Application Note

Stepper Motor System Power Loss Reduction Using Auto-Torque

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ABSTRACT

A stepper motor system is an open-loop position control system. The system controller or the motor driver IC has no information on how much load torque is being applied or what should be the optimal current for operation without step loss. Since the driver is imperceptive of the load torque demand, motors are generally driven at constant full-scale current which can sustain maximum load torque. However, the use of large operating current is needless at lighter loads as it results in unnecessary I^2R losses. Apart from lowering overall system efficiency, high coil current leads to thermal issues due to motor heating reducing the durability and longevity of the motor.

Texas Instruments recently introduced the DRV8462, DRV8452 and DRV8461 stepper motor drivers, which include several new features including the auto-torque algorithm. Auto-torque boosts system efficiency by adjusting the stepper coil current automatically according to the load torque. Auto-torque does not require any external sensor. Instead, by monitoring the power delivered to the motor, it generates an internal signal which varies linearly with the load torque, with fast sensing capability. This application report aims to highlight the advantages of the auto-torque algorithm and how it can be tuned for maximum benefits.

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1 Power Efficiency of Stepper Motor Drivers

Stepper motors are popular due to their simplicity of translating excitation changes on the input to precise positional changes on the output without using any external sensor to monitor position. The currents in stepper coils are regulated to achieve precise position and velocity control.

Torque equation for a motor is given by Equation 1. It depends on coil current and motor construction:

$$\tau_{max} = K_T \times I \quad (1)$$

where τ_{max} is the maximum supported torque, K_T is motor's torque constant and I is the coil current.

Equation 1 can be interpreted as torque capability offered by coil current I. To sustain a given load torque, the motor driver must always operate at a coil current which can offer more torque than demanded.

Conventional motor drivers configure operating full-scale current based on the peak load torque demand. This ensures that the motor does not lose steps any time peak load is demanded. The current therefore is constant irrespective of the load torque. As a result, when load torque is lower than the peak load, the driver and the motor dissipate some of the input power as resistive power loss as represented in Figure 1-1.

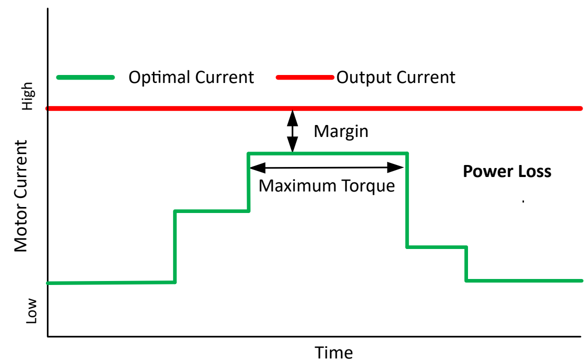


Figure 1-1. Power Loss With Conventional Stepper Driver

In most systems, the demand for peak load torque occurs only rarely. For example, in an ATM machine, the stepper motors might be needed to deliver peak load for less than 15% of their overall run time. A typical stepper driver though ends up delivering full-scale current to the motors all the time - leading to lower system efficiency due to the unwanted power loss, larger system size and shorter lifetime of components.

2 Auto-Torque

The Auto-torque algorithm implemented in the DRV8462, DRV8452 and DRV8461 motor drivers improves system efficiency by dynamically changing the output current according to the load torque. Whenever the load torque is low, the output current is lowered to reduce resistive losses; and when the load torque goes up, the output current increases immediately to prevent motor step loss. This concept is shown in Figure 2-1. As a result of improved efficiency due to auto-torque, the system runs at a lower temperature, which extends the lifetime of the components. Auto-torque can also enable the use of cheaper and smaller sized stepper motors.

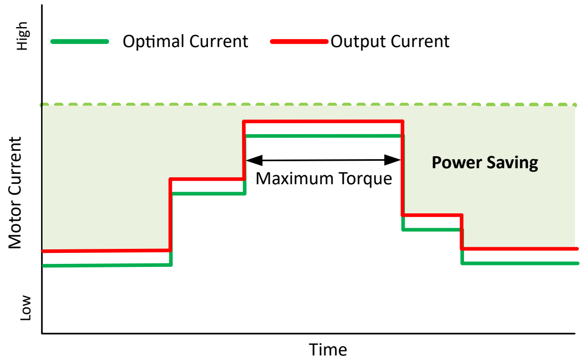


Figure 2-1. Power Saving With Auto-Torque

In a stepper motor system, the total power delivered by the power supply goes into providing for the torque requirement of the load and into power losses such as resistive losses caused by motor winding resistance and driver ON resistance. This is represented by Equation 2:

$$\text{Power delivered by supply} = \text{Constant losses} + \tau \times \omega \tag{2}$$

where τ is load torque and ω is motor speed.

From Equation 2, it is observed that when the load torque increases, the power delivered by the supply increases as well. The auto-torque algorithm obtains information about the load-torque by monitoring the power delivered by the supply. The constant losses are represented by the ATQ_LRN parameter, and the ATQ_CNT parameter represents the power required to support the load torque, as explained in Section 2.1.

2.1 Auto-Torque: Learning Principle

This section explains the steps to follow for the auto-torque algorithm to learn about the motor parameters and motor operating conditions.

As mentioned in Section 2, the ATQ_LRN parameter depends upon the constant losses in the system. For any given motor, ATQ_LRN is directly proportional to the coil current. This can be expressed by Equation 3:

$$\text{ATQ\_LRN} = \frac{k \times I_M}{V_{VM}} \tag{3}$$

where, I_M is the motor current, V_{VM} is the supply voltage to the driver and k is a constant. Equation 3 gives a linear relationship between the ATQ_LRN and the motor current. The auto-torque learning routine learns ATQ_LRN values at any two currents at no load, and then uses this relation to interpolate ATQ_LRN value at any other current.

The ATQ_CNT parameter represents the component of the delivered power that supports the load torque. This relation can be expressed by Equation 4.

$$\text{ATQ\_CNT} = \frac{k_1 \times \tau \times \omega}{I_{FS}} \tag{4}$$

where k_1 is a constant at a given operating condition and I_{FS} is the full-scale current (peak of the sinusoidal current waveform) of the stepper driver.

Equation 4 defines the basic working principle of the auto-torque algorithm. The ATQ_CNT parameter can be used to perform motor coil current regulation based on applied load torque on the stepper motor.

Figure 2-2 shows (ATQ_LRN + ATQ_CNT) measured as a function of load torque at 2.5A full-scale current for a hybrid bipolar NEMA 24 stepper motor rated for 2.8A. ATQ_LRN does not change with load torque, whereas ATQ_CNT changes linearly with load torque.

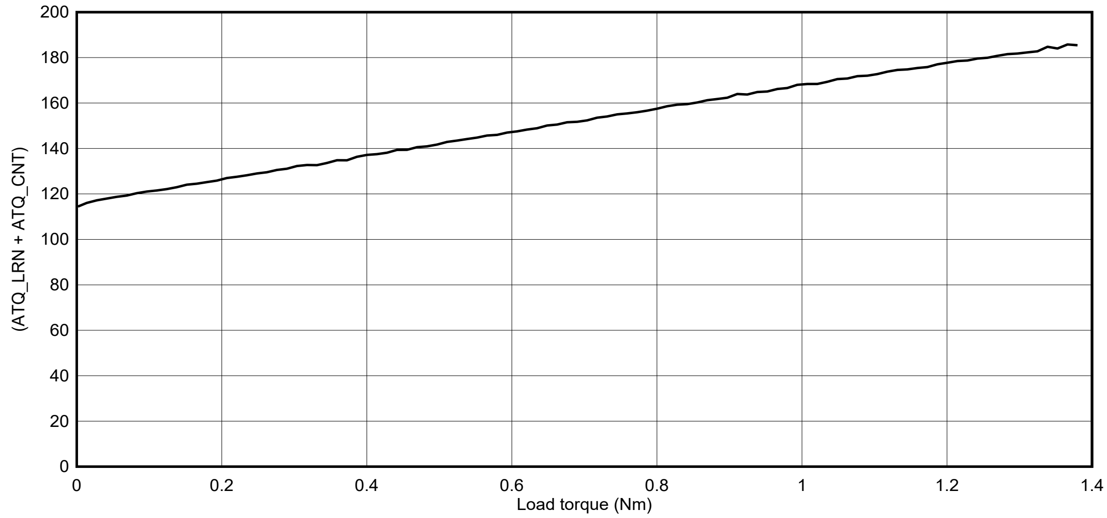


Figure 2-2. (ATQ_LRN + ATQ_CNT) vs. Load Torque

2.1.1 Configuring Auto-Torque Learning Routine

After auto-torque algorithm is enabled, the learning routine must be run to estimate the ATQ_LRN parameters.

The learning routine uses the linear relation between ATQ_LRN and motor current described in Equation 3. You have to select two current values at which learning will be performed, with no load torque applied on the motor. These two current values are programmed by the ATQ_LRN_MIN_CURRENT and ATQ_LRN_STEP registers.

- Initial current level = ATQ_LRN_MIN_CURRENT x 8
- Final current level = Initial current level + ATQ_LRN_STEP

The ATQ_LRN values at these two currents are saved in the ATQ_LRN_CONST1 and ATQ_LRN_CONST2 registers. These two registers are used to interpolate ATQ_LRN value for all other currents within the operating range of the application.

Table 2-1 lists the registers associated with auto-torque learning routine.

Table 2-1. Registers for Auto-Torque Learning Routine

Register Name	Description
ATQ_LRN_MIN_CURRENT[4:0]	Represents the initial current level for auto-torque learning routine.
ATQ_LRN_STEP[1:0]	Represents the increment to initial current level. It supports four options: • 00b : ATQ_LRN_STEP = 128 • 01b : ATQ_LRN_STEP = 16 • 10b : ATQ_LRN_STEP = 32 • 11b : ATQ_LRN_STEP = 64 Example : If ATQ_LRN_STEP = 10b and ATQ_LRN_MIN_CURRENT = 11000b, then: • Initial learn current level = 24*8 = 192 • Final learn current level = 192 + 32 = 224

Table 2-1. Registers for Auto-Torque Learning Routine (continued)

Register Name	Description
ATQ_LRN_CYCLE_SELECT[1:0]	Represents the number of electrical half cycles spent in one current level after which the learning routine allows the current to jump to the other level. It supports four options: • 00b : 8 half-cycles • 01b : 16 half-cycles • 10b : 24 half-cycles • 11b : 32 half-cycles
LRN_START	Writing 1b to this bit enables the auto-torque learning routine. After learning is completed, this bit automatically goes to 0b.
LRN_DONE	This bit becomes 1b after learning is complete.
ATQ_LRN_CONST1[10:0]	Indicates the ATQ_LRN parameter at the initial learning current level.
ATQ_LRN_CONST2[10:0]	Indicates the ATQ_LRN parameter at the final learning current level.
VM_SCALE	When this bit is 1b, the auto-torque algorithm automatically adjusts the ATQ_UL, ATQ_LL and ATQ_LRN parameters as per the supply voltage variation.

Here are few points to consider while setting up the learning routine parameters:

- It is recommended to select the initial current level between 30% to 50% of the maximum operating current.
- Final current level must not exceed 255 and can be selected between 80% and 100% of the maximum operating current.
- Current waveform distortions (due to high speed or low supply voltage) can cause incorrect reading of the ATQ_LRN parameters. The learning current levels should be chosen away from the currents where waveform distortions are observed.
- Low values of ATQ_LRN_CYCLE_SELECT result in quicker learning. However, in systems prone to noise, higher ATQ_LRN_CYCLE_SELECT can result in more stable ATQ_LRN parameter values.
- Learning should be done after the motor attains the steady-state speed.
- Re-learning should be done if the motor is changed, or the motor speed changes by ± 10%.

For a quick summary, the following sequence of commands should be applied to enable automatic learning:

1. Write 1b to ATQ_EN.
2. Run the motor with no load.
3. Program ATQ_LRN_MIN_CURRENT.
4. Program ATQ_LRN_STEP.
5. Program ATQ_LRN_CYCLE_SELECT.
6. Write 1b to ATQ_LRN_START.
7. The algorithm runs the motor with initial current level for ATQ_LRN_CYCLE_SELECT number of electrical half cycles.
8. Next, the algorithm runs the motor with final current level for ATQ_LRN_CYCLE_SELECT number of electrical half cycles.

- After learning is complete:
  - ATQ_LRN_START bit is auto cleared to 0b
  - ATQ_LRN_DONE bit becomes 1b
- ATQ_LRN_CONST1 and ATQ_LRN_CONST2 are populated in their respective registers
- Motor current goes to ATQ_TRQ_MAX

Once the ATQ_LRN_CONST1 and ATQ_LRN_CONST2 are known from the prototyping tests, they can be used for mass production without invoking the learning routine again. The following sequence of commands should be applied in mass production:

1. VREF set to the same value as during learning in prototype tests
2. Program ATQ_LRN_MIN_CURRENT
3. Program ATQ_LRN_STEP
4. Program ATQ_LRN_CONST1
5. Program ATQ_LRN_CONST2
6. Write 1b to ATQ_EN

Figure 2-3 shows the consolidated flowchart of the auto-torque learning routine.

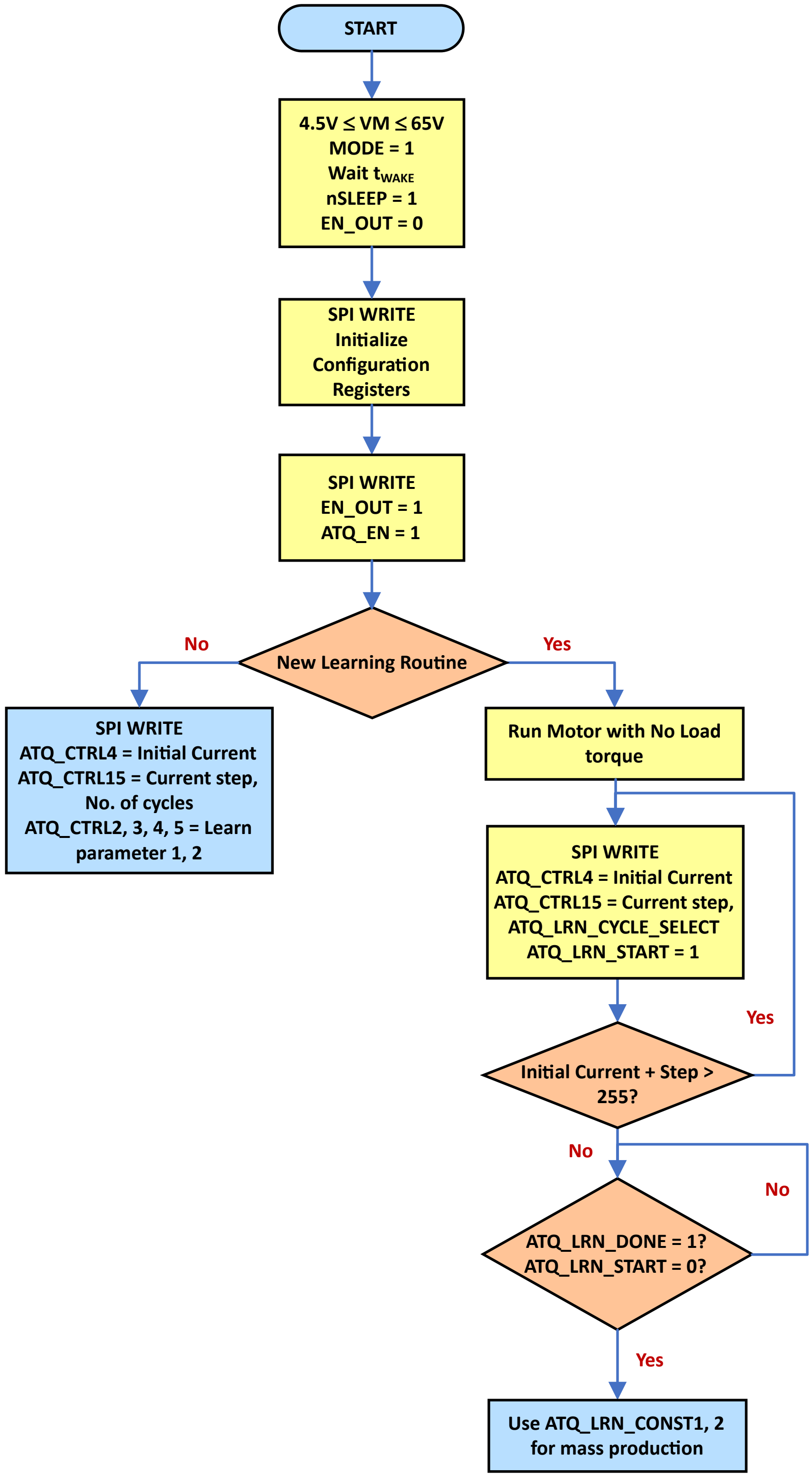


Figure 2-3. Auto-Torque Learning Flowchart

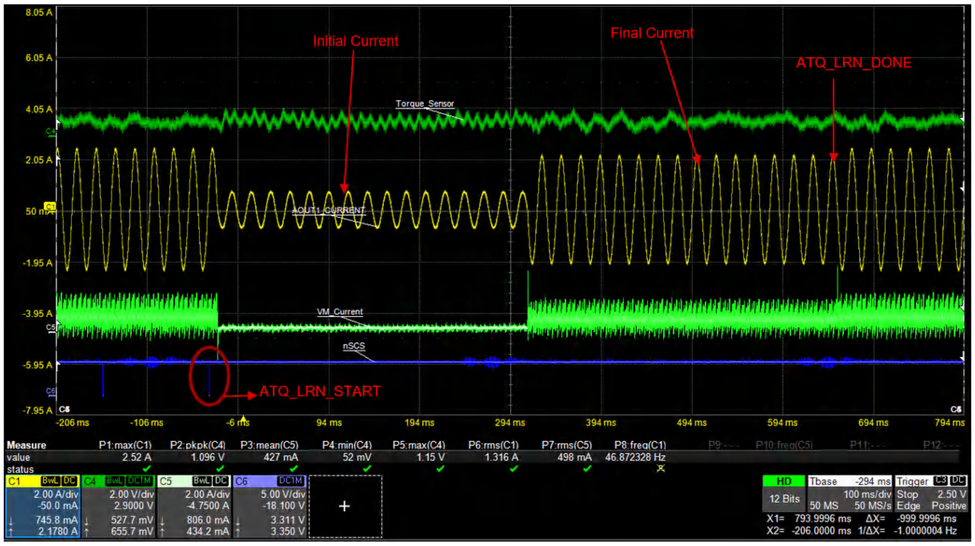


Figure 2-4. Auto-Torque Learning

Traces from top to bottom: load torque, coil current, supply current, nSCS.

Figure 2-4 shows an automatic learning process with 740 mA initial current (I_{FS1}) and 2.2 A final current (I_{FS2}). The ATQ_LEARN_CYCLE_SELECT corresponds to 32 half-cycles.

2.2 Current Control

This section explains how the auto-torque algorithm modifies the motor coil current according to the applied load torque to minimize the resistive losses in the system.

Table 2-2 lists the registers associated with current control.

Table 2-2. Registers for Current Control

Parameter	Description
ATQ_UL[7:0] ATQ_LL[7:0]	Upper and lower boundaries of the hysteretic band within which ATQ_CNT is controlled by modifying the motor current.
ATQ_TRQ_MIN[7:0] ATQ_TRQ_MAX[7:0]	Programmable minimum and maximum current limit when auto-torque is enabled.
ATQ_TRQ_DAC[7:0]	Outputs the value of motor current when auto-torque is enabled. ATQ_TRQ_DAC can vary between ATQ_TRQ_MIN and ATQ_TRQ_MAX.
CNT_OFLW	The CNT_OFLW flag becomes 1b if ATQ_CNT is more than ATQ_UL.
CNT_UFLW	the CNT_UFLW flag becomes 1b if ATQ_CNT is less than ATQ_LL.

As shown in Equation 4, the ATQ_CNT parameter is proportional to the load torque and inversely proportional to the current setting of the stepper driver.

An idealized representation of this relation is shown in Figure 2-5.

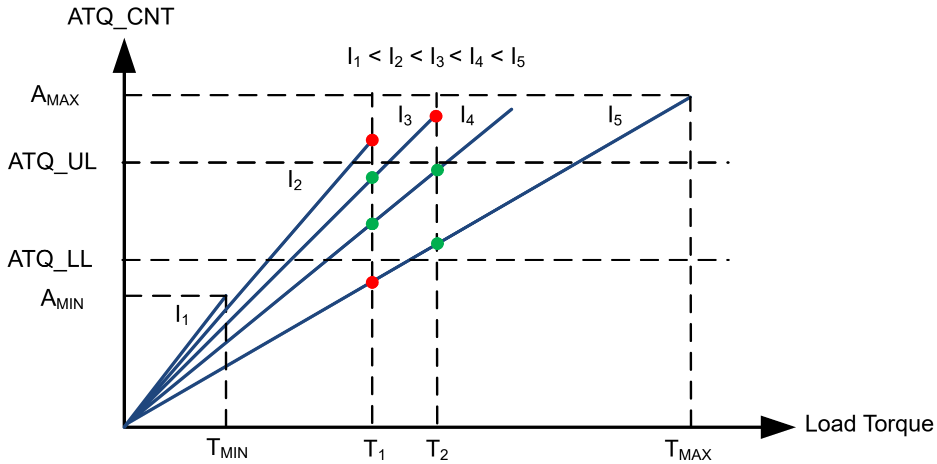


Figure 2-5. ATQ_CNT as a Function of Load Torque

The auto-torque algorithm confines the ATQ_CNT within the hysteretic band defined by the user programmable ATQ_UL and ATQ_LL parameters, by modulating the motor current, as shown in Figure 2-5.

- Maximum amount of load torque that the motor can support without step loss or stall is proportional to the motor current.
- If load torque demand increases (T_1 to T_2), the ATQ_CNT goes above the ATQ_UL threshold, and in response, the algorithm brings the ATQ_CNT within the band by increasing the current (I_3 to I_4).
- When load torque demand drops (T_2 to T_1) and ATQ_CNT goes below ATQ_LL, the algorithm reduces the current to bring the ATQ_CNT within the hysteretic band (I_5 to I_4).

2.2.1 Setting Current Control Parameters

The following methodology explains how you select the values of the current control parameters:

ATQ_TRQ_MIN is the minimum motor current needed to support the minimum load torque applied to the motor.

1. To find this parameter:
   a. Load the motor with minimum load torque (T_{MIN}) and drive the motor with full-scale current (I_{FS}).
   b. Set ATQ_UL and ATQ_LL to zero and set KP as 1.
   c. Reduce current till the motor stalls.
   d. Note the current (I_A) at which the motor stalls.
   e. Set ATQ_TRQ_MIN = 1.1 x I_A.
2. To find ATQ_TRQ_MAX:
   a. With the motor current at I_A, load the motor with maximum load torque (T_{MAX}) and the motor will stall.
   b. Start increasing the motor current. Note the current (I_B) at which the motor restarts from stall.
   c. Set ATQ_TRQ_MAX = 1.1 x I_B. Note the ATQ_CNT (A_{MAX}) with current at ATQ_TRQ_MAX and load torque at T_{MAX}.
3. For the ATQ_UL:
   a. Set an initial value of 0.5 x A_{MAX}.
   b. Apply the load profile (peak load and idle load) specific to the application.
      i. If the motor stalls, decrease the value ATQ_UL until the motor is no longer stalled.
      ii. If the motor does not stall after applying the load profile, ATQ_UL can be increased until the motor stalls.
   c. Higher value of ATQ_UL saves more power at peak load, but in case of a fast load transient, the motor can stall.
   d. Lower value of ATQ_UL reduces the power saving at peak load, but also reduces the chances of motor stall and step loss.
4. For most applications, a difference of 2 between ATQ_UL and ATQ_LL is a good starting point.
5. VM_SCALE bit should be made 1b only after ATQ_UL and ATQ_LL have been set by the user.

The flowchart for selecting ATQ_UL, ATQ_LL, ATQ_TRQ_MAX and ATQ_TRQ_MIN parameters is shown in Figure 2-6.

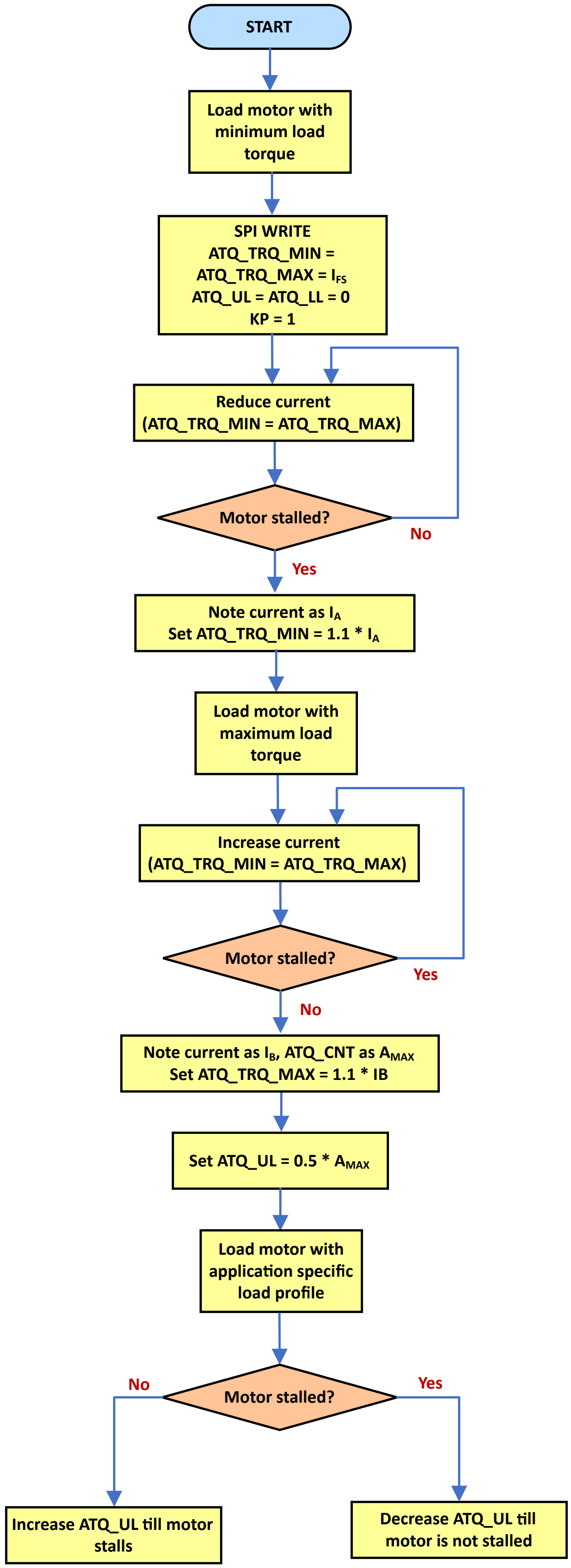


Figure 2-6. Selecting ATQ_TRQ_MIN, ATQ_TRQ_MAX, ATQ_UL, ATQ_LL

2.3 PD Control Loop

This section explains how the internal PD control loop smoothens the response to sudden load torque transients while minimizing the error.

Table 2-3 describes the major parameters associated with the PD control loop -

Table 2-3. Parameters for PD Control Loop

Parameter	Description
KP[7:0], KD[3:0]	Proportional and differential gain parameters for the PD control loop.
ATQ_AVG[2:0]	The ATQ_CNT parameter is a moving average of ATQ_AVG number of half-cycles. Therefore, a high value for ATQ_AVG slows down the loop response time to a sudden peak load demand, but ensures smooth jerk-free transition to higher torque output. A low value causes the loop to respond immediately to a sudden load demand. • 010b - 2 cycle average • 100b - 4 cycle average • 111b - 8 cycle average • Other values : no averaging
ATQ_FRZ[2:0]	Delay in electrical half-cycles after which current is changed in response to the PD loop. A small value increases the current quickly to meet peak load demand. This parameter has a range of 1 to 7. 001b - Fastest response time, but the loop can become unstable 111b - Slowest response, but the loop will be stable
ATQ_D_THR[7:0]	If error change is less then ATQ_D_THR, then KD does not contribute to correction. KD contributes only when error change is greater than ATQ_D_THR. For example: if ATQ_D_THR = 10, If error change is 9, u(t) = KP * e(t) If error change is 12, then u(t) = KP * e(t) + KD * de(t)/dt
ATQ_ERROR_TRUNCATE[3:0]	Number of LSB bits truncated from error before used in PD loop equations. A high value reduces any oscillation in the current waveform.

The PD control algorithm is expressed as -

$$u(t) = KP * e(t) + KD * de(t)/dt \quad (5)$$

where,

KP and KD = PD loop constants

- *u(t)* = output of controller
- *e(t)* = error signal

Guidelines to tune the PD loop parameters are as follows:

- Set KP = 1, KD = 0, all other PD loop parameters should be at their default values
- Apply load profile specific to the application
- If the motor stalls, increase KP, KD and decrease ATQ_D_THR till the motor stops stalling
- Once the motor does not stall any more, observe the current waveform at constant load torques
- If the current waveform has oscillations, increase ATQ_FRZ, ATQ_AVG and ATQ_ERROR_TRUNCATE
- Very high values of ATQ_FRZ, ATQ_AVG and ATQ_ERROR_TRUNCATE can deteriorate load transient response, so it is recommended to check load transient response once more to ensure the PD control loop is stable.

Figure 2-7 is the flowchart for selecting PD control loop parameters.

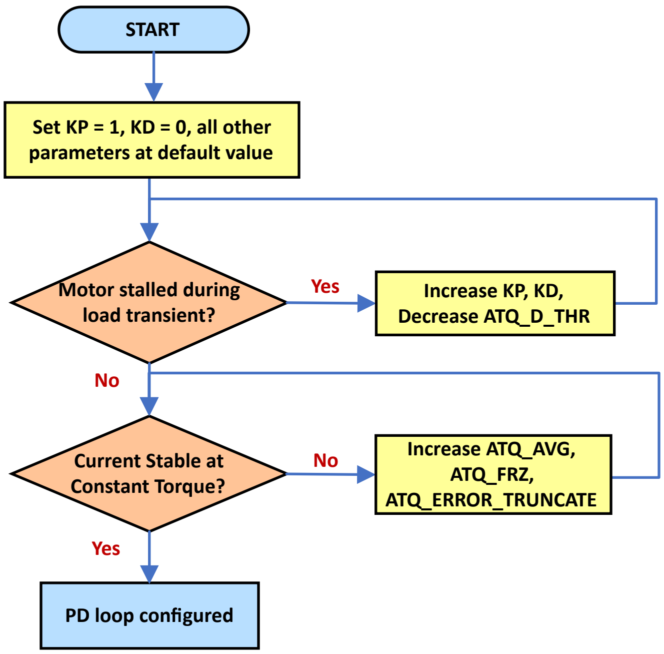


Figure 2-7. Selecting PD Control Loop Parameters

2.4 Impact of Auto-Torque Tuning Parameters

2.4.1 Impact of Learning Parameters on Load Transient Response

As mentioned in Section 2.2.1, the choice of ATQ_TRQ_MIN and ATQ_UL influenecs how the control loop responds to load torque transients. This is shown in Figure 2-8 to Figure 2-11.

For all the following traces, from top to bottom: load torque, coil current, supply current:

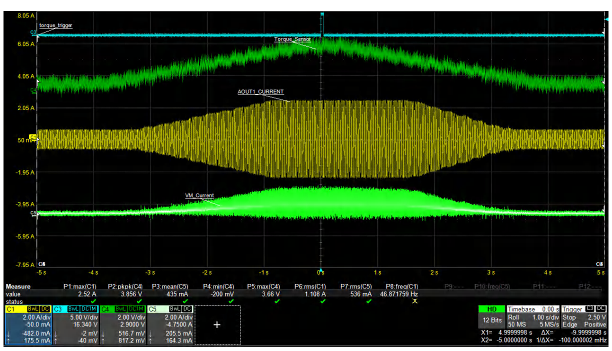


Figure 2-8. ATQ_TRQ_MIN = 0.6 A, ATQ_UL = 40

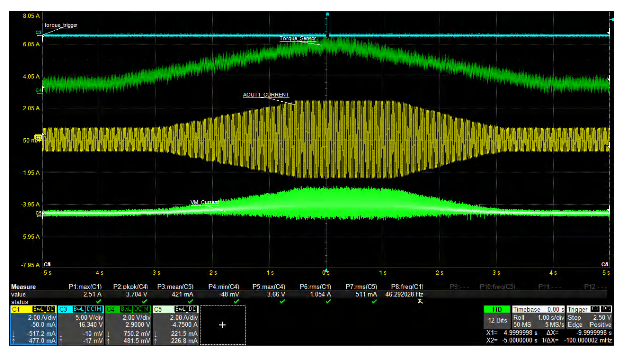


Figure 2-9. ATQ_TRQ_MIN = 0.74 A, ATQ_UL = 45

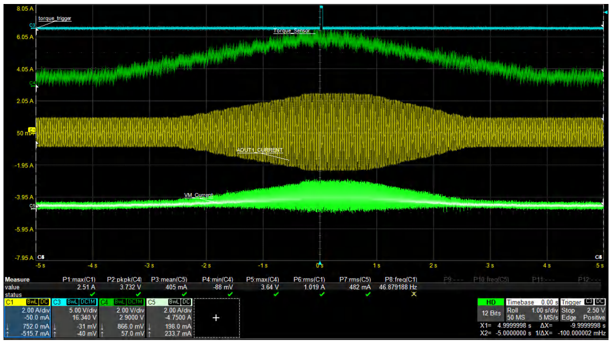


Figure 2-10. ATQ_TRQ_MIN = 0.93 A, ATQ_UL = 50

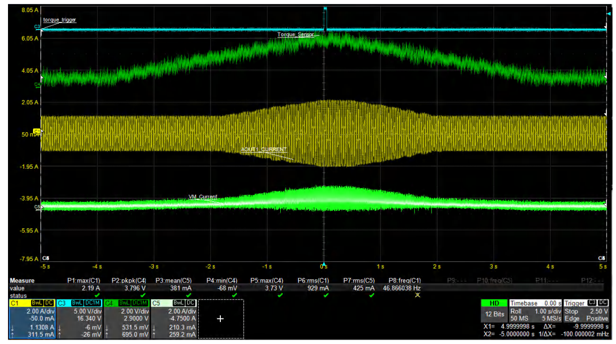


Figure 2-11. ATQ_TRQ_MIN = 1.2 A, ATQ_UL = 60

- In Figure 2-8, with lowest ATQ_UL, the motor current reaches ATQ_TRQ_MAX earlier than the other settings. This setting therefore saves the least amount of power, though it has the quickest response time for fast load torque transients.
- In Figure 2-11, the motor current takes long time to increase. This setting saves the most power, but has the slowest response to load torque transients.

2.4.2 Impact of ATQ_UL, ATQ_LL Hysteresis

If the hysteresis band between ATQ_UL and ATQ_LL is widened by increasing the difference, it improves the immunity of the algorithm against system noise.

- As shown in Figure 2-12, smaller hystsresis means the response to load increase or decrease is similar.
- Figure 2-13 shows that larger hysteresis causes the current take longer time to reduce when load is reducing, leading to slower response to decreasing load, and slightly poorer efficiency. But it helps in situations where the load has noisy transients.

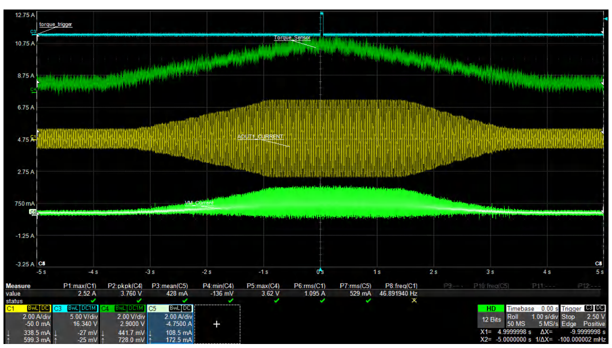


Figure 2-12. ATQ_UL = 40, ATQ_LL = 40

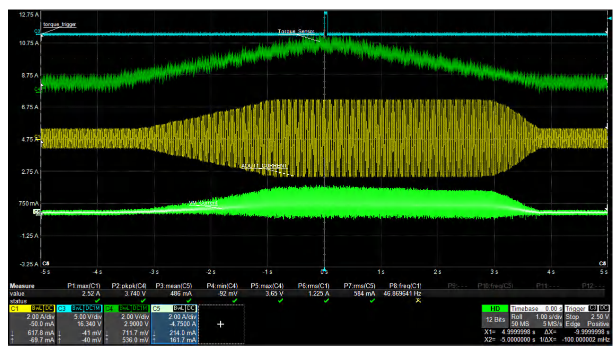


Figure 2-13. ATQ_UL = 40, ATQ_LL = 20

2.4.3 Impact of Load Profile on Power Saving

This section explains how the nature of the load torque profile determines the power saving, as shown in Figure 2-14.

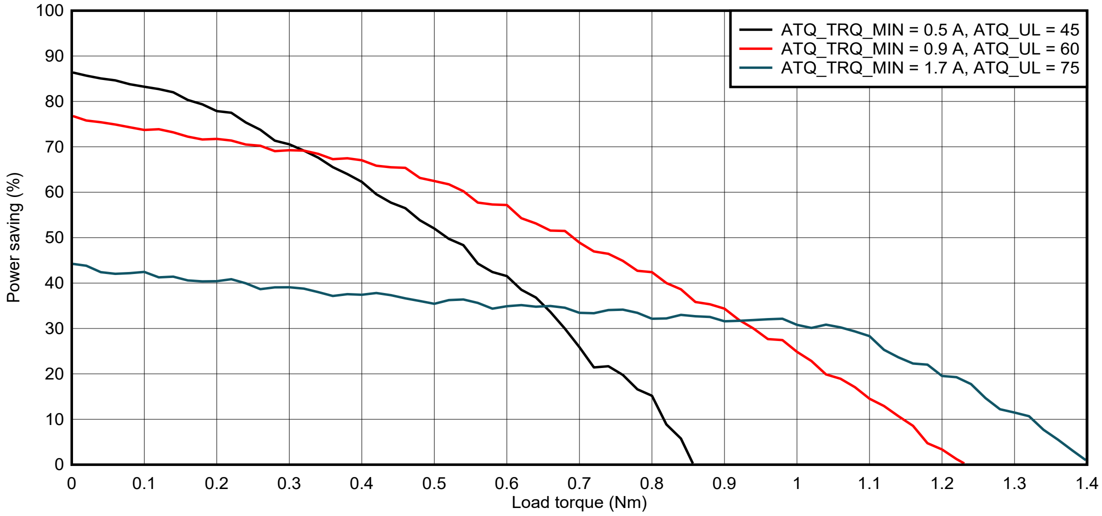


Figure 2-14. Power Saving as a Function of Load Torque

- For a low value of ATQ_TRQ_MIN and ATQ_UL, the power saving at light loads is higher, but the power saving curve drops off to zero at a lower load torque.
- A higher value of ATQ_TRQ_MIN and ATQ_UL result in only moderate power saving at light loads, but drops off at a higher load torque.

The choice of the power saving profile depends on the frequency and duty cycle of the peak load, as shown for three hypothetical load torque profiles and two power saving profiles in Figure 2-15.

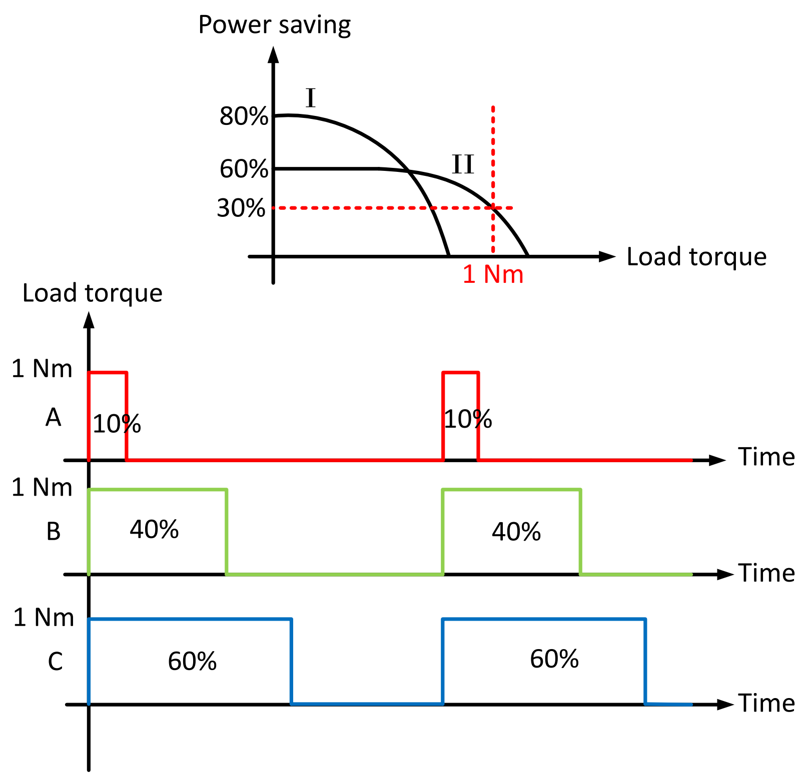


Figure 2-15. Selecting Power Saving Profile

Table 2-4. Power Saving for Load Profiles A, B and C

Load Profile	Peak Load Duty	Power Saving With Plot I	Power Saving With Plot II
A	10 %	72 %	57 %
B	40 %	48 %	48 %
C	60 %	32 %	42 %

- As shown in Table 2-4, for load profile A, power saving plot I saves most power.
- For the load profile B, both power saving plots save same amount of power.
- For the load profile C, power saving plot II saves the most power.
- Therefore, if the load profile is such that peak load duty is small, then choose low values of ATQ_TRQ_MIN and ATQ_UL.
- If the peak load duty is high, choose higher values of ATQ_TRQ_MIN and ATQ_UL.

2.4.4 Adaptive ATQ_UL, ATQ_LL

The power saving can be improved even further, if the ATQ_UL adapts to the maximum ATQ_CNT at each current level. This adaptive ATQ_UL can be implemented in firmware by continuously updating the value of ATQ_UL as a function of the motor current, as shown by the envelope plot in Figure 2-16.

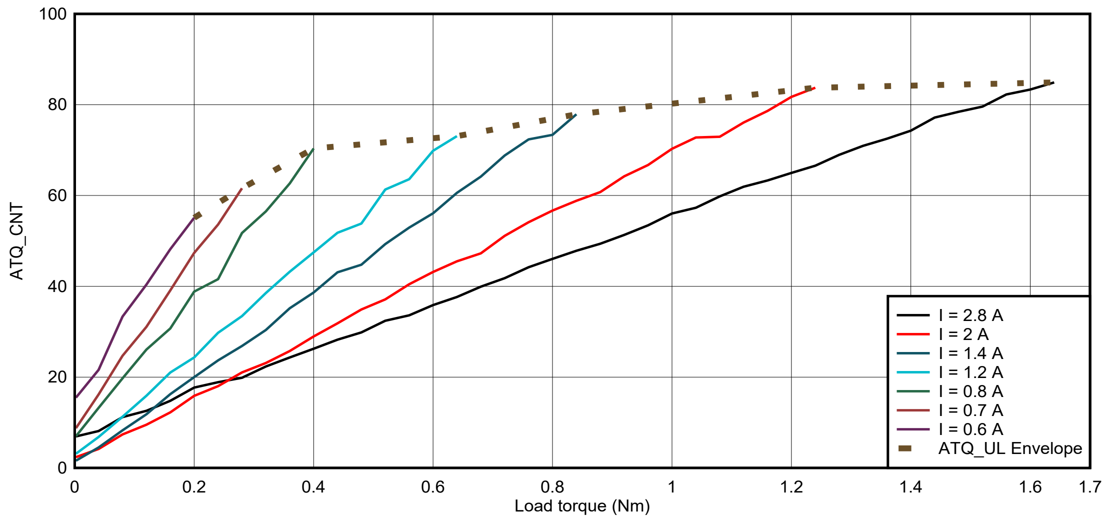


Figure 2-16. Adaptive ATQ_UL

With adaptive ATQ_UL, the current waveform in Figure 2-18 saves more power than the non-adaptive case shown in Figure 2-17.

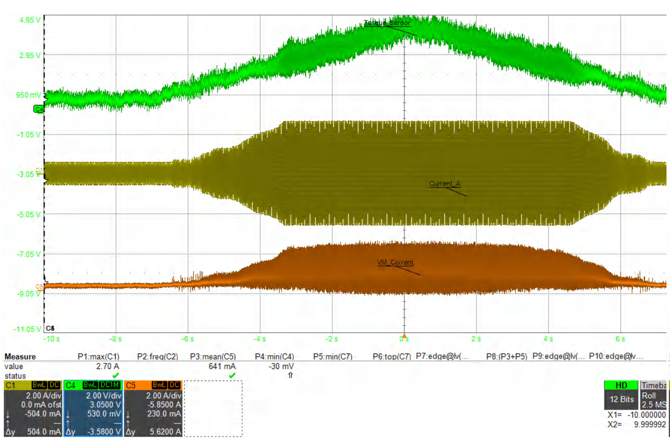


Figure 2-17. Current Waveform With Non-Adaptive ATQ_UL

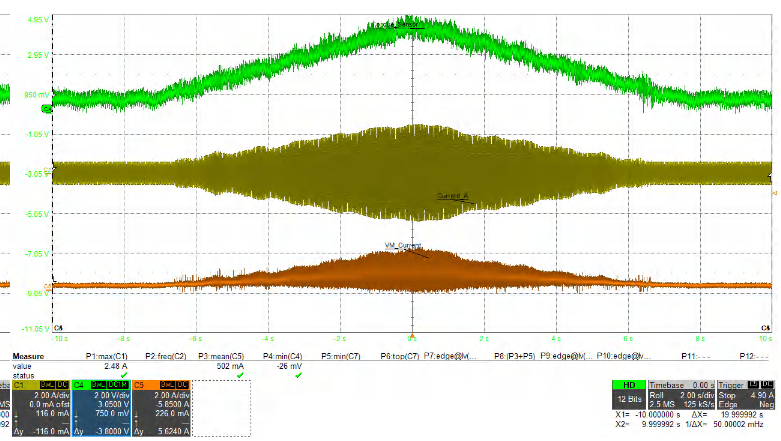


Figure 2-18. Current Waveform With Adaptive ATQ_UL

2.4.5 PD Parameter Dependency Curves

This section shows how the response to load transient depends on the PD control loop parameters.

2.4.5.1 Dependency on KP

- In general, increasing the KP increases the speed of the control system response, as shown by Figure 2-19 and Figure 2-20.
- However, if KP is too large, the current waveform starts to oscillate.
- If KP is increased further, the oscillations becomes larger. The system becomes unstable and may even oscillate out of control, as shown in Figure 2-21.

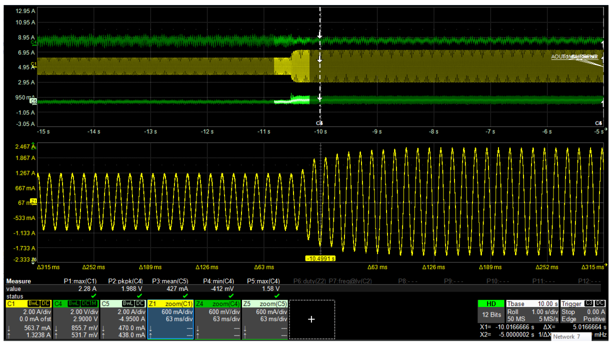


Figure 2-19. Load Transient With KP = 1

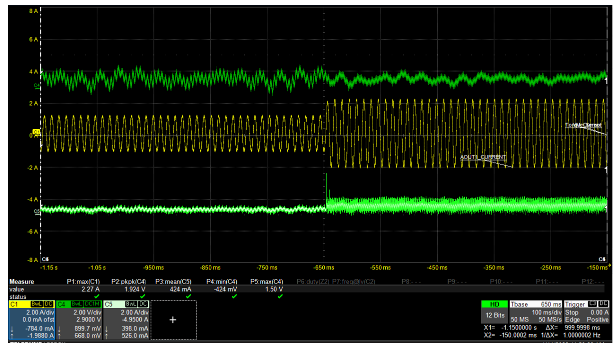


Figure 2-20. Load Transient With KP = 5

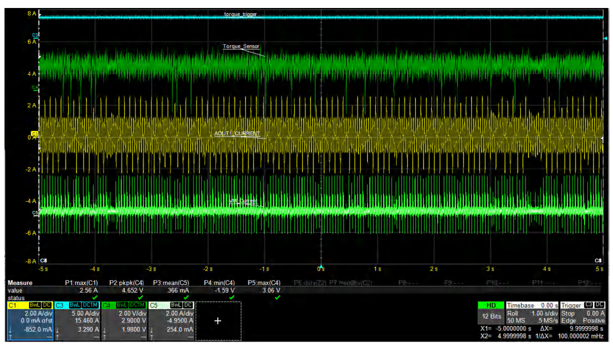


Figure 2-21. Current Waveform With KP = 7

2.4.5.2 Dependency on KD and ATQ_D_THR

- Increasing the value of KD will cause the control system to react more strongly to changes in the error term and will increase the speed of the overall control system response, as shown by Figure 2-22 and Figure 2-23.
- It is recommended to use small value of KD, because the derivative response is highly sensitive to noise.
- When non-zero values of KD is selected, to improve noise immunity of the system, a high value of ATQ_D_THR should be used.

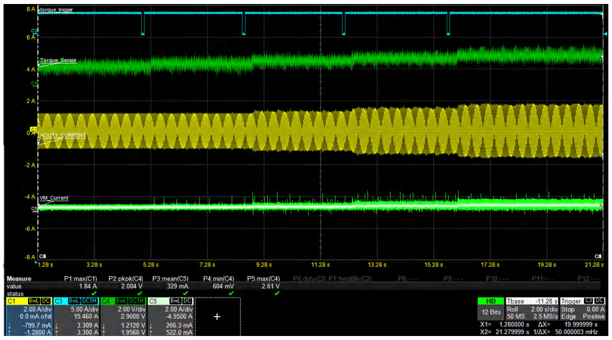


Figure 2-22. KD = 0, Load Torque Changed From 0.3 Nm to 0.57 Nm

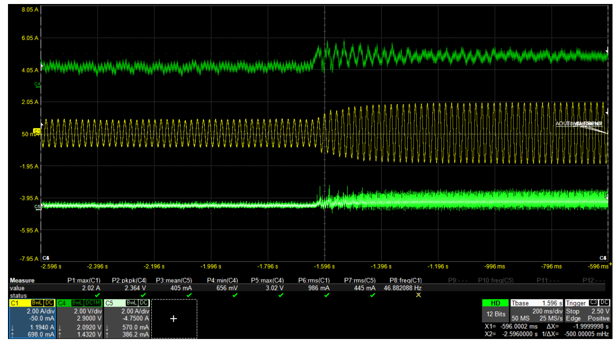


Figure 2-23. KD = 5, ATQ_D_THR = 30, Load Torque Changed From 0.3 Nm to 0.57 Nm

2.4.5.3 Dependency on ATQ_FRZ and ATQ_AVG

- A high value for ATQ_AVG slows down the loop response time to a sudden peak load demand, but ensures smooth jerk-free transition to higher torque output.
- A low value of ATQ_AVG means the loop responds immediately to a sudden load demand.
- A small value of ATQ_FRZ increases the current quickly to meet peak load demand.

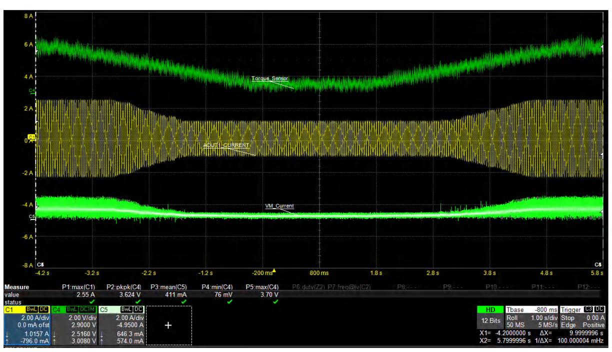


Figure 2-24. KP = 1, FRZ = 1, AVG = 1

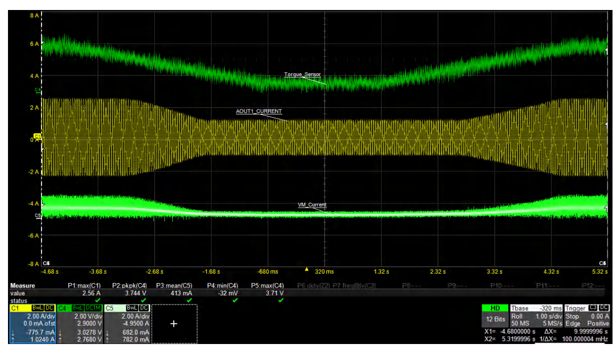


Figure 2-25. KP = 1, FRZ = 1, AVG = 8, Very Stable for Slow Transients

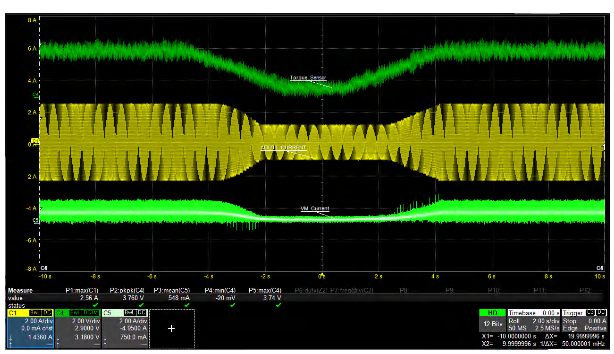


Figure 2-26. KP = 1, FRZ = 7, AVG = 8, Slow Response

2.4.5.4 Dependency on ATQ_ERROR_TRUNCATE

Increasing the value of ATQ_ERROR_TRUNCATE reduces any oscillation in the current waveform.

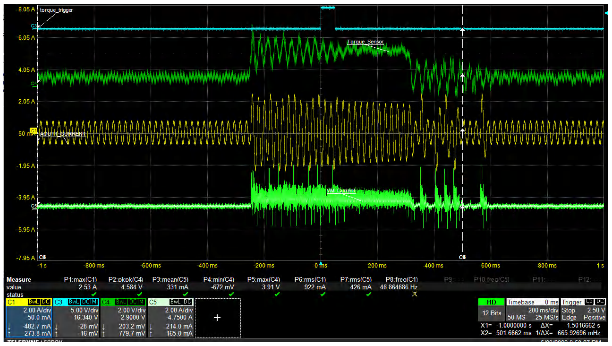


Figure 2-27. ATQ_ERROR_TRUNCATE = 0, Loop Takes Long Time to Stabilize During a Fast Load Transient

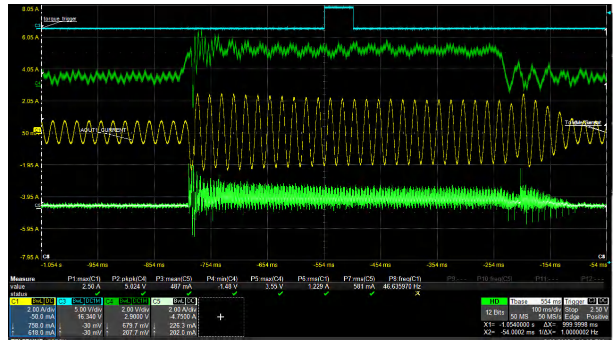


Figure 2-28. ATQ_ERROR_TRUNCATE = 2, Reduced Oscillation

2.4.6 ATQ_CNT at Different Motor Speeds

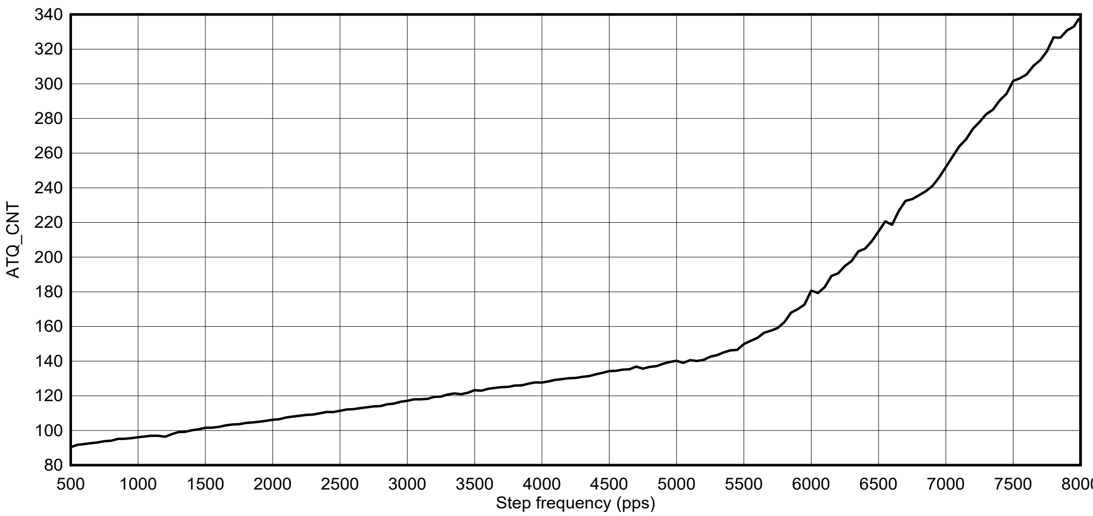


Figure 2-29. ATQ_CNT as a Function of Motor Speed

Figure 2-29 shows how ATQ_CNT varies with motor speed with all other operating conditions remaining same. As is evident, there are two distinct segments with different slopes in the ATQ_CNT vs. speed plot.

- The segment with lesser slope corresponds to sinusoidal current waveforms, as shown in Figure 2-30 and Figure 2-31.
- At higher speeds, when the current waveform starts becoming triangular (as shown in Figure 2-31 and Figure 2-33), the ATQ_CNT vs. speed plot has a steeper slope.
- For a given range of motor speed, firmware can adjust the ATQ_LRN parameters and ATQ_UL, ATQ_LL based on a curve like Figure 2-29.
  - To start with, user can vary the motor speed and plot this curve at maximum current.
  - During normal operation, at any speed, they can find the correction factor from the curve and apply it to the ATQ_LRN parameters, ATQ_UL and ATQ_LL.

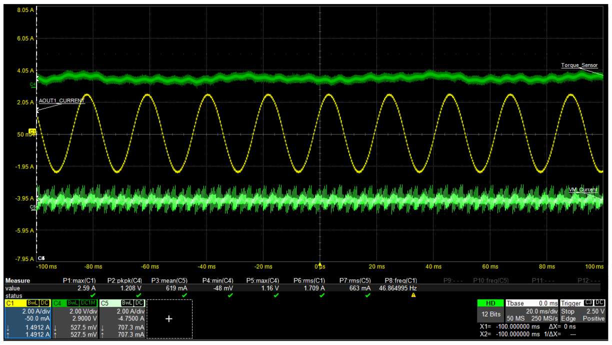


Figure 2-30. 3000 pps Step Frequency

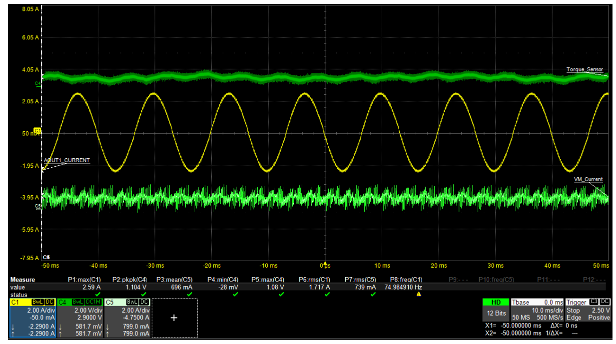


Figure 2-31. 4800 pps Step Frequency

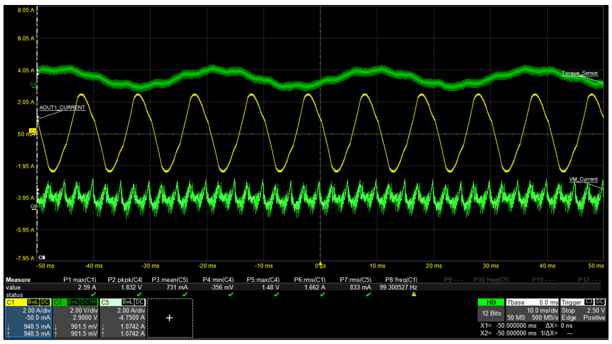


Figure 2-32. 6400 pps Step Frequency

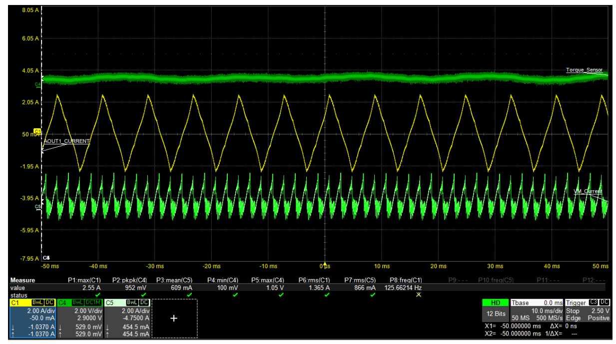


Figure 2-33. 8000 pps Step Frequency

2.4.7 ATQ_CNT at Different Supply Voltages

Figure 2-34 shows the variation of ATQ_CNT as a function of motor supply voltage, with all other operating conditions remaining same.

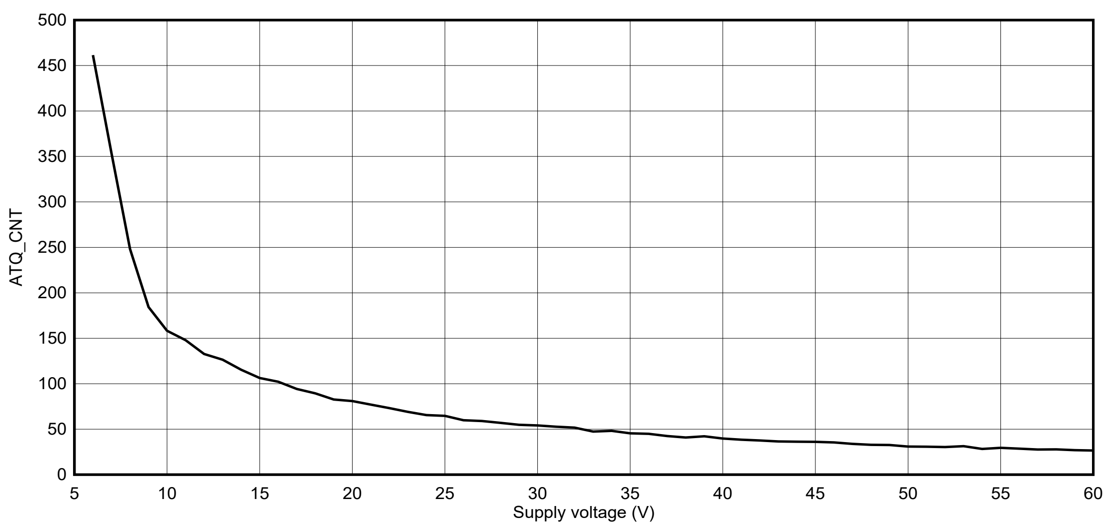


Figure 2-34. ATQ_CNT as a Function of Supply Voltage

When the VM_SCALE bit is configured to be 1b, the auto-torque algorithm automatically adjusts the ATQ_UL, ATQ_LL and ATQ_LRN parameters as per the supply voltage.

Figure 2-35 shows how the ATQ_LRN parameters automatically vary with the supply voltage when VM_SCALE bit is set to 1b.

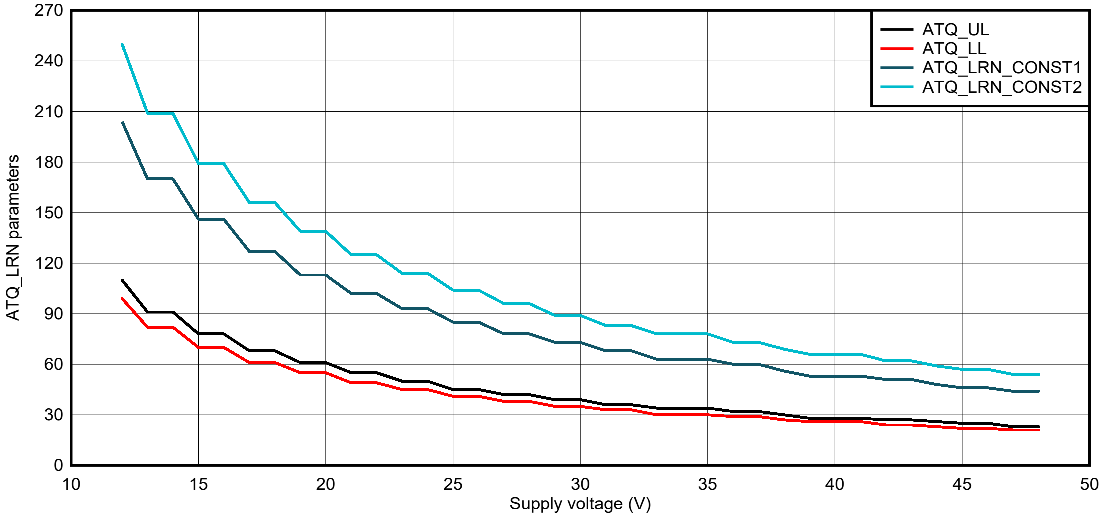


Figure 2-35. ATQ_LRN vs VM

2.4.8 Motor Temperature Estimation

With all other operating conditions remaining constant, change in the ATQ_CNT value can be correlated to the motor case temperature variation, as shown below for a stepper motor with 25 Ω coil resistance. This property can be used in applications to monitor the PCB and motor temperature. By monitoring changes in motor temperature over time, system robustness can be increased and predictive maintenance of the motor can be performed.

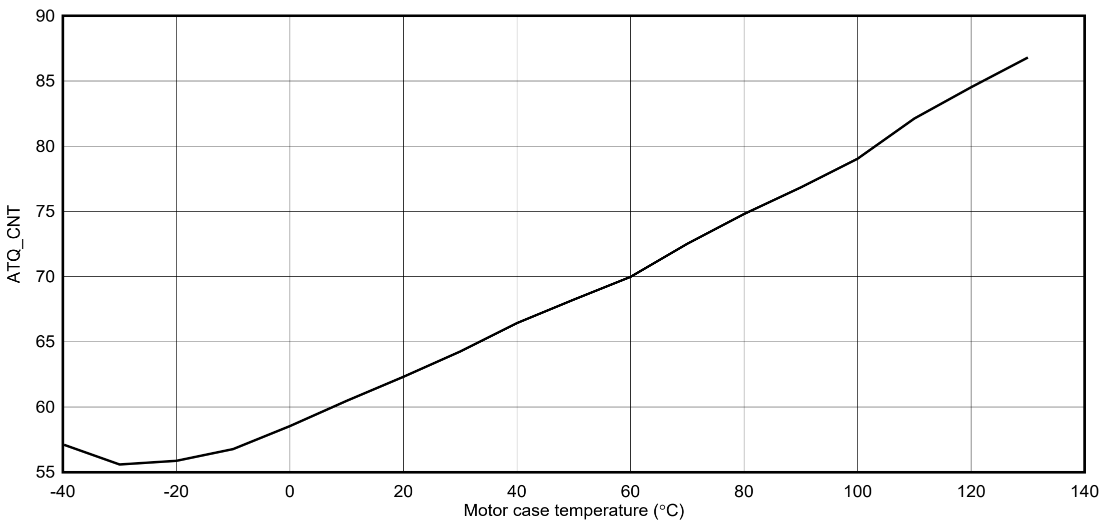


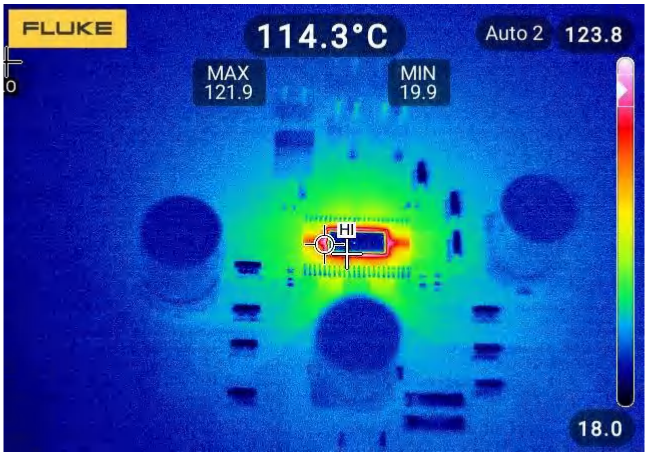
Figure 2-36. ATQ_CNT vs Motor Temperature

2.5 Efficiency Improvement With Auto-Torque

Table 2-5 shows the thermal performance improvements as a result of auto-torque. The thermal images are captured at the following condition:

VM = 24 V, 1/16 microstep, 4A full-scale current, 3000 pps speed, No load, Room temperature ambient

Table 2-5. Thermal Performance Improvement With Auto-Torque

<table>
<tr>
<td>
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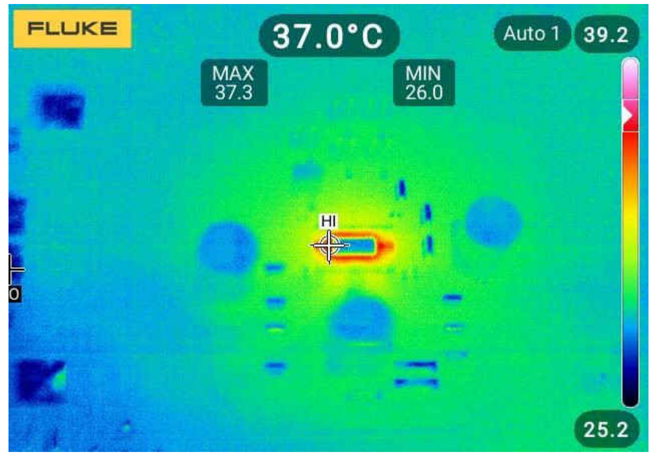
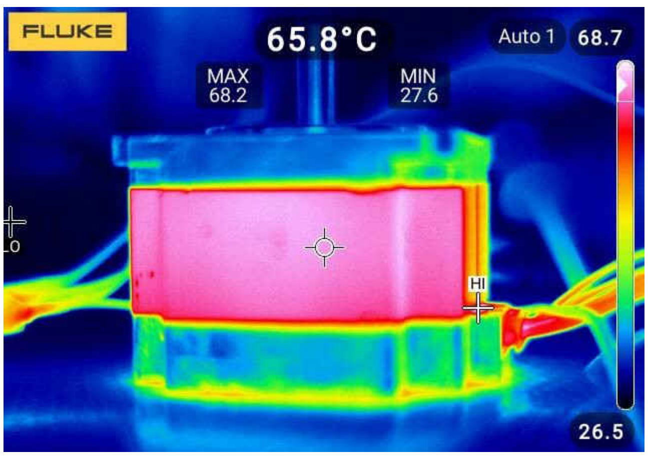
<td>
</td>
</tr>
<tr>
<td>Thermal image: auto-torque disabled, IC temperature = 114.3 °C</td>
<td>Thermal image: auto-torque enabled, IC temperature = 37 °C</td>
</tr>
<tr>
<td>
</td>
<td>
</td>
</tr>
<tr>
<td>Thermal image: auto-torque disabled, motor temperature = 65.8 °C</td>
<td>Thermal image: auto-torque enabled, motor temperature = 28.1 °C</td>
</tr>
</table>

Reduction in IC and motor temperature as a result of auto-torque improves long term reliability of the stepper motor system.

3 Case Studies

This section looks at specific use cases where auto-torque results in significant power saving.

3.1 Application 1: ATM Machines

Stepper motors are used inside ATM machines for various subsystems such as cash dispenser, bill picker and cash transport belt. A single ATM machine can sometimes contain more than 15 stepper motors.

Auto-torque is a desirable feature in an ATM system because it reduces the power loss whenever load torque is less than peak load, such as when cash is not being dispensed. On average, an ATM machine might be used only 10-15% of the time in an hour; therefore, auto-torque can significantly reduce the power consumed by an ATM machine. Industry wide, there is a trend towards introducing energy efficient 'green' ATMs to save money for consumers by lowering electricity costs. Auto-torque can help manufacturers achieve those power saving targets.

3.1.1 ATM Motor Operating Conditions

This section describes the operating conditions of a typical stepper motor used in an ATM.

Parameter	Value
Motor Current rating	2.8 A
Motor coil Resistance at 20°C	1.5 Ω
Motor coil Inductance	6.8 mH
Holding Torque	3.1 Nm
Motor frame size	NEMA 24
Motor supply voltage	24 V
Microstep	16
Step frequency	3 kHz

3.1.2 ATM Motor With Auto-Torque

Based on measured data, a typical stepper motor used in a cash transport belt will experience load torque change at a rate of about 300 mNm every 40 ms.

In lab, one such stepper motor was subjected to load torque transients between 176 mNm and 1.46 Nm at a rate of 300 mNm/40ms. The on time for the peak load was 500 ms, and the duration between peak load events was 4.5 s, corresponding to a 10% duty cycle for the peak load.

For this motor, the auto torque learning routine was run at no load with the following parameter values:

- ATQ_LRN_MIN_CURRENT = 00110b
- ATQ_LRN_STEP = 11b
- ATQ_LRN_CYCLE_SELECT = 11b

Figure 3-1 shows the snapshot of the learning routine for this motor.

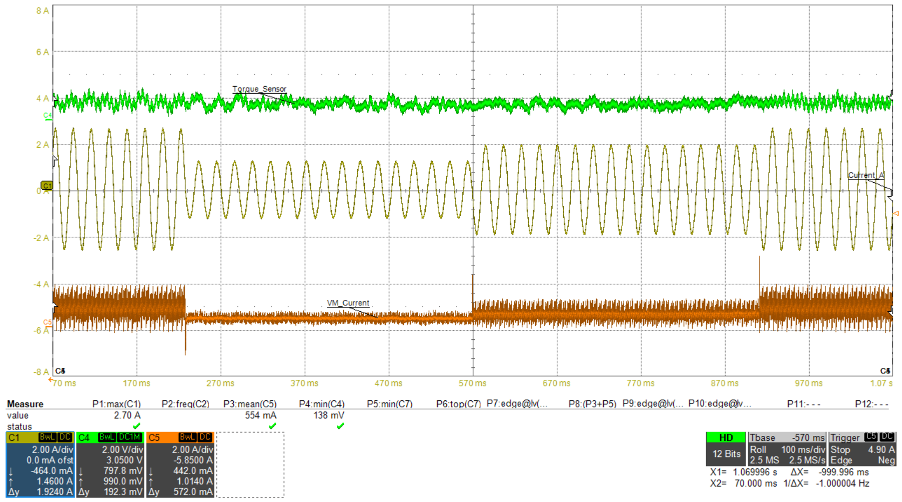


Figure 3-1. Learning Routine Snapshot for ATM Motor

Resulting values for the ATQ_LRN parameters are -

- ATQ_LRN_CONST1 = 83
- ATQ_LRN_CONST2 = 120

The parameters for current control and PD loop control were selected as:

- ATQ_TRQ_MAX = 120
- ATQ_TRQ_MIN = 35, corresponding to the current needed to support the motor when no cash is transported
- ATQ_UL = 45
- ATQ_LL = 43
- ATQ_LL = 43
- ATQ_FRZ = 1
- ATQ_AVG = 0

Figure 3-2 to Figure 3-5 showcases the output current and supply current waveforms with and without auto-torque in the event of a load torque change.

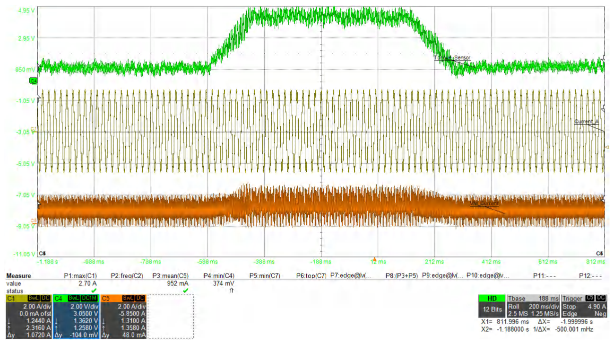


Figure 3-2. ATM Motor Loading/Unloading Without Auto-Torque

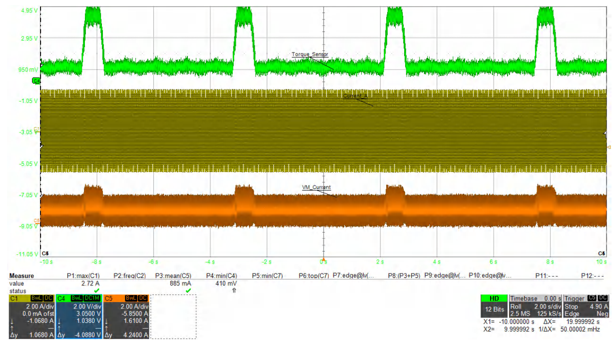


Figure 3-3. ATM Motor Loading/Unloading Without Auto-Torque

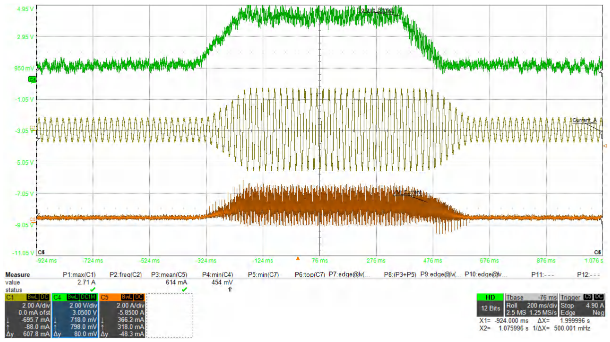


Figure 3-4. ATM Motor Loading/Unloading With Auto-Torque

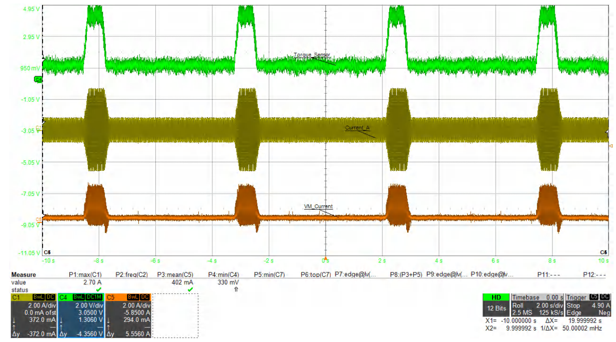


Figure 3-5. ATM Motor Loading/Unloading With Auto-Torque

As seen from the scopeshots, supply current consumption is significantly lower with auto-torque. Based on lab measurements -

- Power consumed without auto-torque = 24 V * 885 mA = 21.24 W
- Power consumed with auto-torque = 24 V * 402 mA = 9.65 W
- This represents a power saving of 55% for this motor with the specified load profile.

As for the power dissipation in the motor -

- Power loss in the motor without auto-torque = (2.8 A * 2.8 A * 1.5 Ω) = 11.76 W
- Power Loss in the motor with auto-torque = (0.1 * 2.8 A * 2.8 A + 0.9 * 0.85 A * 0.85 A) * 1.5 Ω = 2.15W
- This corresponds to a heat reduction of 82 % in the motor coils, leading to lifetime and long term reliability improvement.

3.2 Application 2: Textile Machines

All the major textile machine manufacturers worldwide have introduced energy efficient textile machines in the market. Emerging technologies like auto-torque can help reduce the energy bill of textile machines even further.

In a textile knitting machine, the roller motor is generally a high power stepper motor. In a winding machine, high power stepper is used for the suction motor. Thermal management is a key concern in all textile machines, and auto-torque improves the longevity and long term reliability of the components by moderating the temperature exertions over the lifetime of the textile machine.

3.2.1 Textile Motor Operating Conditions

This section describes the operating conditions for a stepper motor used in a textile machine.

Parameter	Value
Motor Current rating	9 A
Motor coil Resistance at 20°C	0.15 Ω
Motor coil Inductance	0.6 mH
Holding Torque	3 Nm
Motor frame size	NEMA 24
Motor supply voltage	24 V
Microstep	16
Step frequency	3 kHz

3.2.2 Textile Motor With Auto-Torque

In this application, the stepper motor was subjected to load torque transients between 50 mNm and 1.5 Nm at a fast rate of 1.5 Nm/15ms. The on time for the peak load was roughly 1 s, and the duration between peak load events was 4 s, corresponding to a 20% duty cycle for the peak load.

Figure 3-6 shows the snapshot of the learning routine for this motor.

The auto torque learning routine was run at no load with the following parameter values:

- ATQ_LRN_MIN_CURRENT = 1011000b
- ATQ_LRN_STEP = 00b

Values for the ATQ_LRN parameters are:

- ATQ_LRN_CONST1 = 43
- ATQ_LRN_CONST2 = 99

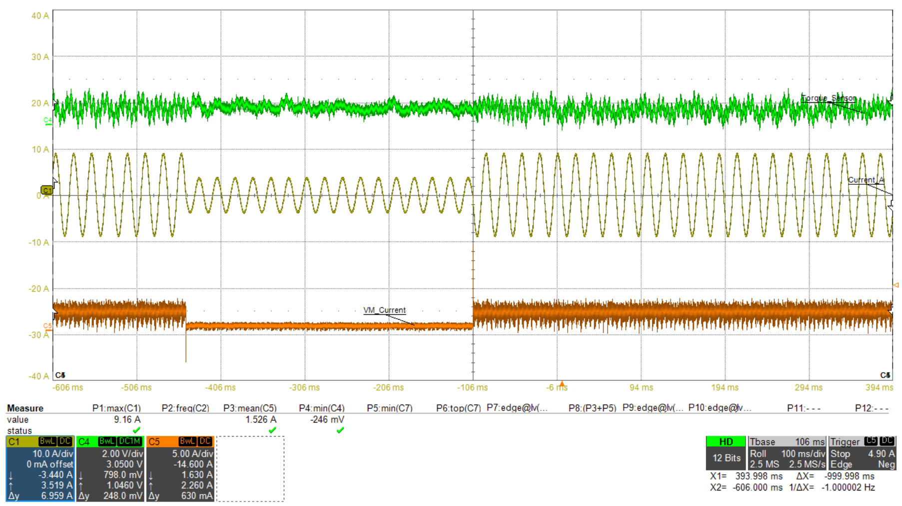


Figure 3-6. Learning Routine Snapshot for Textile Motor

The parameters for current control and PD loop control were selected as:

- ATQ_TRQ_MAX = 216
- ATQ_TRQ_MIN = 80
- ATQ_UL = 13
- ATQ_LL = 12
- KP = 1
- KD = 15
- ATQ_D_THR = 7
- ATQ_ERROR_TRUNCATE = 0
- ATQ_FRZ = 1
- ATQ_AVG = 0

Figure 3-7 to Figure 3-10 showcase the output current and supply current waveforms with and without auto-torque in the event of a load torque change. As is expected, supply current consumption is significantly lower with auto-torque.

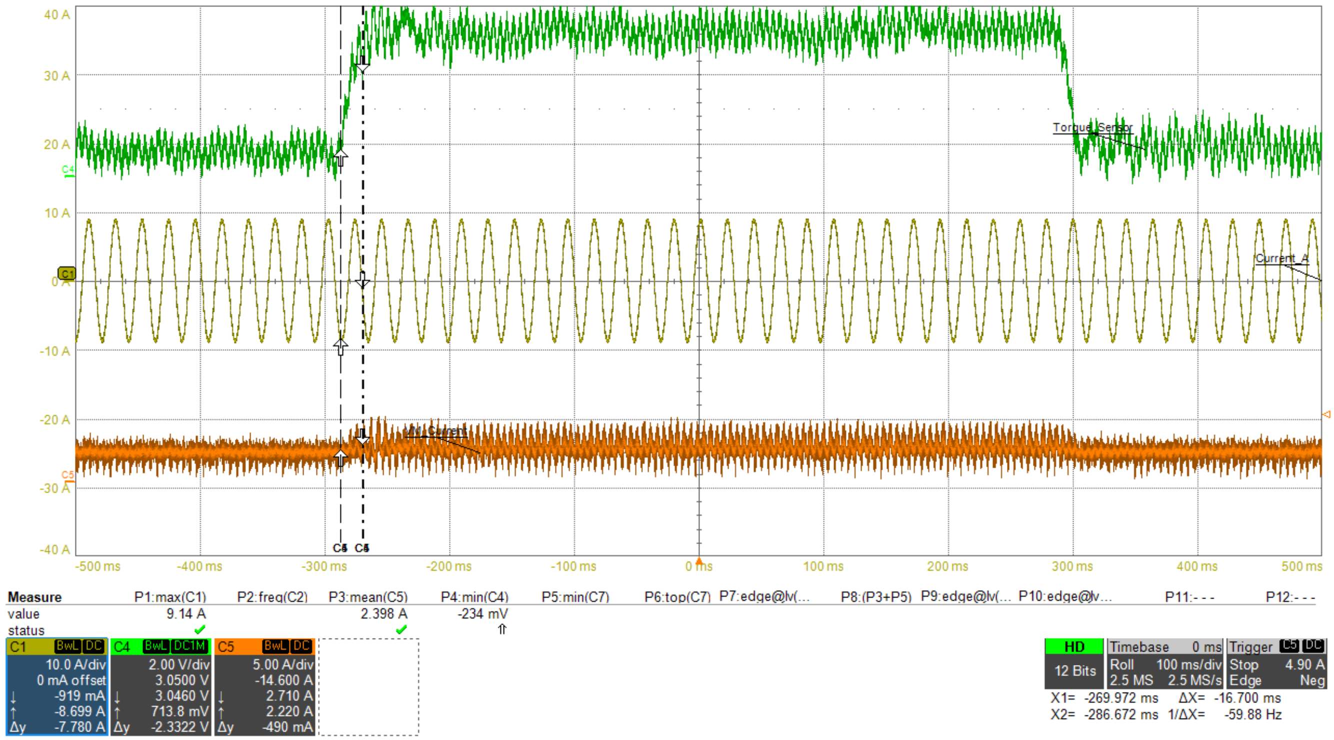


Figure 3-7. Textile Motor Loading/Unloading Without Auto-Torque

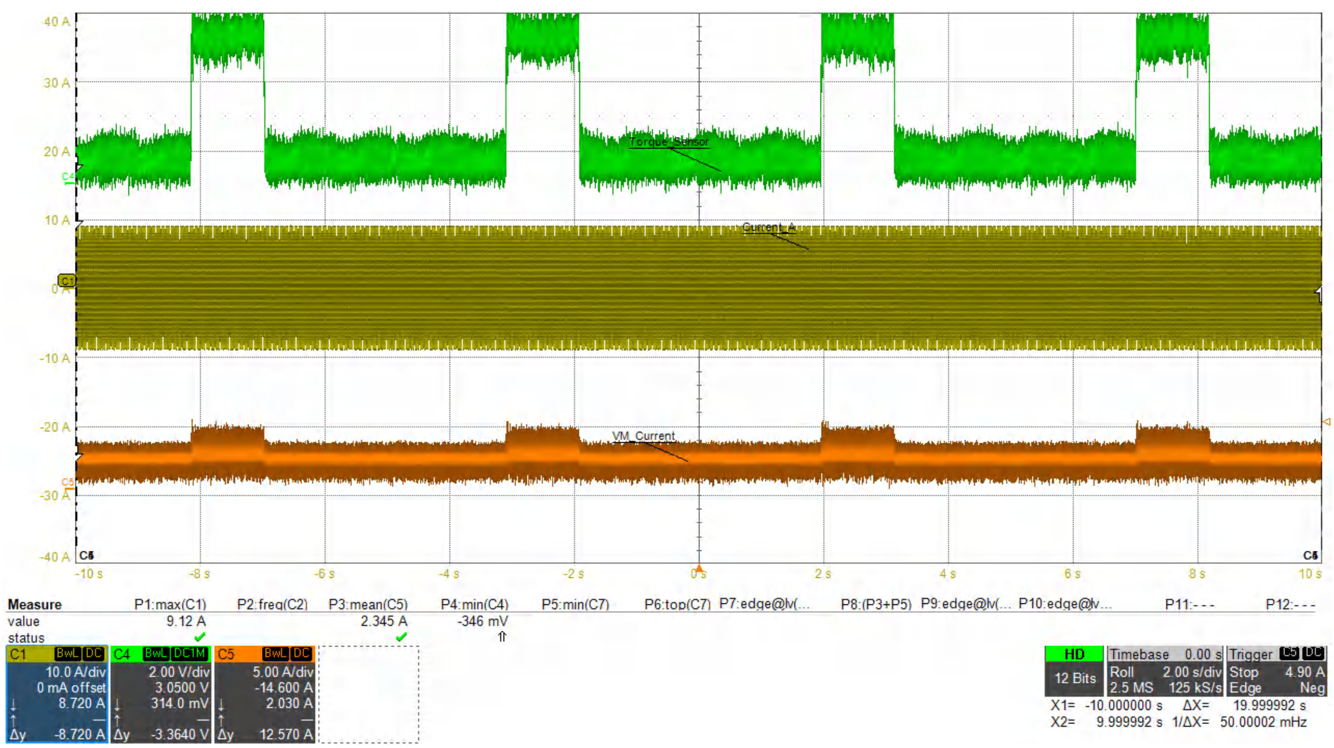


Figure 3-8. Textile Motor Loading/Unloading Without Auto-Torque

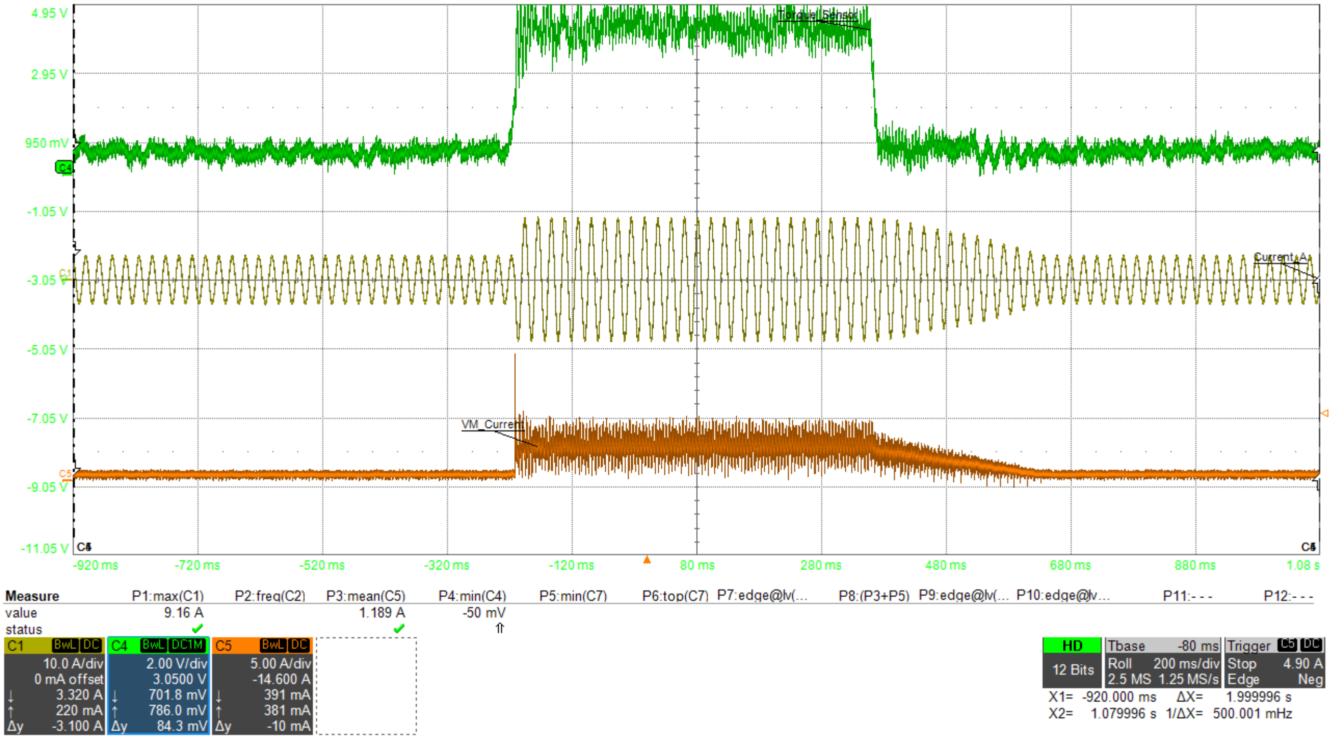


Figure 3-9. Textile Motor Loading/Unloading With Auto-Torque

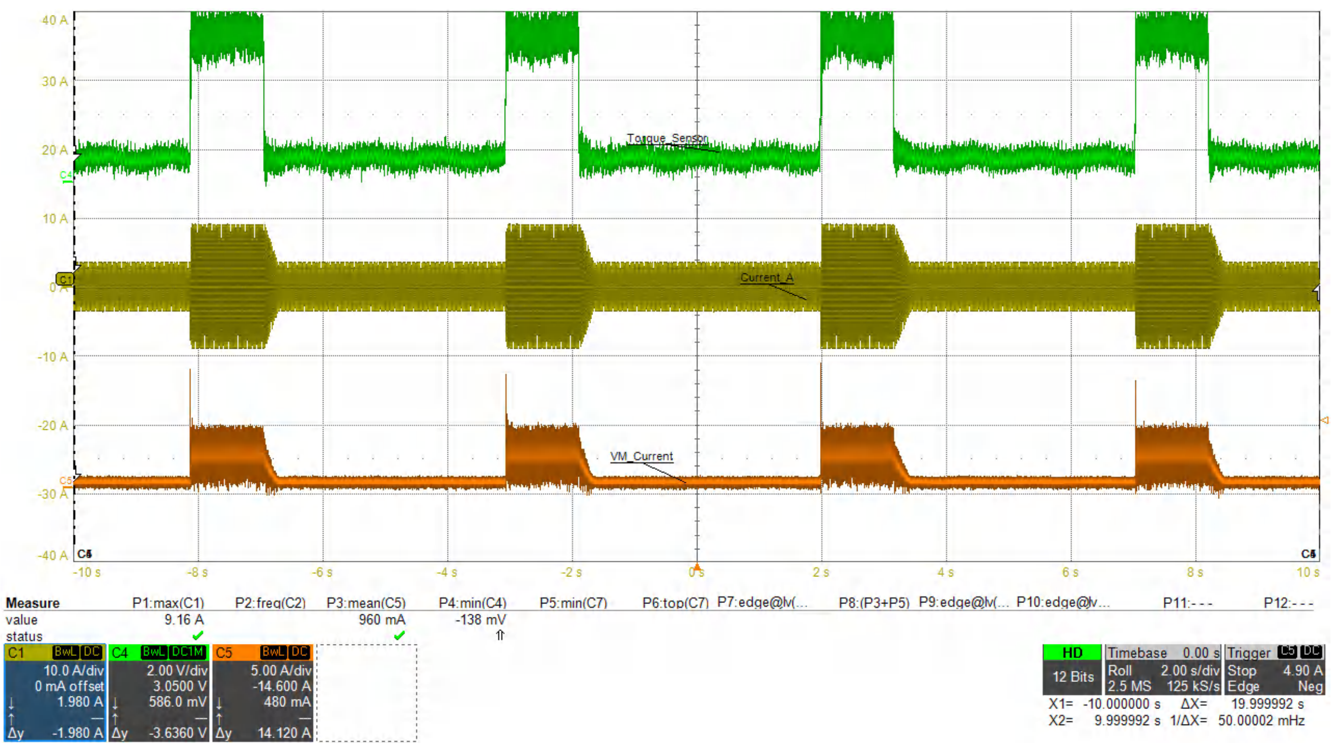


Figure 3-10. Textile Motor Loading/Unloading With Auto-Torque

Based on lab measurements:

- Power consumed without auto-torque = 24 V * 2.345 A = 56.28 W
- Power consumed with auto-torque = 24 V * 960 mA = 23.04 W
- This represents a power saving of 59 %.
- Power loss in the motor without auto-torque = (9 A * 9A * 0.15 Ω) = 12.15 W
- Power Loss in the motor with auto-torque = (0.2 * 9 A * 9 A + 0.8 * 3.6 A * 3.6 A) * 0.15 Ω = 4 W
- This corresponds to a heat reduction of 67 % in the motor coils.

3.3 Application 3: Printer

A typical home inkjet printer draws about 4 W in standby and 40 W when printing. Large office printers draw almost 10 times the power compared to a home inkjet printer. Roughly 50% of this power loss can be attributed to the electronic components. Depending on the complexity of the model, a printer can contain 2 to 15 stepper motors. Auto-torque can significantly reduce the power loss and energy consumption when the printer is not in standby, by reducing the coil current whenever the printer is not printing papers.

All major imaging equipment manufacturers follow Energy Star standards for their products. Sustainable green printers are increasingly becoming the norm in the marketplace. There are instances where a printer which uses 60% less electricity than the company's other models, has become the number-one seller despite cheaper options on the market.

3.3.1 Printer Motor With Auto-Torque

In this application, a 1.5 A rated stepper motor used in printers was subjected to load torque transients and the motor speed was simultaneously changed, to mimic the conditions for a typical printer.

Figure 3-11 and Figure 3-12 showcase the output current and supply current waveforms with and without auto-torque.

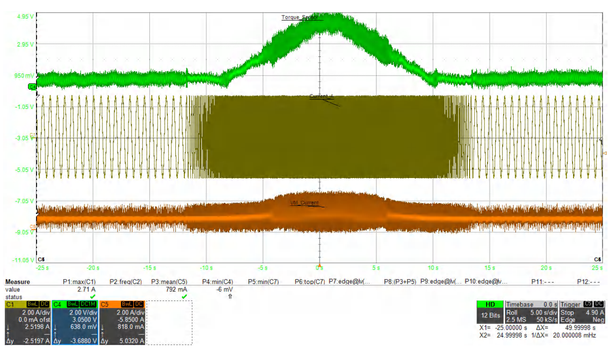


Figure 3-11. Printer Motor Loading/Unloading Without Auto-Torque

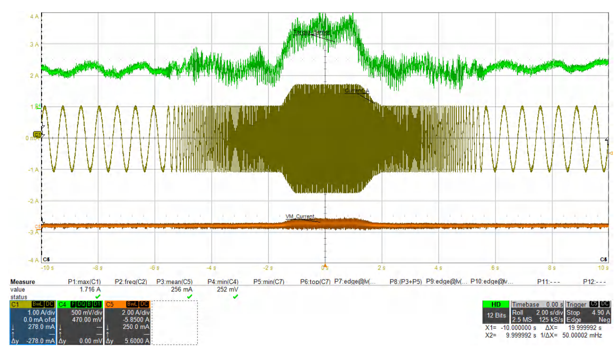


Figure 3-12. Printer Motor Loading/Unloading With Auto-Torque

4 Summary

State-of-the-art auto-torque algorithm in the DRV8462, DRV8452 and DRV8461 motor drivers from Texas Instruments significantly reduces the power loss in stepper motor systems, while ensuring that the motor does not experience step loss. The algorithm is highly configurable to the needs of a specific application. By reducing the power loss in stepper motors and motor drivers, auto-torque helps equipment manufacturers achieve their power loss budget and energy star certification.

5 References

- Texas Instruments: *DRV8462: 65 V, 5-10 A Stepper Motor Driver for High Efficiency and Noiseless Operation Data Sheet*
- Texas Instruments: *DRV8452: 50 V, 5 A Stepper Motor Driver for High Efficiency and Noiseless Operation Data Sheet*
- Texas Instruments: *DRV8461: 65 V, 3 A Stepper Motor Driver for High Efficiency and Noiseless Operation Data Sheet*

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