**: The primary of the transformer should be fused with a slow blow fuse (F1). The fuse should be rated so that it will not blow at full power – 1500VA in the above example. It should also be rated to be able to handle the in-rush current that develops when the power supply is first turned on. The fuses in the Vm supply for each axis should be fast blow, rated as per each drive's current requirements.

4.7. **Shunt regulator:** A zener diode connected across the Vm supply is a shunt regulator, but practically it cannot be used because zener diodes are manufactured only up to several ten's of Watts. The picture below shows a shunt regulator, where the power-limiting factor is the rating of transistor – this is simplified illustrative drawing only. The design of a proper shunt regulator is beyond the scope of this document.