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Transconductance vs Voltage Amplifiers

The purpose of an amplifier in a motion control system is to provide a controlled amount of current or voltage to a motor based on a command signal from the motion controller. This is done by a current (transconductance) or voltage amplifier. Each of these two types of amplifier has benefits and drawbacks which must be considered in order to choose the correct structure for a given motion control application. This paper will examine the similarities and differences between the two main types of switching amplifiers by addressing three key areas: performance, safety, and efficiency.

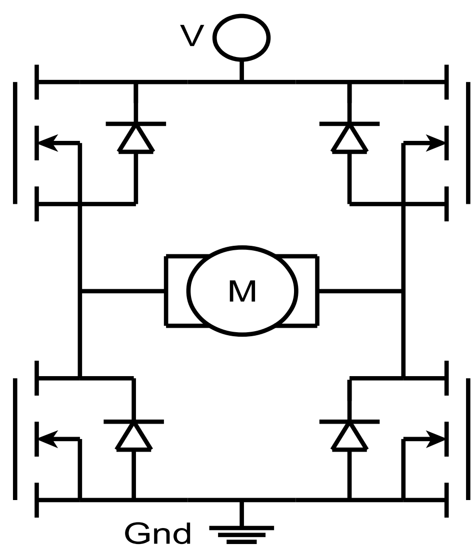

Figure 1: Typical H-Bridge Circuit of Switching Amplifier

Switching amplifiers operate by turning each transistor either fully on or fully off and managing their duty cycles, the torque output from the motor can be controlled by the switching amplifier. It is worth mentioning that linear amplifiers on the other hand operate the transistors in their linear zone, where the transistors are turned partially on depending on the required output. Linear amplifiers are useful in applications where current ripple – the fluctuation in current due to switching – can be an issue, as well as for low power applications. However, because the transistors are being operated in their linear region, linear amplifiers are inherently inefficient. Due to their higher efficiency and usefulness for a wider range of applications, switching amplifiers are more common.

Basic Operational Principles

Switching amplifiers receive a command from a motion controller. This command can take the form of a digital word or an analog signal coming from a digital-to-analog converter (DAC). In both cases, the resolution of the command is typically 12 or 16 bit. For more information on how the resolution of the amplifier affects performance, see Galil's Effects of Amplifier Resolution White Paper. Once received, this command is converted to the correct units and scaled by the amplifier's gain. For a voltage amplifier this has units of volt/volt or volt/count, and similarly for a current amplifier has units of amps/volt or amps/count. Many amplifiers include configurable gains which should be chosen such that the maximum command from the motion controller results in the maximum required torque for a given application.

Once the command signal is properly converted, the amplifier then generates either a current or voltage to match the command. For the voltage amplifier, a duty cycle is generated such that the voltage output matches the voltage command. The current amplifier is slightly more complex, but ultimately a duty cycle is created based on the error measured between the actual output current and the commanded current. This current or voltage then creates a torque on the motor. The torque output of a motor is proportional to the current flowing through the motor's windings multiplied by the motor's torque constant as shown in Equation 1.

$$T = K_{\tau} * I$$

Equation 1: Motor Torque based on Current

Equation 1 demonstrates that the maximum torque output from the motor is limited by the current the amplifier is able to produce. Equation 2 shows how voltage across a motor affects it.

$$V = I * R + \omega * K_e + L * \frac{di}{dt}$$

Equation 2: Motor Voltage

Based on Equation 2, there are three factors that influence the voltage across the motor. The first term, I*R where I is the current and R is the motor resistance, represents the voltage drop due to the motor's resistance. Second, $\omega * K_e$, where ω is the rotational speed of the motor, and K_e is the Back EMF constant of the motor, represents the voltage drop across the motor due to its speed. The third term, L * di/dt, where L is the motors inductance and di/dt is the rate of change of the current in the motor, represents the voltage drop across the motor due to switching current. One important takeaway from this equation is that the maximum voltage output of the amplifier dictates the maximum speed the motor can reach based on its back EMF constant. Rearranging this equation gives a clearer look at how the voltage ultimately affects the torque of a motor, and is shown as Equation 3.

$$T = \frac{V - \omega * K_e - L * \frac{di}{dt}}{R} * K_\tau$$

Equation 3: Motor Torque based on Voltage

Performance

Now that the theory has been established for how voltage and current affects the torque of a motor, the ramifications of these equations on current and voltage amplifiers can be examined. Comparing the above equations gives a picture of one of the key differences between current and voltage amplifiers – linearity. Equation 3 shows that the torque created by a voltage amplifier is dependent on the speed of the motor. This means that the torque output will vary for a given voltage depending on the speed. Transconductance amplifiers do not suffer from this same issue as they control current directly.

Another important item is that voltage amplifiers operating in chopper mode are inherently non-linear when operating near the origin. In chopper mode, the amplifier sends a 0 to +V (where V is the voltage applied to the transistors of the amplifier) PWM signal to the motor when moving in the forward direction, and a 0 to -V PWM to the motor when moving in the negative direction. Figure 2 shows the nonlinear response of a voltage amplifier running in chopper mode.

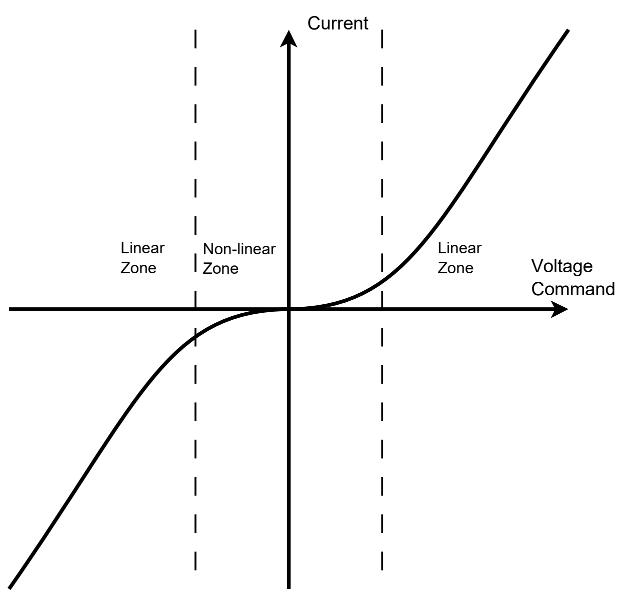

Figure 2: Output of Voltage Amplifier in Chopper Mode

This behavior occurs when the current, which is created by the amplifier, reaches 0 between times when the transistors are turned on. When this occurs, the average current across the motor follows a quadratic curve rather than a linear curve. Linear behavior resumes as soon as the current waveform no longer reaches 0 between switches. Figure 3 demonstrates this concept.

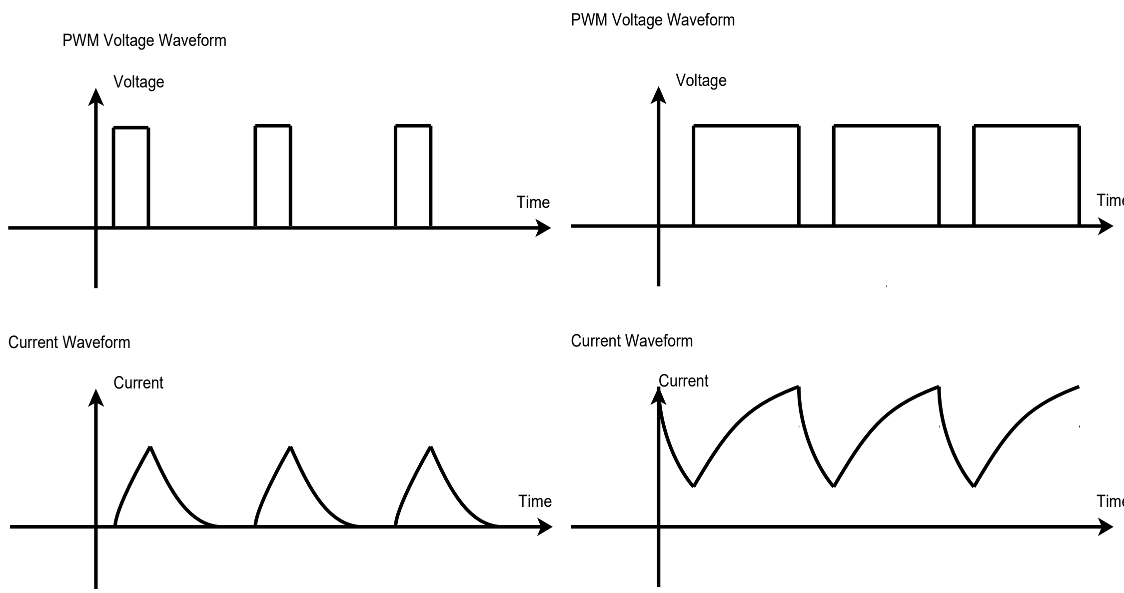

Figure 3: Chopper Mode PWM and Current Waveform Near the Origin

Another key measurement of performance is bandwidth. There are two types of bandwidth that need to be addressed with respect to current amplifiers: current loop bandwidth and position loop bandwidth. Current loop bandwidth is a measurement of the ability of the current amplifier to react to changes to the commanded current. Position loop bandwidth is a measurement of the ability of the system being controlled to react to changes in the commanded position. In order for the position loop bandwidth to not be affected by the current amplifier, the current loop bandwidth should be an order of magnitude greater than the position loop bandwidth. Voltage amplifiers have no current loop, and thus do not have an equivalent issue. However, because the current amplifier is more linear than a voltage amplifier, higher position loop bandwidth can be achieved.

Safety

For the sake of safety, it is necessary to be able to limit the current output from the amplifier. Motors have two current ratings to be concerned with - a continuous rating and a peak rating. The average current in the motor must be kept at or below its continuous rating, whereas the peak rating deals with higher current over much shorter time periods. The reason for this is that as current is applied to the motor, the temperature of the motor will increase. If the temperature of the motor rises too high, the insulation on the motor coils will melt. Current amplifiers are able to ensure that the current in the motor never exceeds that which is requested by the motion controller because they are directly controlling the amount of current across the motor. This means that there is no risk of overheating the motor if the motion controller gives commands which are appropriate for the motor. Voltage amplifiers however do not naturally monitor current, and so there is the potential to overheat the motor if additional over-current protection is not present on the amplifier. This can happen if the motor stalls or becomes shorted, as well as if the commanded voltage causes an excessive current to be output to the motor. The Over-current circuitry adds additional cost and complexity to the voltage amplifier.

Similarly, over-voltage is a potential hazard to the amplifier itself. Motors can also act as a generator when trying to quickly decelerate if there is a large inertial load or if the motor is fighting large external forces. This power generated causes a problem because current is applied in the opposite direction of normal back through the amplifier and up to the power supply. This power has to be dealt with somewhere, and if the power generated is large enough to overcharge the capacitive elements in the circuitry damage will occur. In order to combat this, shunt regulators, or other protective circuitry, need to be added to both types of amplifiers.

Lastly, the reliability of each amplifier type is a key metric for safety. Voltage amplifiers construction is simpler than that of a current amplifier, and thus they can be slightly more reliable. However, reliability is primarily related to the power components of the amplifier, which are common between both current and voltage amplifiers.

Efficiency

The last topic which will be used as a benchmark for the comparison of voltage to current amplifiers is their efficiency. Efficiency is defined as the ratio of useful power generated to the total amount of power consumed as shown in Equation 4.

$$Efficiency = \frac{useful\ power}{total\ power} * 100\%$$

Equation 4: Efficiency

Due to operating their transistors fully on or fully off, the efficiency of both types of switching amplifiers is typically greater than 90%.

Lastly, as a side-note, commutation of brushless motors adds some additional engineering challenge to current amplifiers which need to be overcome in order for them to properly deliver current to the motor. Commutation is the process of correctly energizing the brushless motor phases in order to rotate it. While both current and voltage amplifiers must commutate their output in order to correctly operate a brushless motor, current amplifiers must have additional current measuring circuitry in order to achieve this. This additional feedback must also be commutated for each phase of the motor so that it can be correctly scaled.

While transconductance and voltage amplifiers are identical when it comes to efficiency, the transconductance amplifier is a better choice for motion control applications due to its linearity and higher capability for position loop bandwidth. Though they do have some added complexity for commutation, this is outweighed by their performance benefits. Galil Motion Control is always ready to assist in determining the appropriate amplifier for even the most challenging motion control applications. If you have any questions about amplifiers, contact our Applications Engineering Department at (916) 626-0101 or by email at support@galil.com.