Celera
MOTION
A Novanta Company

Efficiency and Power in Servo Drives

REV200605

OVERVIEW

This paper explains the origins of power losses in a servo drive. The concepts of switching, conduction and quiescent losses are discussed. A comprehensive method for calculating drive efficiency is presented. The paper concludes with recommendations and guidelines to improve efficiency.

POWER FLOW AND LOSSES

In the process of converting electrical energy to mechanical energy, all the elements in-between the input electrical power and the output mechanical power present power losses in the form of heat dissipation. The servo drive's electronics (logic system and power stage), power cables, motor windings, and the motor mechanical losses, are some of the sources of power losses in this energy transformation from electrical to mechanical. The diagram in Figure 1 depicts the power flow and its losses.

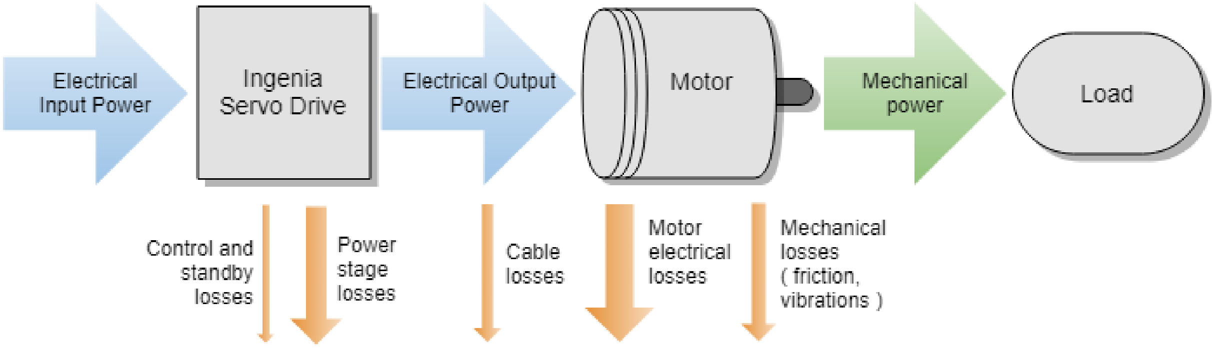


Figure 1

Power losses not only increase the power consumption of the system, but are transformed into heat. System heat must be evacuated, since a rise in temperature worsens system operation (increases the power losses, components drift, and electrical noise) and reduces the life expectancy of the components. Furthermore, heat evacuation measures are expensive and complicate high-density integrations and size reductions. For these reasons, the minimization of power losses should always be an objective in a servo driven system.

EFFICIENCY

The efficiency (η) is defined as the ratio between the output mechanical power (P_{out}) and the input electrical power (P_{in}).

$$\eta = P_{out} / P_{in}$$

In a DC servo driven motor, the input power is the electrical power provided by the power supplies or battery systems. When a single supply is used, P_{in} can be calculated as:

$$P_{in} = V_{bus} * I_{bus}$$

Where V_{bus} is the power supply DC voltage (between POW_SUP and GND_P terminals) and I_{bus} is the current provided by this power supply.

However, when the servo drive uses a dual supply source (different supply for power and logic), both supplies must be considered. In a dual supply system, P_{in} can be calculated as:

$$P_{in} = V_{bus} * I_{bus} + V_{logic} * I_{logic}$$

Where V_{logic} is the logic supply voltage (between +LOG_SUP and GND_D terminals) and I_{logic} is the current provided by the logic supply.

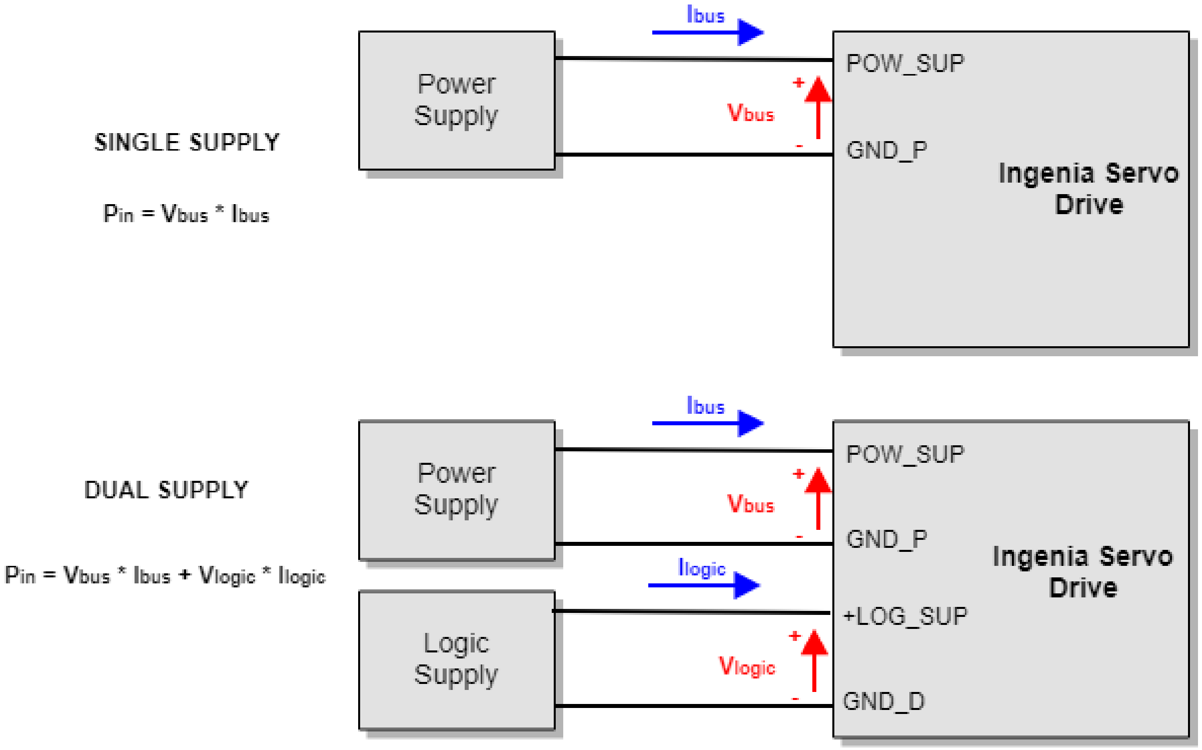


Figure 2

The output power is the mechanical output power provided by our motor, defined as:

$$P_{out} = \omega_{out} * \tau_{out}$$

Where ω_{out} is the output rotatory velocity in rad/s and τ_{out} is the output torque in N·m.

POWER LOSSES IN A SERVO DRIVE

All the elements in the system have losses, and therefore, contribute to the heating of the system. Mechanical losses are mainly generated on the bearings and gears, and motor losses are mainly composed of resistive losses on the windings and the magnetic losses on the core. For further information about mechanical and motor losses, please refer to the manufacturer's data.

Power losses in servo drives are mainly caused by the power stage, which converts from a DC input supply to an AC output voltage. However, other blocks in the servo drive contribute to the power losses. Figure 3 shows a block diagram of the main power losses sources in a servo drive.

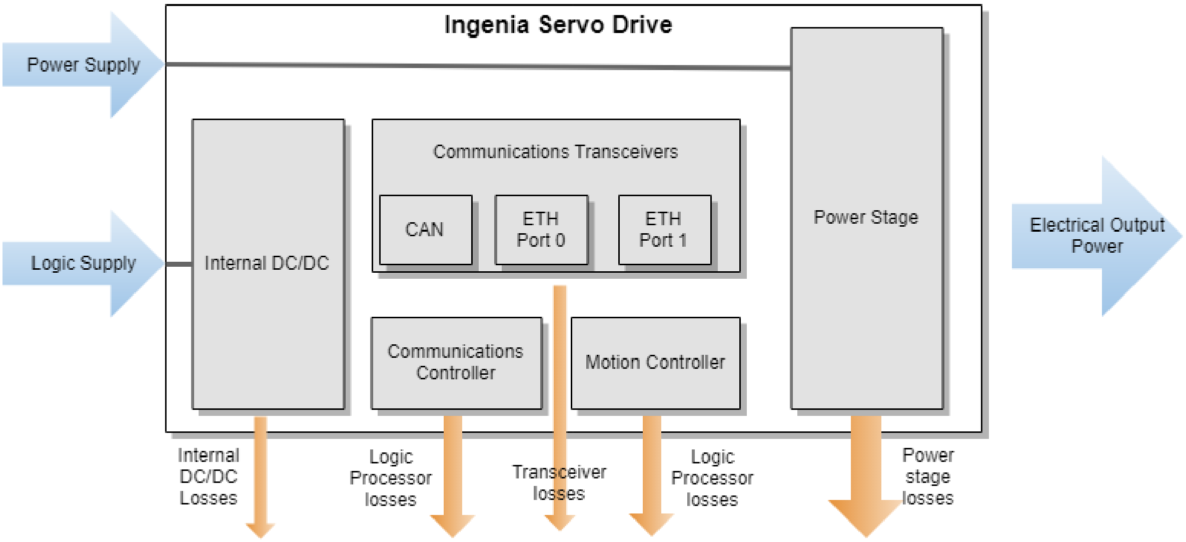


Figure 3

Power Stage

The power stage is, without any doubt, the main source of power losses in a servo drive. It consists of six transistors that convert a DC input supply to an AC output motor voltage. Each pair of transistors (known as a half-bridge) switches complementarily, generating a Pulse Width Modulated (PWM) output voltage. Since the motor windings are mainly an inductive circuit, when applying high-frequency PWM (from 20 kHz to 200 kHz), the voltage becomes filtered and generates a continuous current. Each half-bridge excites a motor phase with a different ON-time to period ratio (duty cycle), generating different average output voltages, and therefore, causing a current flow through the motor. When the duty cycle varies with time, the output voltage can become a low-frequency AC signal.

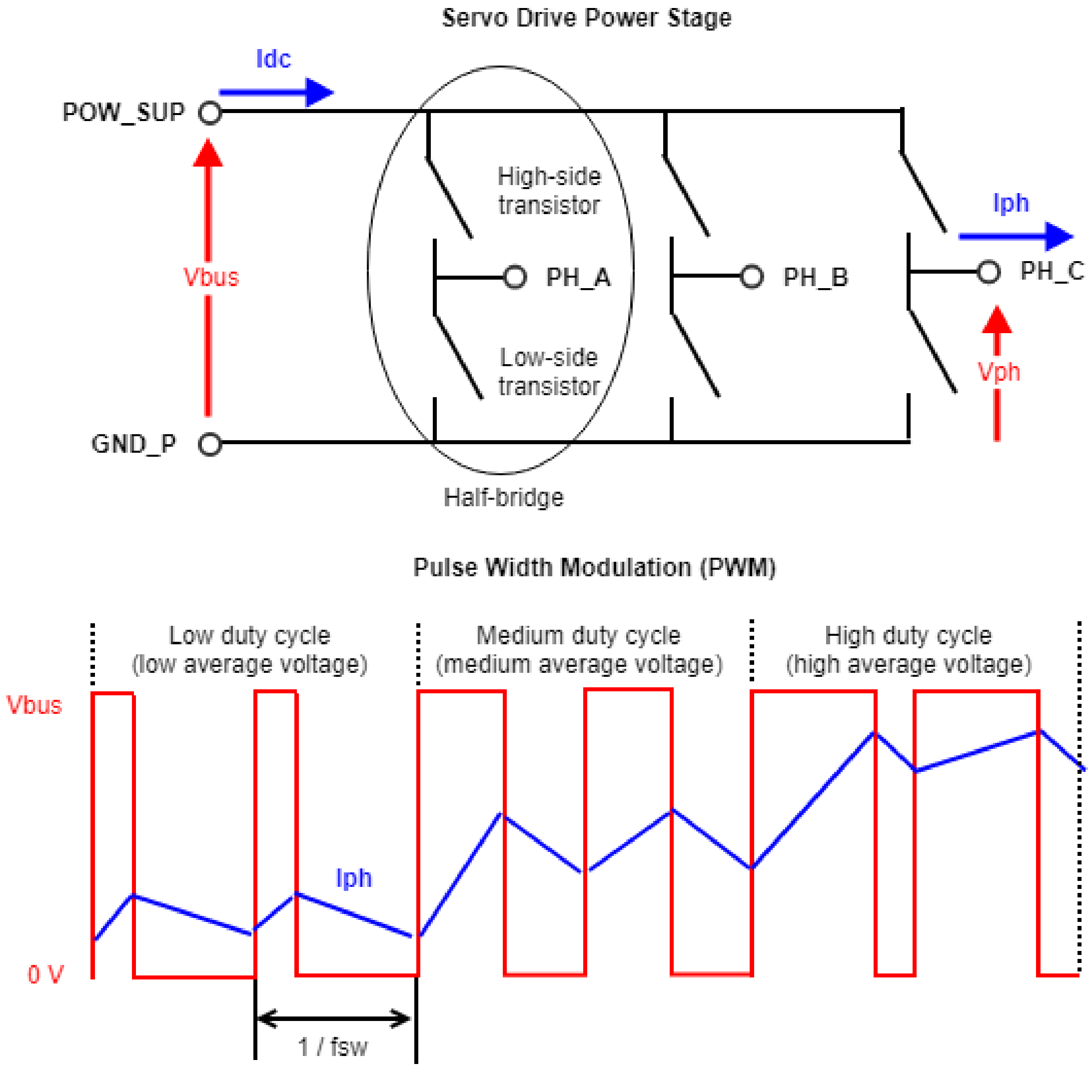


Figure 4

The current flow through the transistors generates what is called conduction losses, while the activation and deactivation of the transistors generate what is called switching losses.

Celera Motion's Ingenia servo drives are based on MOSFET or GaNFET transistors. These transistors can be modeled as voltage-controlled resistors. When the transistor is activated, the resistance is very small (known as R_{dson}) and the current flows through the transistor. When the transistor is deactivated, the resistance is very high and it can be considered as an open-circuit. Conduction losses (P_{cond}) are the losses generated on the R_{dson} resistors. Since there is always one transistor per half-bridge activated, the total conduction losses per phase can be modeled as:

$$P_{cond} = R_{dson} * I_{ph}^2$$

Where I_{ph} is the phase output current.

The R_{dson} is not constant, but increases with temperature. Therefore, the higher the temperature, the higher the power losses. It is very important to correctly dissipate the servo drive in order to reduce its power losses.

When a transistor is deactivated, it handles a high voltage between its terminals while the current is zero. When it is activated, it can flow a high amount of current while the voltage in its terminals is very small.

The normal operation of the transistors is to have a high voltage between its terminals when the current is zero (transistor deactivated), or having a very small voltage drop (R_{dson}) when the current is high (transistor activated). However, the switch between the two states is not instantaneous and during this process, both high current and high voltage are present between the transistor terminals at some points. This causes a high amount of instantaneous power losses during a very short period of time (< 100 ns). The Switching Losses (P_{sw}) are defined as the average of instantaneous power losses. The instantaneous loss of each commutation is proportional to the power supply voltage (V_{bus}) and to the phase current (I_{ph}). The switching losses are also proportional to the number of commutations per second, that is, to the switching frequency (f_{sw}).

$$P_{sw} \propto V_{bus}, I_{ph}, f_{sw}$$

Internal DC/DC

The input logic supply voltage provided to a servo drive (i.e. 24 V) is not appropriate for supplying internal electronics. For this reason, all of Celera Motion’s Ingenia servo drives include internal DC/DC converters that adapt the logic supply source to the required internal voltages (i.e 5V, 3.3V, or 1.2V).

The internal DC/DC converters are based on small power converters, containing only one or two transistors. Like the power stage, the DC/DC converters generate a PWM voltage that is filtered to achieve a continuous DC voltage and current. In order to reduce the size of the DC/DC converter and the filtering elements, DC/DC converters switch at a very high frequency (from 150 kHz to 2 MHz). Due to the high-frequency, main DC/DC losses are caused by switching losses, which are proportional to the input voltage.

Even when using cutting-edge technology, small and compact DC/DC converters have maximum efficiencies between 90 to 95%. This means that up to 10% of the input logic power can be lost in the voltage conversion to power the internal circuitry.

Logic Processors

All the power consumed by the logic processors included on a servo drive (Motion Controller, Communications Controller, etc), can be considered power losses since they are not provided to the output mechanical power. The higher the processing capabilities of a servo drive are, the higher its processing losses.

These losses are minor when compared to the power stage losses at maximum current, but are very important when considering the standby power losses.

Communication Transceivers

The logic transceivers managing fieldbus communications are other power losses and heat generation sources. As many communication channels are connected/activated at the same time, the higher the losses. In some communication interfaces, like Ethernet, the single presence of point-to-point connections, even if no messages are sent, generates power losses.

STANDBY POWER LOSSES

The standby power consumption refers to the input power consumption, when no power is provided to the motor. In applications where motor movement is not constant and current on the motor is usually null, standby power losses are critical.

In some applications, the standby power losses require to maintain motor control, even if the output current is zero. That is, handling a motor position with no external torque. For this reason, Celera Motion's Ingenia servo drives define standby power losses as power consumption when:

- Communication is active
- Motion Controller is active, with all the loops at maximum frequency
- DC-bus voltage is supplied
- The power stage is enabled and switching
- The output current is zero

POWER LOSSES REDUCTION

The following are some recommendations to maximize the efficiency of the servo drive(s) in our system:

- **Dual supply:** Whenever possible, use a dual supply topology, with different voltage values for the power supply and the logic supply. The dual supply allows using a lower supply voltage for the internal DC/DC input, improving its efficiency.
- **Minimum Logic Supply voltage:** Generally, the logic supply is only used for supplying the internal DC/DC. In that situation, using the minimum voltage supply does not have any drawbacks. If the logic supply is used for other functions (supplying the electro-mechanical brake), use the minimum voltage required for the other functions.
- **Minimum Power Supply voltage**: Switching losses of the power stage are proportional to the power supply voltage. Analyze the minimum voltage required for your speed and acceleration requirements in your application and use it for increasing efficiency.
- **Minimum Switching Frequency:** Switching losses are also proportional to the servo drive switching frequency. Therefore, use the minimum voltage frequency required by our motor inductance and control loop update rate requirements.
- **Reduce communication ports:** The use of multiple communication interfaces increases logic consumption. Use only the communication interfaces or ports that are really needed at any given time.
- **Provide good heat dissipation:** The power losses increase the temperature of the components, which will generate higher losses the higher the temperature is. Improving the heat dissipation will reduce components temperature, and therefore, its losses.

POWER LOSSES ESTIMATION

Power Losses Estimation from Product Manual

As explained above, the calculation of the servo drive losses is complex and depends on many factors. For this reason, the best way is to obtain the servo drive power losses from the Product Manual. Celera Motion's Ingenia servo drives provide graphical and numerical representation of the power losses on the Product Manual / Product Description / Thermal and Power Specifications. The following is an example of the Everest XCR servo drive:

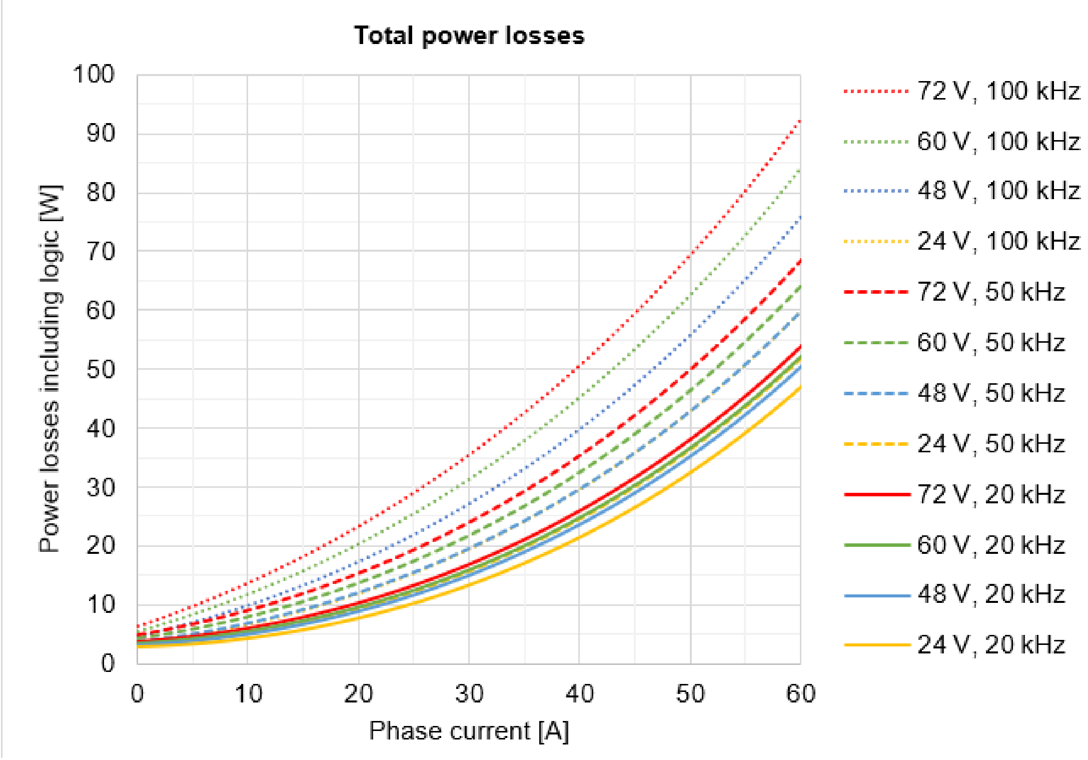


Figure 5

The losses depend on the phase current provided to the motor (I_{ph}), the power supply voltage (V_{bus}), and the switching frequency (f_{sw}).

Phase current I_{ph}

To calculate the servo drive losses, calculate which is the motor phase current required by your application. The phase current (I_{ph_mot}) is proportional to the motor torque (τ_{mot}). The motor parameter "torque constant" (usually named Kt) determines how much torque (N·m) is generated per amper of input current to the motor. Therefore, if the required torque is known, the phase current can be estimated.

$$I_{ph\_mot} = \tau_{mot}/Kt$$

*Note that this equation is only an approximation. Different factors like motor losses or temperature can affect to the ratio between torque and phase current.

In Y-wired BLAC motors, I_{ph_mot} equals to the servo drive current I_{ph} required for calculating the losses:

$$I_{ph} = I_{ph\_mot\text{-}Y}$$

However, in ∆-wired BLAC motors, the servo drive current is √3 times bigger than motor phase current

$$I_{ph} = \sqrt{3} * I_{ph\_mot\text{-}\Delta}$$

Supply voltage V_{bus}

In order to optimize the power losses, use the minimum power supply voltage required by your system. The supply voltage defines the maximum AC phase voltages that can be provided to the motor, which defines the maximum speed that can be reached by the motor in nominal operation. To calculate the voltage required, we have to consider the simplified electrical model of a motor, where each phase is composed of a resistor, an inductor and a back-electromotive force (BEMF), modeled as an electrical source:

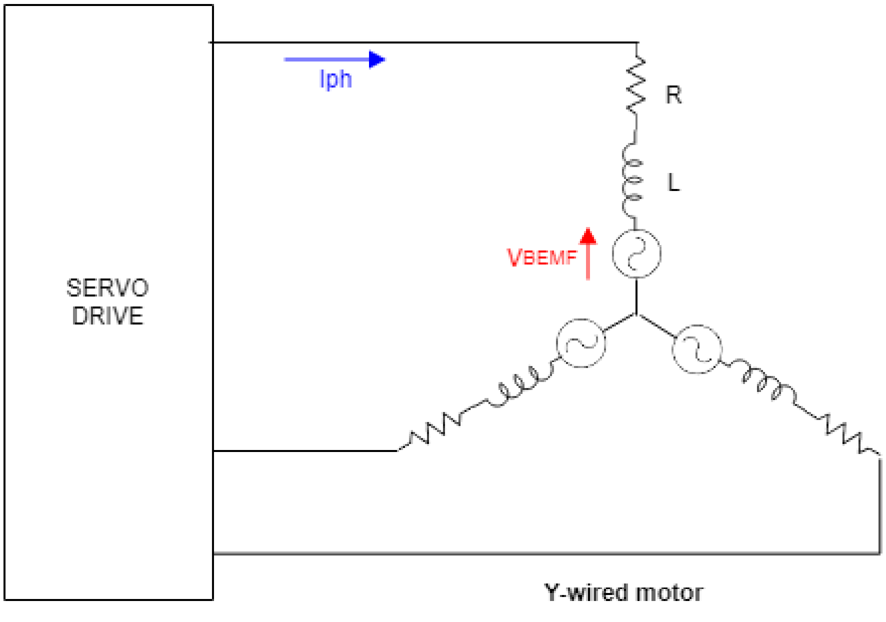


Figure 6

Similar to the torque and current, the motor parameter "velocity constant" (usually named Ke or $K\omega$) determines the BEMF voltage (V_{BEMF}) generated by the motor at a certain speed (ω_{mot}).

$$V_{BEMF} = \omega_{mot} / K\omega$$

The current flow through the motor (and therefore the torque) depends on the difference between the phase voltage and the BEMF voltage. If the phase voltage is lower than the BEMF, current and torque will be reduced, slowing down the motor. If the phase voltage is higher than the BEMF, the motor will generate torque, accelerating the motor or maintaining the velocity. Note that the acceleration will depend on the difference between generated torque and torque losses (load and friction).

For simplification, we will not consider the voltage drop in the motor resistance and inductance, calculating the minimum power supply voltage without considering torque.

In a Y-wired BLAC motor, V_{BEMF} is provided phase-to-neutral. Considering that V_{BEMF} is measured in RMS value:

$$V_{bus} > VB_{EMF\_Y} * \sqrt{3} * \sqrt{2} / D_{max}$$

Where D_{max} is the maximum duty cycle that can be provided by the servo drive. This value is also expressed as "Bus voltage" in the Product manual / Product Description.

In a Δ-wired BLAC motor, V_{BEMF} is provided phase-to-phase. Considering that V_{BEMF} is measured in RMS value:

$$V_{bus} > V_{BEMF\_\Delta} * \sqrt{2} / D_{max}$$

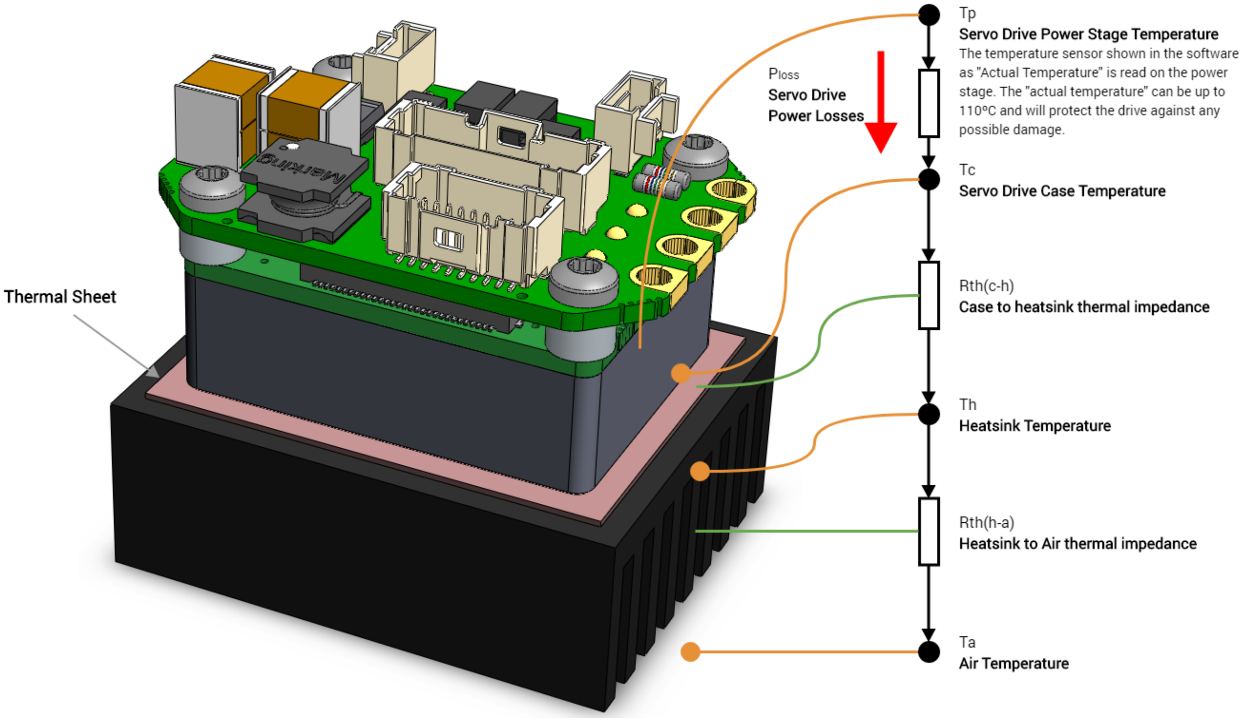
Switching frequency f_{sw}

The third parameter required for calculating the power losses is the switching frequency f_{sw}. Switching frequency usually ranges from 20 kHz to 100 kHz (some drives can reach up to 200 kHz) and can be adjusted by firmware. Like with the power supply voltage V_{bus}, it is recommended to use the minimum switching frequency that allows the desired performance of the system.

The choice of the switching frequency is related to the current loop frequency (the switching frequency cannot be smaller than the current loop update rate) and to the inductance of our motor (the smaller the inductance, the bigger the switching frequency must be).

HEAT DISSIPATION

To minimize the temperature rise in the servo drive, the system heat must be properly dissipated. Once the power losses are calculated, the heatsink requirements can be determined. The following diagram depicts a simplified dissipation model for the Everest XCR servo drive.



The temperature sensor shown in the software as "Actual Temperature" is read on the power stage. The "actual temperature" can be up to 110ºC and will protect the drive against any possible damage.

Figure 7

The power losses generated by the servo drive flow from the power stage to the air. The resistance of the different materials to the conduction of heat (known as thermal impedance, R_{th}) generates a temperature difference between the air and the power stage. If we know the power losses (P_{loss}), the thermal impedances (R_{th}), we can determine the temperature that will reach the power stage.

The thermal model of a power stage is complex, with multiple heat sources (multiple transistors) and considerations. To avoid using complex models between the power stage to the servo drive case impedance (Rth(p-c)), we provide the maximum temperature that can be reached on the case (T_c). These temperatures can be found on the current derating graphs (see Product Manual / Product Description / Current Derating). See an example in Figure 8 for the Everest XCR servo drive:

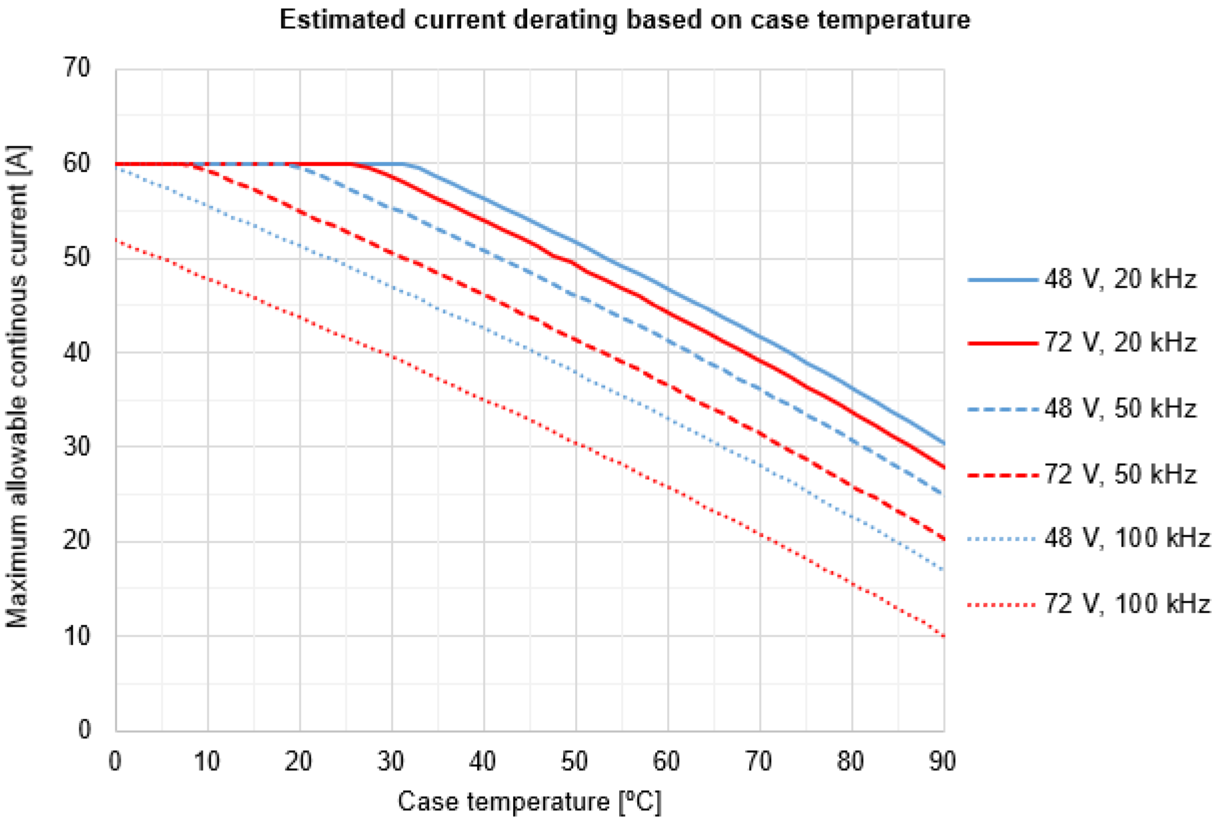


Figure 8

This graph defines the maximum temperature of the servo drive case (T_c) for different power supply voltage (V_{bus}), phase current (I_{ph}) and switching frequency (f_{sw}).

Once we have defined the maximum case temperature (T_c) and the system power losses (P_{loss}), the required heatsink can be calculated. Celera Motion's Ingenia servo drives are designed to be mounted on a cooling plate or heatsink to achieve its maximum ratings. See the Product Manual / Installation for further details about the assembly.

Please, use the following procedure to determine the required heatsink:

1. Based on the power supply voltage (V_{bus}), the phase current (I_{ph}) and switching frequency (f_{sw}) required by your application, determine the maximum case temperature T_c that can be handled.
    1. For example: If the application requires 30 A @ 72 V (20 kHz) the T_c will be 85 ºC
2. Based on the power supply voltage (V_{bus}), the phase current (I_{ph}) and switching frequency (f_{sw}) required by your application, determine the Power Losses P_{loss} to be dissipated.
    1. For example: If the application requires 30 A @ 72 V (20 kHz) the P_L will be 25 W

3. Determine the Thermal impedance of the used thermal sheet $R_{th(c-h)}$
    1. For example, a thermal sheet TGX-150-150-0.5-0, which has an estimated thermal impedance of $R_{th(c-h)} = 0.2$ K/W
4. Based on the ambient temperature (T_a) and using the following formula, determine the maximum thermal impedance to air of the required heatsink $R_{th(h-a)}$

$$R_{th(h-a)} \leq (T_c + P_{loss} * R_{th(c-h)} - T_a) / P_{loss}$$

    1. For example: If the application requires 30 A @ 72 V (20 kHz) working at $T_a = 25$ ºC and we use a thermal sheet with $R_{th(c-h)} = 0.2$ K/W the required thermal impedance of the heatsink will be $R_{th(h-a)} = 2.6$ K/W

EFFICIENCY AND POWER MEASUREMENT

According to the previous definitions, the efficiency of a servo drive could be calculated as the ratio between the power provided to the motor (P_{mot}) and the input power (P_{in}).

$$\eta_{drive} = P_{mot} / P_{in}$$

Input power can be easily calculated as the product of input voltages and currents. These are continuous magnitudes that can be measured with standard laboratory instruments.

$$P_{in} = V_{bus} * I_{bus} + V_{logic} * I_{logic}$$

Servo drive output power can also be calculated as the product of the phase voltages and currents. Since servo drive outputs are AC signals, the average power for a cycle must be used:

$$P_{mot} = 1/T * \int (V_a \cdot I_a + V_b \cdot I_b + V_c \cdot I_c) dt$$

If the phase currents and voltages were simplified to sinusoidal AC signals, a good approximation to the motor power could be achieved. However, this method does not consider the non-idealities of the power stage (PWM switching, the voltage drops in the transistors, etc.), which are the cause of the power losses. Therefore, the sinusoidal approximation is not valid for calculating the servo drive efficiency.

Three-phase power analyzer

The easiest way of measuring the servo drive output power (P_{mot}) is to use a multi-channel power analyzer. This instrument measures the three phase voltages and the three phase currents of the motor and multiplies them, calculating the instantaneous power losses and averaging them. In principle, this should be the most accurate way to measure the servo drive output power. Since power losses in a servo drive are only a small fraction of the output power (efficiency could be around 97%), the power measurement has to be very accurate. That is, an accuracy of 1% in the power measurement can imply an error of 50% in the power losses. Due to this fact, the accuracy and sampling frequency required for measuring the servo drive efficiency are too demanding for most commercial power analyzers.

The voltage meters included on the power analyzer must be able to accurately measure the voltage drop in the power stage transistors in order to measure conduction power losses. Considering a transistor on-state resistance (R_{dson}) of 3 mΩ when providing a current of 30 A, it causes a voltage drop of 90 mV. Considering that phase voltage is a PWM signal swinging from 0 to 72 V (V_{bus} voltage) a normal scale for the voltage meter could be 100 V. With these considerations, and limiting to 1% of error of the measured voltage, the voltage meter requires accuracy of 0.01% of full scale at 100 V. This is a very demanding requirement not fulfilled by most commercial power analyzers.

The sampling rate of the power analyzer is as critical as the voltage accuracy. To correctly measure the output power, the duty cycle (percentage of time during the signal is high) of the output signal must be correctly measured. For a switching frequency of 100 kHz, (10 µs of period) a minimum sampling rate of 10 ns is recommended, which means a 0.1% accuracy of the duty cycle. This is also a very demanding requirement, not fulfilled by most power analyzers.

Calibrated thermal impedance

Instead of measuring the output power and finding the efficiency, an easier approach is to directly measure the power losses, and after that, calculating the efficiency:

$$P_{mot} = P_{in} - P_{loss}$$

$$\eta_{drive} = (P_{in} - P_{loss}) / P_{in}$$

A method for measuring the power losses is to measure the heat generated. To do it, a setup with a known heat transfer path is required. The proposed setup consists of a calorimeter with a small dissipation aperture. On the heat conduction path (implemented in an aluminum block) we place two temperature sensors on different points of the path. If the thermal impedance between the two points is known, the temperature difference will provide a measure of the power that is being dissipated.

Note that a minimum dissipation is required to achieve a thermal steady state below the maximum temperature of the drive. If the dissipation is too small, the drive will reach excessive temperature and will stop operation (overtemperature protection).

The following diagram in Figure 9 shows the proposed setup.

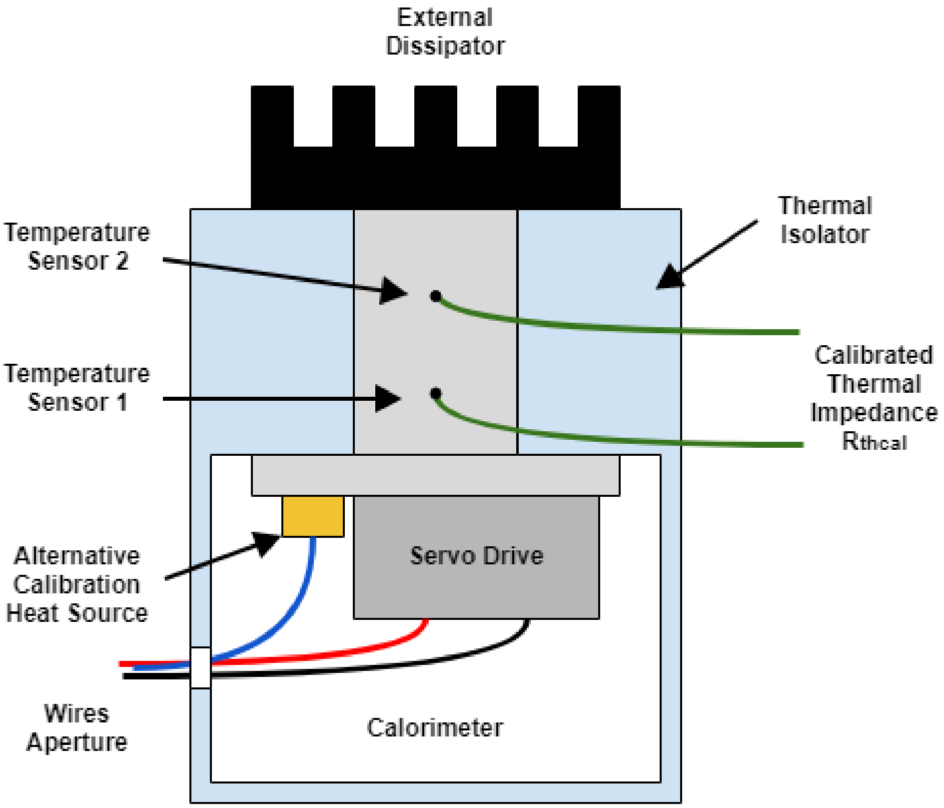


Figure 9

Before each use of the setup, the thermal impedance R_{thcal} must be calibrated using a known thermal source. The most accurate way of doing it is by generating heat on the reverse diodes of the power stage. If a negative voltage is applied between phases and GND, a current would flow through the diodes, generating losses. Be careful, if not properly done, this method could damage the power stage.

An alternative method is to place a known power resistor on the same dissipation plate than the servo drive. To achieve an accurate measure, the resistor must be placed very close to the servo drive and must have a similar thermal coupling with the dissipater.

Apply a constant voltage to the calibration thermal source and measure the current and voltage applied to determine the power. To achieve proper calibration, the generated power (P_{cal}) must be similar to the servo drive power losses (P_{loss}). While applying the calibration power, measure the temperature on the sensors 1 (T_1) and 2 (T_2). Once the temperature has reached the steady-state, record the values of input power (P_{cal}), and the temperature T_1 and T_2. After this test, the thermal impedance can be calculated as:

$$R_{thcal} = (T_2-T_1) / P_{cal}$$

After the calibration, the power losses can be measured. Supply the servo drive at the desired power supply voltage (V_{bus}) and excite the motor at the desired phase current (I_{ph}). Maintain the tested conditions until reaching a thermal steady-state. At that point, measure temperatures T_1 and T_2 and calculate the servo drive power losses:

$$P_{loss} = (T_2-T_1) / R_{thcal}$$

CONCLUSIONS

- All the elements in a servo actuator generate power losses. The power losses are transformed into heat, which worsens the system performance. Therefore, power losses must be dissipated.
- Power losses dissipation complicates system integration. The best approach is to minimize the power losses.
- The main source of power losses in a servo drive is the power stage. However, logic processors and internal DC/DC also contribute.
- Standby power consumption is the input power when no power is provided to the motor, but PWM switching is still active.
- To reduce the servo drive power losses, use a dual supply scheme (logic and power), use the minimum required supply voltage, use the minimum required switching frequency, and provide good thermal dissipation.
- Guidelines for estimating the power losses and calculating the heatsink requirements have been provided.
- Efficiency measurement with power analyzers is difficult since the accuracy and sampling rate requirements are too demanding. Power losses can be measured with a modified calorimeter with a calibrated thermal impedance.