POWER, PRECISION, AND SAFETY: A GUIDE TO 48 V ROBOTIC ACTUATOR DESIGN

Allegro MicroSystems

INTRODUCTION

As the enabling technologies become more capable and cost effective, robotic systems continue to be increasingly integrated into numerous applications. One architecture choice that enables robotic systems is the use of 48 V to 60 V battery power. This supply voltage allows for high-power-density designs that do not surpass unsafe voltage levels for nearby humans. In addition, because robots more often work near or around other humans, additional standardized safety requirements and fault monitors are needed. The international standard IEC 61508 defines Safety Integrity Levels (SILs). SIL 2 and SIL 3 require a variety of safety functions for the maintenance of safe states. These functions are analogous to the safety mechanisms in the Automotive Safety Integrity Level (ASIL) definitions of ISO26262.

An essential part of any robotic system is a reliable and accurate actuator that meets the motion requirements for high-level motion-planning trajectories. The performance of the actuator is greatly tied to the construction of the actuator or motor, the configuration of the top-level control firmware, and the efficiency, accuracy, and robustness of the underlying control circuitry. The essential components for a proper actuator or motor driver board are a microcontroller, gate driver, current sensor, and position sensor. One type of architecture for a robotic servo joint is shown in the block diagram in Figure 1.

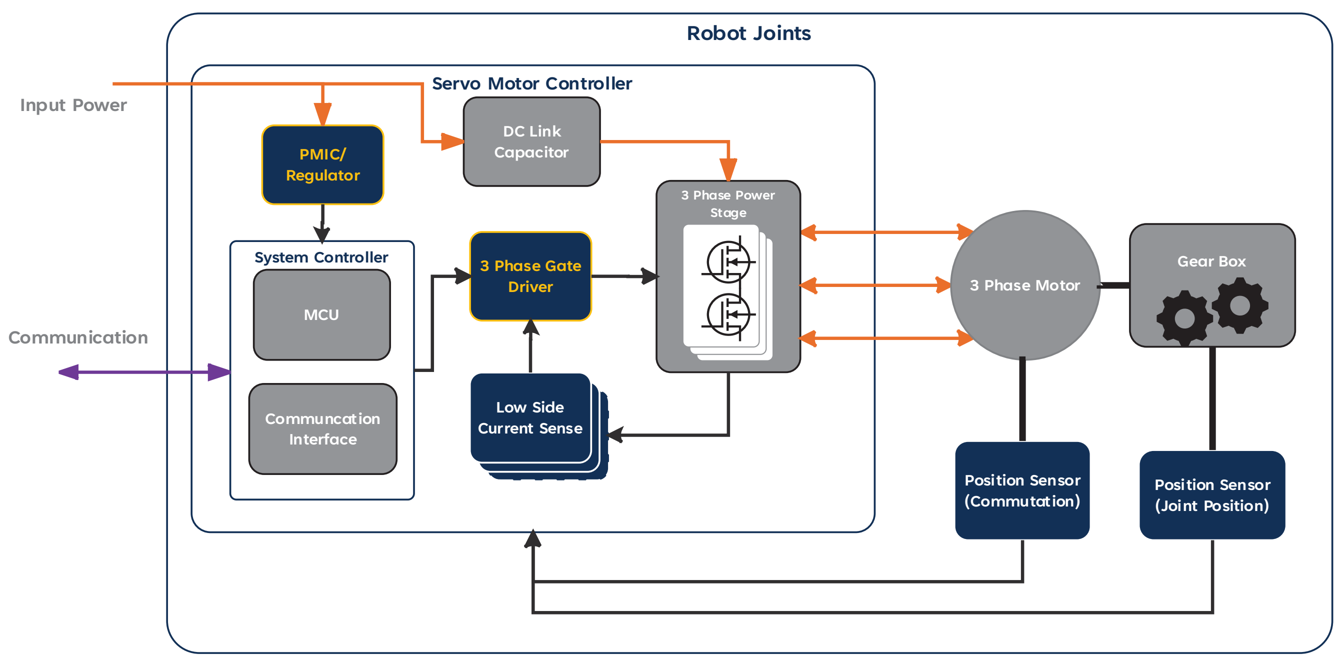

Figure 1: Robotic Servo Block Diagram

For the sense function, latency, accuracy, and bandwidth are all pivotal performance parameters. In field-oriented control (FOC), delays and inaccuracies result in greater torque ripple, and thereby forfeits smooth motion and reduces the efficiency of the electric drive. High-accuracy current and position sense functions enable more-repeatable, smooth motion. In low-side sense applications, the bandwidth and the settling time of a current-sense amplifier limits the switching frequency. A faster switching frequency: reduces current ripple, which results in lower torque ripple; and enables circuit design with reduced-bulk DC-link capacitance, which can reduce the size and cost of the implementation. In addition, if the control-loop computation permits, a higher switching frequency can enable a boosted control frequency and creation of a more-responsive system.

Innovative Allegro product solutions are available are for all blue blocks shown in Figure 1. The Allegro AMT49100 or AMT49101 48 V three-phase motor driver (AMT49100/1) is an automotive-safety-rated device that is perfect for robotic servo applications. The innovative semiconductor process from Allegro allows device operation with a supply of up to 80 V. This additional safety factor allows headroom for high voltages that might occur at full battery charge or other transients. Both devices support 100% duty cycle operation in hardware. The block diagram of the AMT49101 device is shown in Figure 2. The AMT49100 has three high-performance low-side current-sense amplifiers, while the AMT49101 has an integrated low-voltage regulator controller and only two low-side current-sense amplifiers, as shown in the block diagram. With an external MOSFET and inductor, the AMT49101 can create a power supply for the microcontroller and other sensors. The device also has an internally adjustable gate-drive strength for reduced electromagnetic interference (EMI) and reduced stress on the power switches. The charge-pump regulator uses the voltage reference from the high-side drain-voltage sense (VBRG) to drive the high-side MOSFETs and to enable 100% duty cycle operation. The low-side MOSFETs are powered by the gate-drive supply output (VREG). The SAL, SBL, and SCL outputs from the phase-comparator block can be used for active dead-time compensation. A serial port interface (SPI) provides communication with the parts to facilitate tasks like EEPROM setting and diagnostic readout. All these features culminate in a device that benefits the operational requirements and provides safety monitors to help implement the proper safety features on the high-level module.

This application note reviews some of the design considerations needed for the integration of the AMT49100/1 into a robotic actuator design. The next sections focus on the regulated output of the AMT49101, the benefits of the current-sense amplifiers, the benefits of the gate drives, and a brief analysis of some of the safety monitors of the device.

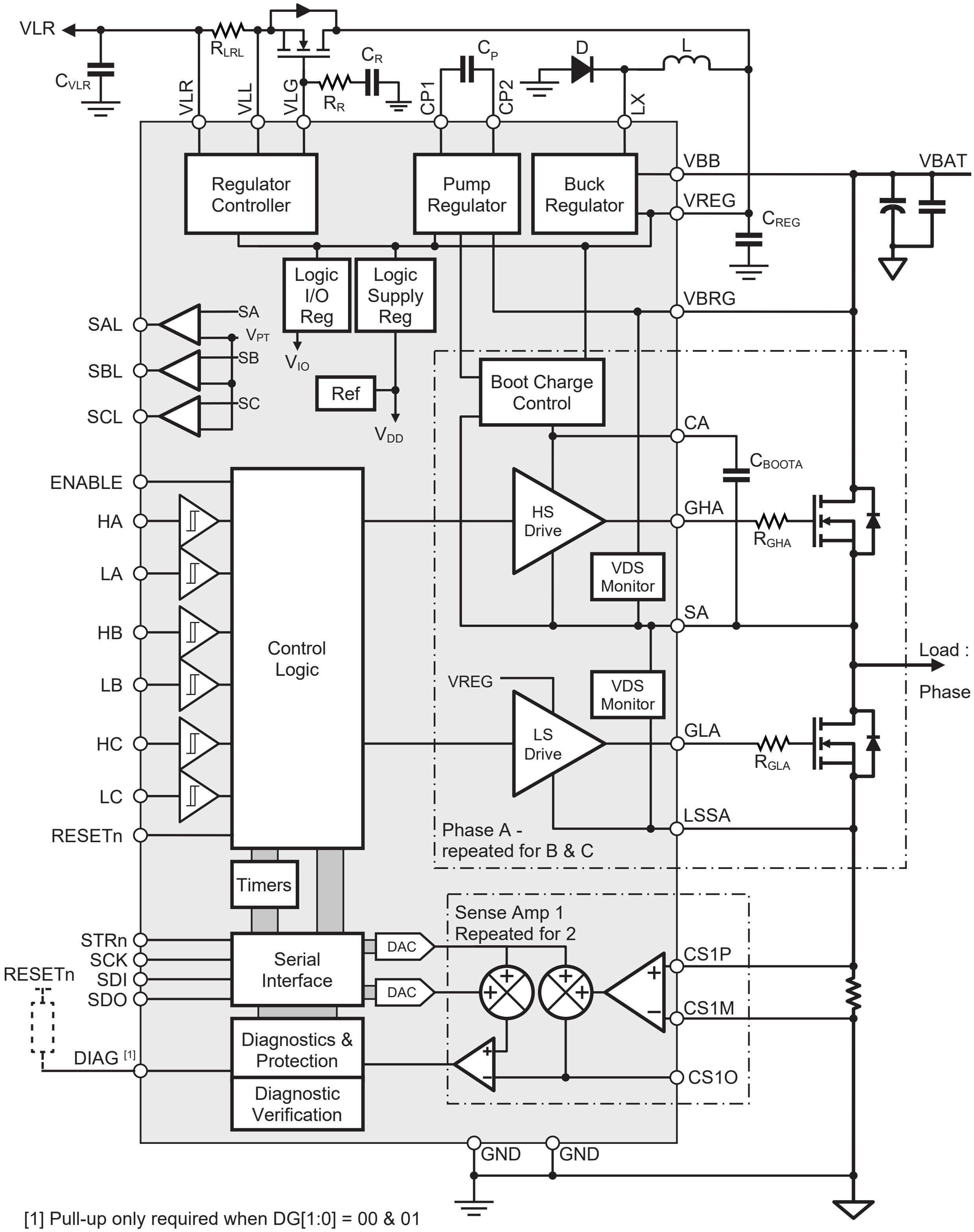

Figure 2: AMT49101 Architecture Block Diagram

PROGRAMMABLE LOGIC SUPPLY LINEAR REGULATOR CONTROLLER

The AMT49101 has an integrated controller for a linear regulator, and it is programmable for either 3.3 V or 5 V logic. Only the controller is integrated into the IC, so the designer must choose an external N-channel MOSFET based on the power-consumption needs of the design. The external MOSFET also distributes the thermal load to reduce temperature increase in the AMT49101. This regulator can be used to power the sensors, microcontrollers, or other ICs that are on the same board as the motor-driver IC. This reduces board space that would otherwise be required for an additional regulator circuit in the tightly constrained spaces of robotic joints.

The linear regulator controller also has an integrated overcurrent detection function. The threshold is set internally to 1 V. Based on the design, the current-sense resistor can be sized appropriately for the current requirements. A standard load could comprise a microcontroller (60 mA), two position sensors (14 mA each), and a transceiver IC (10 mA), with a total current requirement of ~100 mA. If an overcurrent limit of 120 mA is chosen, an ~8.3 Ω resistor (1 V/0.12 A) is required. For systems that require three shunt-sense circuits in addition to a space-efficient 48 V capable regulator, refer to the application note "Allegro APM81815 Buck Power Module for 48 V Bus: Insights on Power Loss and Thermal Performance (AN296359)." [1]

INTEGRATED LOW-SIDE CURRENT-SENSE AMPLIFIERS

The high-performance integrated current-sense amplifiers of the AMT49100/1 help enable design of a compact, efficient system. The performance of the current-sense amplifiers directly affects the maximum switching frequency, torque ripple, and efficiency of the system. A high torque ripple results in vibrations in the motor that are related to the speed of the motor. These vibrations can create audible noise and accelerate wear on the joint components. Torque ripple can also affect the response of the system to a change in torque, which causes errors in the position, velocity, and acceleration profiles. The magnitude of the current ripple also increases the magnitude of the current profile, which can cause more resistive losses. The following sections review an example of an interface with the device and some key advantageous parameters of the AMT49100/1.

INITIAL DESIGN

Here, a 1000 W actuator is considered in a 48 V system. The designer might optimize the current-sense architecture for a nominal 20 A of current and a buffer of up to 30 A. An overcurrent condition might be considered as 32 A. The output is defined by:

Equation 1: Current Amplifier Equation

$$V_{out} = (V_{CSP} - V_{CSN})\, A_v + V_{oo}$$

For a 5 V system, the dynamic range of the output is 0.3 V to 4.8 V. The gain (A_V) of the device is programmable. However, for this example, the gain is 20 V/V. This results in an input range of –0.11 V to 0.115 V. The offset (V_{OO}) can be adjusted internally, but the default is 2.5 V. A resistance of 3.4 mΩ is calculated for this setup. With the use of $P = I^2 \times R$, the design requires a resistor of greater than 3.5 W. If the system may experience higher transient currents, the power rate of the resistor can be increased to ensure it does not experience overstress.

The device has an internal overcurrent check with a threshold that is set in intervals of 300 mV. If additional current sensors are needed in the system, incorporate an integrated conductor current sensor. Because an integrated conductor current sensor is inherently isolated, it can be placed in-phase or on the high side of the power bridge. These devices also have very low conductor resistances for the reduction of losses, as well as dedicated overcurrent fault output pins. The shunt-resistor value can be optimized for the current-sense amplifier, and the magnetic-current sensor allows the design to maintain safe operation.

[1] See https://www.allegromicro.com/-/media/files/application-notes/an296359-apm81815-power-loss-thermal-performance.pdf?sc_lang=en

ACCURACY AND TIMING

The AMT49100/1 current-sense amplifier has a 1 MHz bandwidth and a maximum settling time of 1 µs. The settling time is defined as settlement within 40 mV of the final output. With a 20 V/V gain and a 0.4 mΩ resistor, that equates to a settlement within ~500 mA of the final current. The shunt resistors are large components, so it is advantageous to operate with only two in the system. The AMT49101 has only two dedicated amplifiers. Simple design techniques can be used for to minimize any errors associated with the use of only two shunt resistors. To determine all three-phase currents, the third current can be calculated with:

Equation 2: Current Conservation in Motors Equation

$$I_A + I_B + I_C = 0$$

The currents can be sampled only when the low-side MOSFET is in the on state. A higher duty cycle brings the operational voltage closer to the DC bus voltage of the servo drive, but the low-side MOSFET is in the on state for only a short period. The current-sense amplifier might not be readable within this time interval. A 100% duty cycle is a special case with the use of space-vector pulse-width modulation (SVPWM); if one phase is at a 100% duty cycle, one of the other phases is also at a 0% duty cycle (which means a current pass-through does not occur). Therefore, even with the capacity to read only one of the voltages, the third phase can be calculated. If the driver brakes the motor through the activation of either all high-side or all low-side MOSFETs as shown in shown in Figure 3, this condition is not valid.

Below 100% duty-cycle operation, the maximum duty cycle that can be applied relates to the response of the current sensors. At 20 kHz, the designer is allotted 50 µs per cycle. From the time that the low-side signal is sent, a delay occurs from the driver. This delay, known as dead time, is typically in the hundreds of ns range. This dead time is followed by the settling time of the current-sense amplifier. The device has a maximum settling time of 1 µs, which allows a 97% to 98% maximum duty cycle. The user can jump from 97% to 100% duty cycle if the full duty-cycle range of operation is needed. This quick settling time allows the design to use most of the available voltage range. Use of the full operational range allows for better power density in the design.

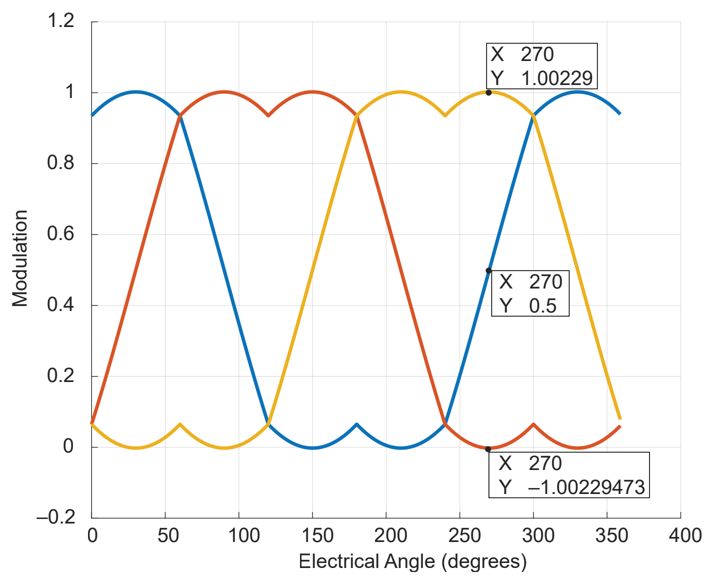

Figure 3: SVPWM Duty-Cycle Modulation

SENSITIVITY ERROR

With a focus on the accuracy of the device, the device specifies a maximum gain error over the operational temperature range of the device of ±1.6%. This value has a temperature coefficient of ±50 ppm/°C, which results in a maximum 2% gain error at 125°C. If the channels are matched, a torque ripple does not exist, but the estimated output torque is different than the actual output. If the standard gain error is calibrated out, the 0.4% error over temperature should result in a torque estimation error over temperature of only ~1%. A mismatch in the gain error introduces a torque ripple at 2× the electrical frequency of the motor. The current-sense amplifiers are colocated, so the temperature differential should be minimal, which reduces the torque ripple that mismatch causes.

OFFSET ERROR

Of the current-sense errors, the offset error is the main contributor to torque ripple. The torque ripple appears at the same frequency as the electrical frequency of the device. The output offset error has a typical value of ±25 mV. This value can easily be calibrated when the motor is not active. When the YOL bit is set in memory, the sense-amplifier inputs are shorted to allow easy measurement of the output offset of the amplifier. In a two-shunt system, because the calculation of the third phase compounds the errors of the other two phases, it is essential to calibrate out the offset error, as evident in:

Equation 3: Calculated Phase Current Error for Two-Shunt System

$$\hat{i}_a = m_a i_a + b_a$$

$$\hat{i}_c = -(m_a i_a + m_b i_b + b_b + b_a)$$

Once calibrated, the offset drift over temperature is the main source of error. The AMT49100/1 has a very stable offset drift of a maximum value of 135 μV/°C, with a resultant worst case change of 13.5 mV at 125°C. Because the current-sense amplifiers are all in the same package, the temperature is common between them.

GATE-DRIVE PERFORMANCE

Complementary to high-performance current-sense amplifiers, the motor driver needs robust gate-drive performance. The current capability of each driver determines the power of the MOSFETs that can be used and the switching frequency. Higher-power MOSFETs typically have a higher gate-charge specification. This gate driver has a maximum peak source current of 2400 mA and a maximum peak sink current of 4200 mA, which enables fast turn-on and turn-off times. However, not all systems require a large peak current output from the driver.

To avoid damage to the MOSFET or driver IC, many designs implement current-limit resistors on the gate. The AMT49100/1 has a current-controlled gate driver for control of the gate-charge slew rate without the need for additional resistors. The method by which the device uses two current levels for the control of the slew rate for the gate drive is shown by the green trace in Figure 4. This approach is advantageous because slower slew rates can help the system meet EMI requirements; however, a slower slew rate increases the losses caused by switching. An in-depth review of the design of this feature into the system is provided in the Allegro application note "Practical Considerations for MOSFET Slew-Rate Control in Smart Gate-Driver Applications." [2] This application note can help robotic-system designers and integrators determine the balance between efficiency and other performance criteria.

High-current gate drivers also enable faster switching frequencies to boost the efficiency of the system. If the power device has a low on-resistance ($R_{DS(on)}$), an increased switching frequency can reduce the size of the DC-link capacitance, which can enable a reduced board size. The relationship between maximum switching frequency and gate charge is shown in Figure 5. Each line represents a different average current draw. The equation used for this calculation is:

Equation 4: Average Current Consumption for Switching Frequencies

$$I_{AVG} = 6 \times Q_g \times f_{sw}$$

[2] See https://www.allegromicro.com/-/media/files/application-notes/an296347-mosfet-slew-rate-control.pdf?sc_lang=en

Uncalibrated dead-time in the switch of the MOSFET can reduce the efficiency of the system. If the dead time is too long, the system efficiency reduces because currents recirculate in the motor and generate heat. If the dead time is too short, power is lost in shoot-through events, which can also cause stress to the power components. In addition, the required time MOSFET turn-on and turn-off events changes over temperature, so it is pivotal to understand and account for these changes. The phase comparator block can help the system actively adjust. The comparators monitor the state of the voltage for each of the three phases of the motor. The threshold is programmable and is set to 50% of the DC bus voltage by default. Status monitoring of these lines allows a designer to observe the moment that voltage drops below a certain threshold—an indication that the high-side switch has turned off—and to adjust the dead time of the system actively in response to the voltage drop.

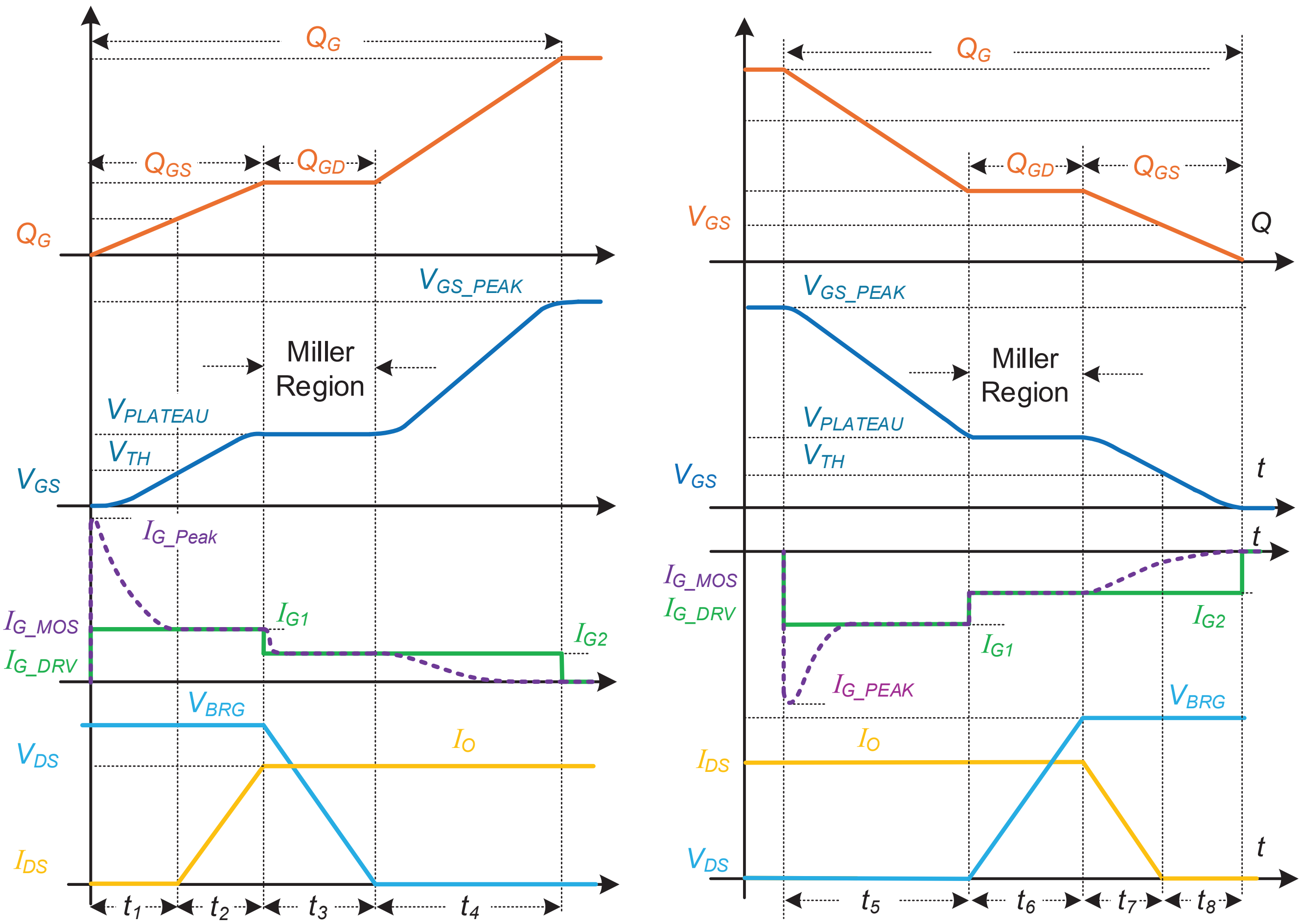

Figure 4: Smart Gate Driver, Gate-Charge Control: Turn-On (Left) and Turn-Off (Right) Characteristics of MOSFET Using a Smart Gate Driver

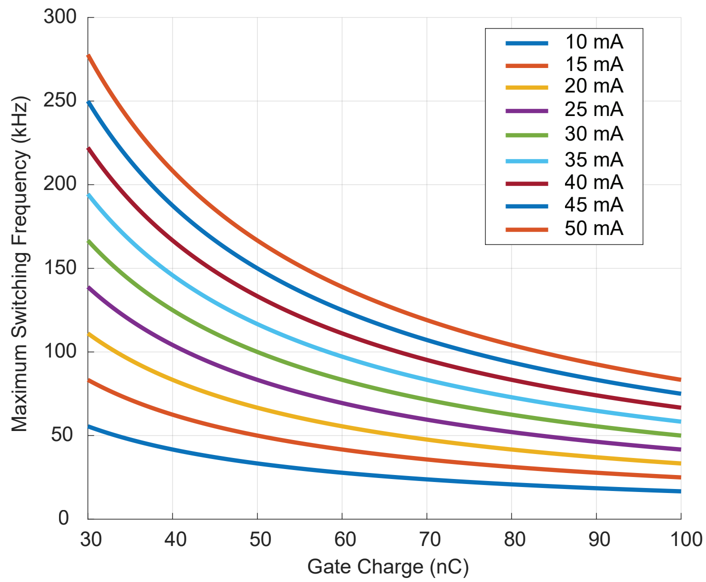

Figure 5: Maximum Switch Frequency vs. Gate Charge for Various Average Current Levels

POSITION SENSE CONSIDERATIONS

Position sensors are important for both the FOC control loop and the position control loop of the robotic joint. For maximum torque control of the motor, a 90-degree angle must exist between the rotor and stator flux vectors. To achieve this, the system must have knowledge of the electrical angle of the motor through the implementation of a rotor position sensor. A delay in the position signal makes it harder to control the constant 90-degree separation. Thus, a delay in the position signal reduces the efficiency and maximum torque that the motor can provide.

To enable an accurate trajectory track to achieve the desired motion profile, the position of a robotic joint must also be known. As robotic-actuator design becomes more compact, designers seek solutions that are inexpensive, small, and robust to signals of increasingly greater interference. Magnetic angle sensors are inexpensive and small, but stray magnetic fields can induce errors in the sense output of the sensor. Inductive angle sensors have high resolution but require more space for integration. Regardless of the requirements, Allegro has IC solutions in both technologies to help customers.

ANALYSIS OF SAFETY MONITORS

Fully defined safety standards for humanoid robotics do not yet exist, but clear patterns from other systems can be observed to understand requirements. Functional safety is a key pillar of many systems. The industrial standard (IEC 61508, SIL) and the automotive standard (ISO 26262, ASIL) are similar, but they are not the same. The AMT49100/1 was developed in compliance with the ISO 26262 standard and can support up to an ASIL D capability for automotive safety-related systems. While the device is not SIL rated, the safety monitors integrated in the IC and the robust design process make these parts ideal a designer to achieve or prove a system-level SIL rating based on the IEC 61508 standard. Some key safety monitors of the AMT49100/1 include:

- VDS monitor and short detection: The device monitors the drain-source voltage of the external MOSFETs and can detect short-circuit conditions. This is a critical safety feature that can prevent catastrophic failures and damage to the motor or driver by detecting a fault before or during joint activation.
- Undervoltage and overvoltage detection: Monitoring of the VBB, VREG, and VBRG supplies ensures that the device operates within safe voltage limits.

- Overtemperature detection: Internal temperature monitoring protects the device from thermal damage.
- Gate drive diagnostics (VGS undervoltage): Monitoring the gate-source voltage of the external MOSFETs ensures they are properly driven.
- LSS disconnect detection: Detects potential issues with the low-side source connections.
- Open-load detection: Can help identify issues with the motor winding connections.

These diagnostics provide the system controller with the necessary information to detect faults, assess system health, and implement appropriate safety reactions, with a contribution to the overall robustness and reliability of the robotic system. The integration of these faults simplifies the safety certification process compared to an implementation with discrete components or software.

In conclusion, as robotic systems become more ubiquitous and sophisticated, the demand for highly capable, cost-effective, and critically safe actuators intensifies. The adoption of 48 V to 60 V power architectures facilitates high power density within the need to maintain human safety. Robotic systems that operate around humans also necessitate rigorous adherence to safety standards, which are still in development. Designers can gain an advantage through the qualification of devices designed with different functional safety standards and the integration of these safety monitors into their systems. The precise and reliable motion required by advanced control algorithms like FOC hinges on the performance of the core components of the actuator: the microcontroller, the gate driver, and the accurate current and position sensors. As demonstrated, critical sensor parameters such as latency, accuracy, and bandwidth directly impact torque ripple, motion smoothness, and overall system efficiency. These challenges are addressed with innovative solutions like the AMT49100/1, which integrates high-performance current-sense amplifiers, smart gate drivers, and robust safety monitors. These features not only optimize operational parameters like switching frequency and power density but also significantly streamline the path to the stringent safety integrity levels crucial for next-generation robotic systems, which ultimately enables safer, more efficient, and more-precise robotic applications.

Revision History

Number	Date	Description	Responsibility
–	December 16, 2025	Initial release	G. Kim