How smart tune regulates current in stepper motors

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Finding a decay scheme that works for a stepper motor system is time-consuming and involves trade-offs. The right setting depends on various factors such as supply voltage, current being regulated, motor characteristics, motor speed and back electromotive force (BEMF). The fixed-decay scheme selected can become suboptimal over time as the battery supply voltage lowers, motor characteristics change, and so on, and does not handle BEMF well. This paper introduces smart tune, a plug-and-play decay scheme implemented in Texas Instruments stepper motor drivers. The scheme works in real time and automatically selects the optimal decay setting. By constantly adapting to changes in the system, this scheme results in quieter, smoother and more efficient motor operation, eliminating the need for any tuning.

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1 Stepper motor operation

Stepper motors are very common in applications needing position control without requiring feedback sensors (open loop control). Automated teller machines (ATMs), surveillance cameras, printers, scanners, robotics and office automation are just a few applications using stepper motors

A stepper motor has electromagnets to control its movement. To make the motor shaft turn, the electromagnets are energized in a controlled manner using a driver integrated circuits (IC). Figure 1 shows a stepper motor with two coils being driven by a stepper motor driver.

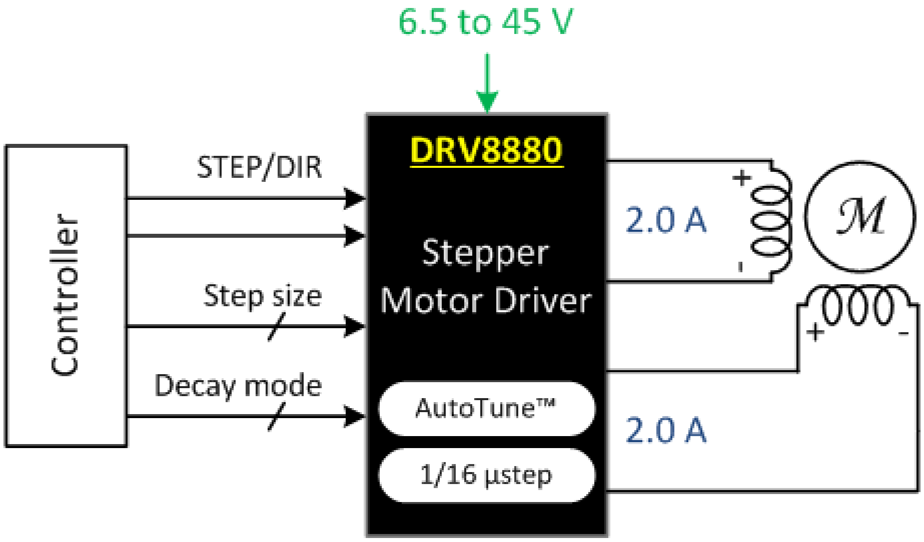


Figure 1. Example of a stepper motor system

The current through the two coils are controlled to generate a sinusoidal profile that is 90 degrees out of phase with each other, as shown by the blue and red waveforms in Figure 2. Each step is associated with a certain amount of current through each coil and results in a particular position of the motor. With each step, the driver advances the current profile to move the motor to the next step.

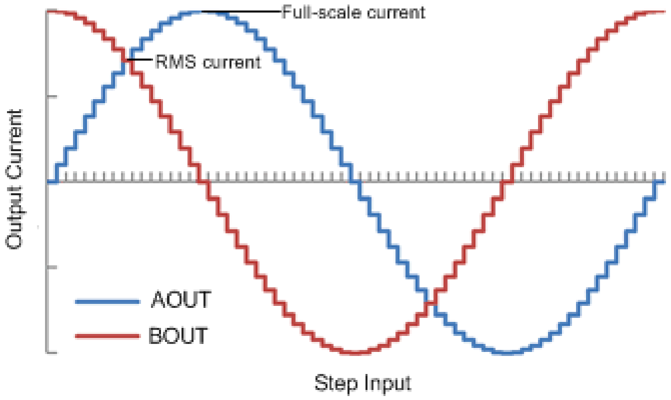


Figure 2. Current profile of the two coils of a stepper motor

2 Current regulation and decay modes

Each coil is usually driven by an H-bridge circuit, as shown in Figure 3. During drive, a high-side field-effect transistor (FET) on one side of the coil and a low-side FET on the other side of the coil are turned on (path 1 marked in Figure 3).

Ignoring BEMF, if the current is not regulated, the current can build up quickly to VM / R and damage the motor and driver IC.

To regulate the current, the method used is commonly referred to as decaying the current or recirculation of the current. Three decay modes are most commonly used.

1. Fast decay: The H-bridge reverses the voltage across the coil (path 2 in Figure 3). This results in a current decay rate, which is same as the charge rate.
2. Slow decay: Current is recirculated using the two low-side FETs (path 3 in Figure 3), which results in a slower decay rate than fast decay.
3. Mixed decay: Fast decay is performed first followed by slow decay.

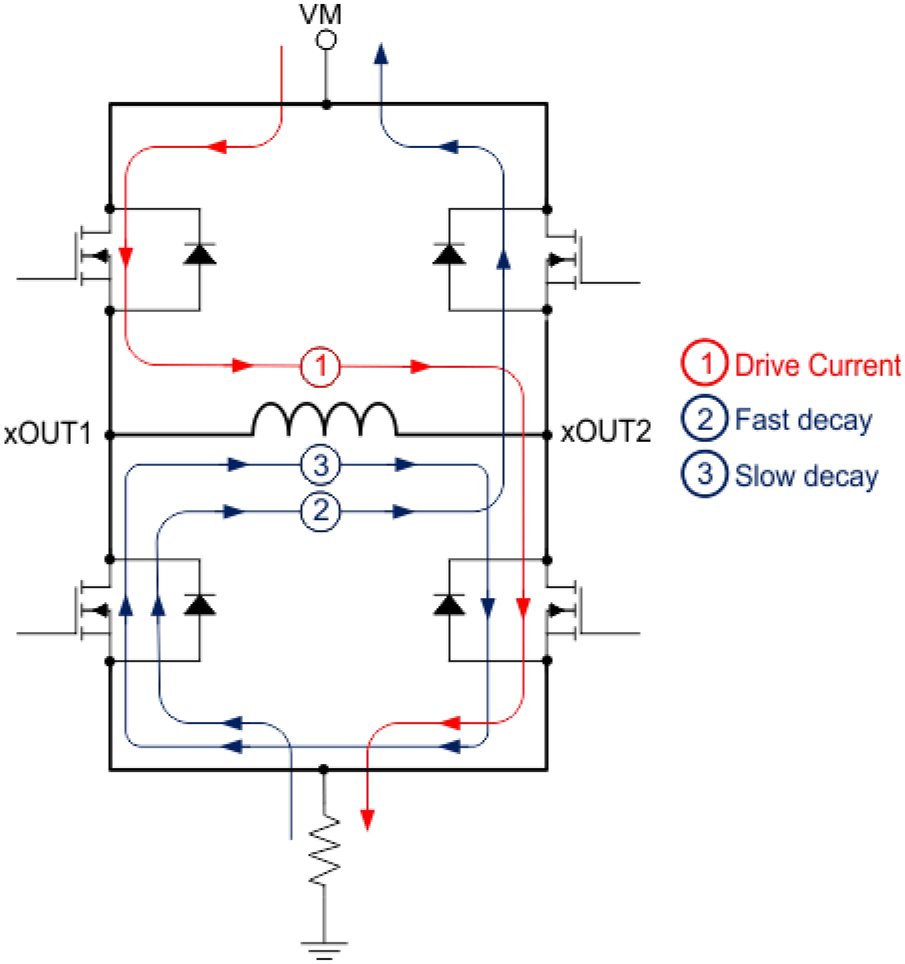


Figure 3. H-bridge circuit showing drive and decay current paths

3 Limitations with fixed-decay schemes

The ideal decay setting depends on the supply voltage, motor characteristics, current being regulated, motor speed, BEMF, and the like. Many times, these parameters change, which poses a challenge for fixed-decay schemes. Careful and time-consuming tuning is necessary to pick the appropriate decay setting by observing the current profile on an oscilloscope. Trade-offs have to be made because the decay mode that is best for reducing ripple is not the best decay scheme to regulate small current. Even when one decay mode is selected, the setting can become sub-optimal as the situation changes (battery supply lowers, motor characteristics change, step frequency changes, and so on). Following are some of the trade-offs and limitations of fixed-decay schemes:

- Slow decay is not ideal for regulating low levels of current. Often, the decay rate cannot discharge the current built up during the minimum motor on time, resulting in current run-off. Figure 4 shows motor current run-off while using slow decay at low-current levels. In this case, fast decay is preferred. However, while regulating larger current, fast decay results in larger ripple due to the charge/discharge rate being the same.
- For faster step response, fast decay is preferred. However, once holding current is reached, this results in undershoot and larger ripple. Slow decay is preferred for reducing ripple, but results in longer step response time.
- For battery-powered applications, the initial decay setting can become sub-optimal as supply voltage drops.
- As the motor resistance change due to temperature change or other factors, the initial decay setting will need to be tweaked.
- Fixed-decay schemes do not handle BEMF well.
- Fixed-decay schemes can result in repeated patterns in current regulation that fall in the audible frequency range, resulting in a noisy motor operation.
- A slow-decay setting is more efficient, but has drawbacks of longer step response, the inability to hold low current, and so on. Fast decay solves these problems, but is less efficient due to switching losses and has more ripple.
- Time-consuming manual tuning is needed for each system to find a decay setting that is acceptable. Re-tuning is necessary when any parameter changes in the system (new motor, changing motor speed, supply voltage change, to name a few).

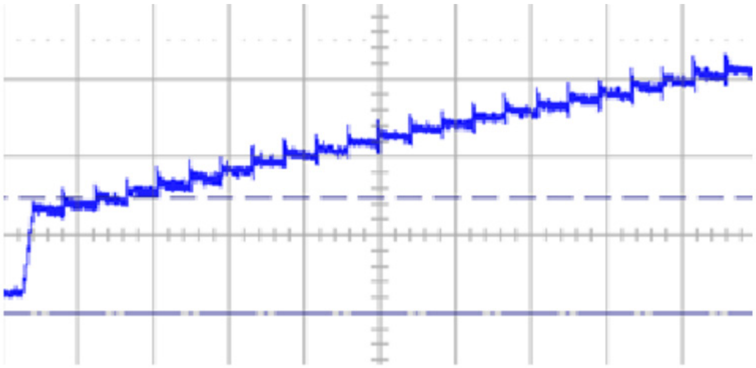


Figure 4. Losing current regulation due to slow decay at low current.

4 Preferred solution

All of the aforementioned trade-offs and limitations with fixed-decay schemes point to the need for a decay scheme with the following characteristics:

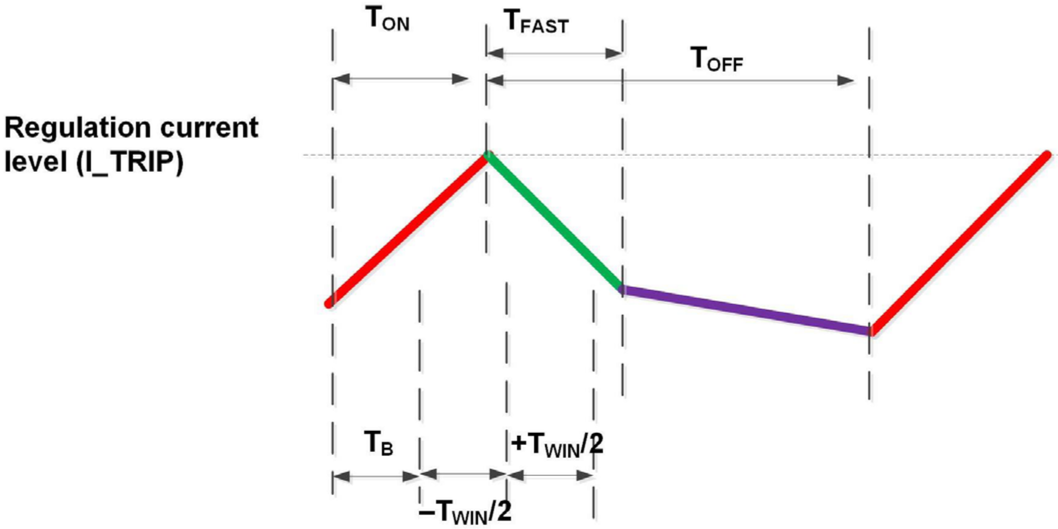
- A plug-and-play scheme that can automatically figure the optimal decay scheme, eliminating the need for time-consuming tuning.
- An adaptive scheme that can keep adapting to changing parameters in the system like supply voltage, motor characteristics, regulation current, motor speed, BEMF and many others.
- Decoupling of step response and holding behavior to optimize overall system performance. What is

ideal for faster step response is not what is ideal for holding a current and vice versa.

5 smart tune

smart tune is an automatic tuning mechanism for decay. This real-time tuning incorporates decay locked loop (DLL). Much like the well-known phase-locked loop (PLL), whose feedback mechanism converges on a predetermined output clock frequency, a DLL converges on a preset drive time (Ton) for the desired current level (I_TRIP) to occur in a pulse-width modulation (PWM) cycle. Once the DLL achieves lock and the time to I_TRIP is fixed, the subsequent Toff is always pre-fixed to ensure that every subsequent PWM cycle time is exactly the same. Since the PWM cycle times are the same, sub-harmonic oscillations can be avoided and all the PWM switching activity can be kept above audio frequency. This makes the motor operation smooth and significantly quieter

Some definitions and breakdown of the time within a PWM cycle are shown in Figure 5. smart tune uses DLL to converge to a precise decay solution needed to make each and every PWM cycle repeatable.



$T_{B:}$ Blank time or minimum on time
T_{ON}: Total drive time
T_{WIN}: Tuning control window
T_{OFF}: Total decay time
T_{FAST}: Fast decay time

Figure 5. PWM cycle with definitions of parameters used in algorithm

In order to do this, DLL uses two feedback control loops. The first is a coarse control loop (CCL) that reacts to sudden changes in load current or step change demands. The next is a fine control loop (FCL) that gradually fine tunes the Tfast time within a fixed Toff. The two loops are depicted in the block diagram in Figure 6.

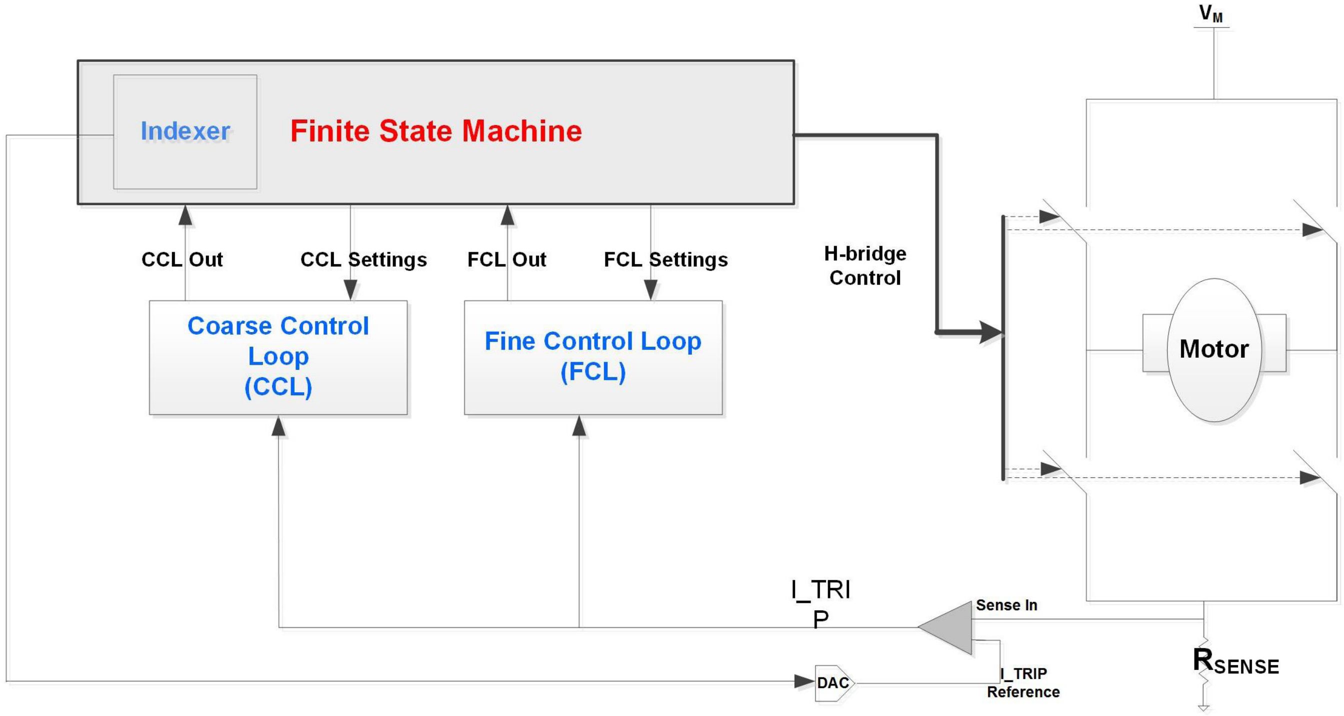


Figure 6. Smart tune block diagram showing CCL and FCL

6 Coarse control loop tuning algorithm

The coarse loop looks to see if the I_TRIP happens within the twin-time window. If it does, then no action is taken and FCL takes over. But, if I_TRIP falls outside the twin window, then CCL increases or decreases the fast decay (Tfast) until it brings the I_TRIP inside the twin window.

The CCL will get the system close to a locked solution state, but it is not enough on its own, which is why the fine control loop may be needed.

7 Fine control loop-tuning algorithm

The FCL defines a window twin in time after the Ton_min and forces the I_TRIP to happen at (Ton_min + Twin/2) by incrementing or decrementing the amount of fast decay (Tfast) in the fixed off-time (by extension changing the amount of slow decay). The fine adjustment happens after the coarse setting has been found. The loop will continue to increment or decrement Tfast until target I_TRIP time is achieved. At this time, the loop has reached the decay-lock condition with an ideal decay solution and the loop has reached steady state.

8 DLL reaction to disturbances in load current

If a disturbance should happen to the loop, it will automatically adjust by changing the Tfast through incrementing and/or decrementing until decay-lock is again re-established.

If the I_TRIP ever happens outside of the twin, then the loop knows that a coarse adjustment is needed and it will go either way that is required, depending on the nature of the loop conditions. After the coarse adjustment, the fine loop will kick in once again and reestablish decay lock.

9 The need for both CCL and FCL

CCL is needed to react quickly to large changes in load current resulting from mechanical load changes or BEMF or change in current regulation step.

FCL is needed because the large steps in the CCL make it very unlikely that the exact amount of decay will be achieved with only a coarse adjustment. If only CCL is used, then the loop would likely jump back and forth between two coarse settings every other PWM cycle because it cannot achieve the perfect decay solution that lies between the coarse settings. This back-and-forth jump creates harmonic content in the spectrum of the output current, which could fall in the audio band and generate undesirable noise.

The FCL in conjunction with the CCL is what enables the DLL feedback system to achieve an exact solution given a reference time, much like a PLL.

Figure 7 shows subharmonics in the audio band with only CCL used. Figure 8 shows that while both CCL and FCL are used, subharmonics in the audio band are eliminated.

Figure 7. Time domain and frequency domain plots using CCL only

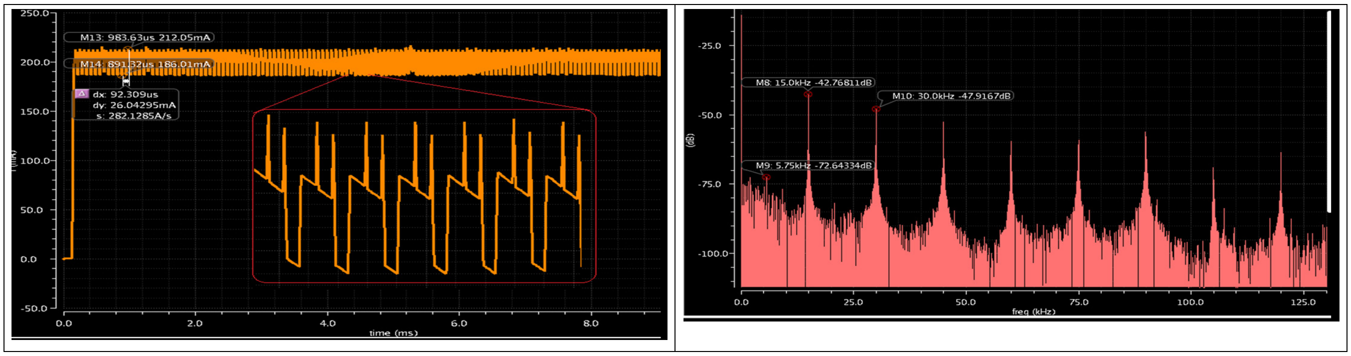
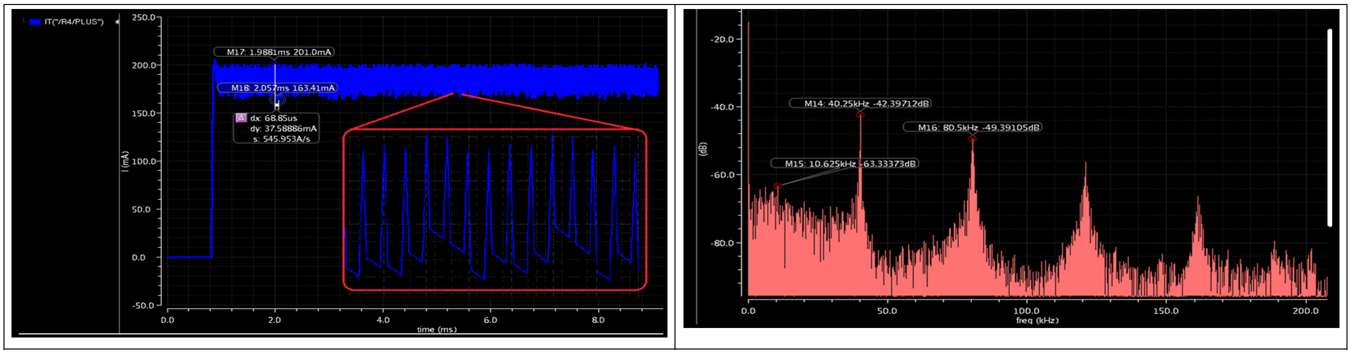


Figure 8. Time domain and frequency domain plots using both CCL and FCL



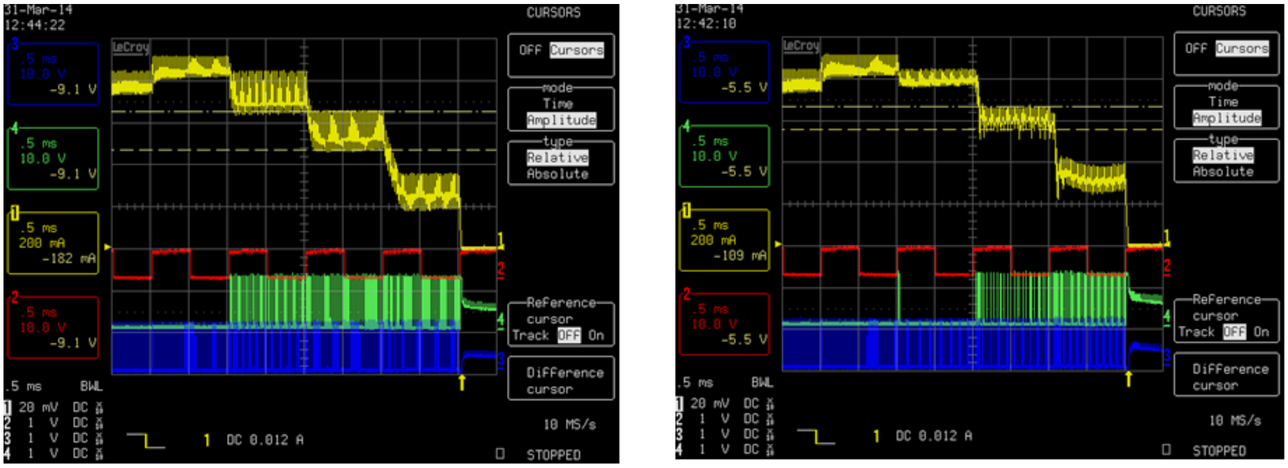
10 Advantages of smart tune

There are many advantages to smart tune. For example, this solution results in lower audio noise, as highlighted in Figure 8. Plug-and-play operation means that no tuning is needed.

Lower ripple is achieved, as shown in Figure 9, compared to fixed-decay schemes. Ripple is minimized by converging to a decay solution that tends to maximize the use of slow decay time in any given PWM cycle.

By reducing the ripple, higher levels of microstepping is now possible with smart tune. smart tune quickly adapts to a higher level of fast decay (Tfast) as a response to an input STEP command. This results in a quicker step transition response. Once the STEP transition is complete, Tfast is scaled back to ensure low ripple performance.

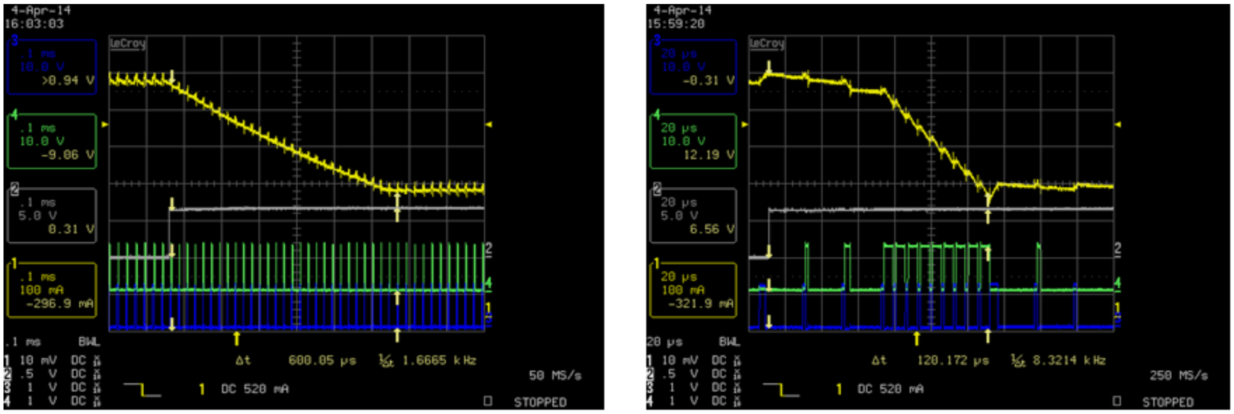
Figure 10 shows much shorter transient response with smart tune compared with mixed decay. Spinning motors create BEMF which can disrupt current regulation.



Fixed-mix decay setting of 25 percent of 182 mA of ripple

Smart Tune keeps the average ripple of 109 mA.
This also makes AutoTune more power-efficient.

Figure 9. Smart tune has much lower ripple compared with mixed decay



Fixed Tfast of 15 percent takes 600 uS for step transition.

Step response with Smart Tune enabled is 120 uS.

Figure 10. Shorter step response time with smart tune compared to mixed decay

smart tune dynamically corrects for this and maintains steady current regulation as shown in Figure 11.

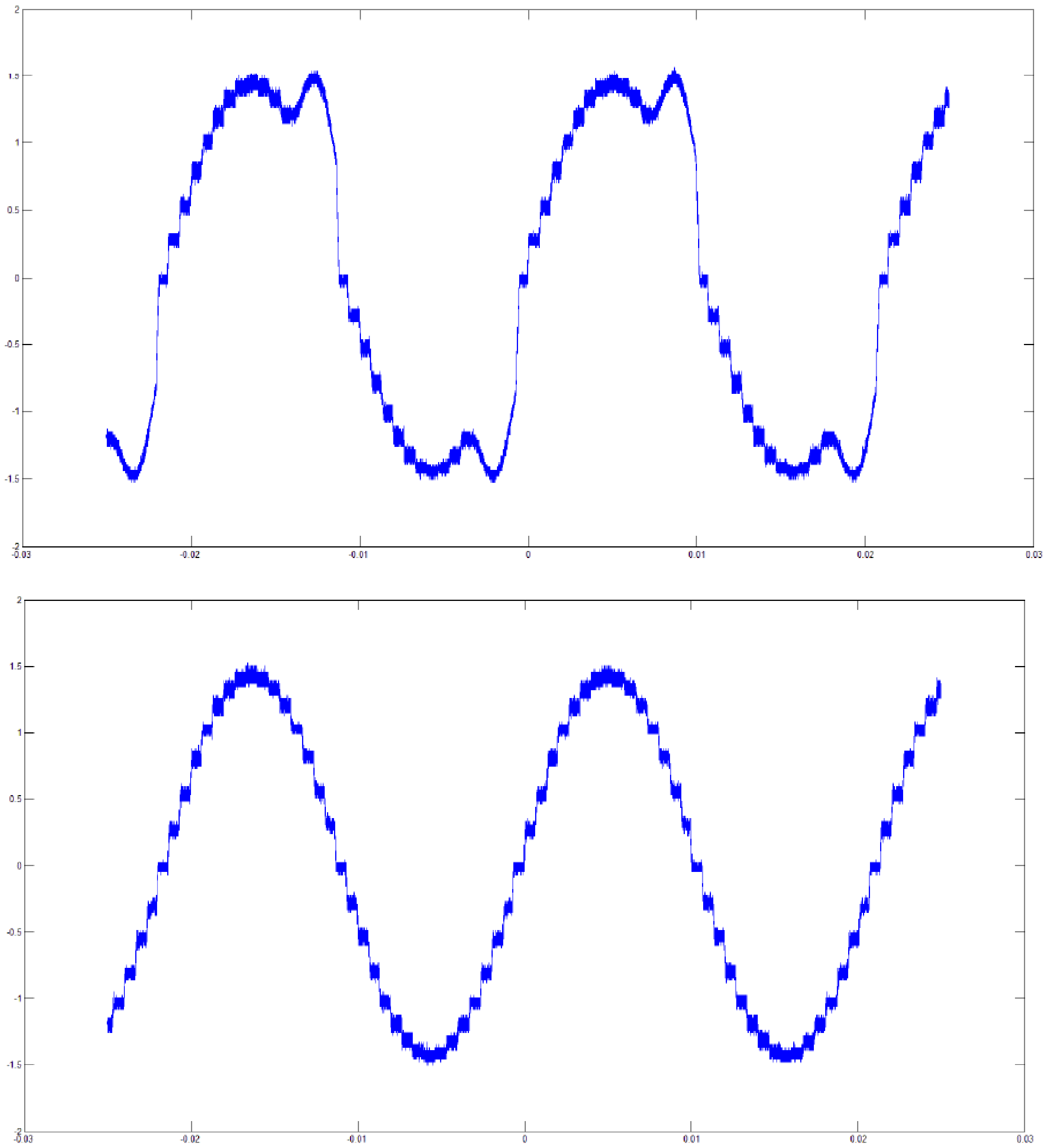
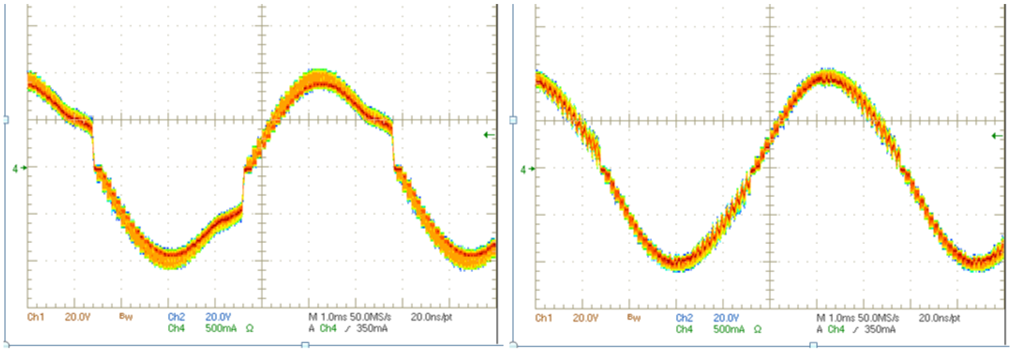


Figure 11. Good taming of BEMF using smart tune (bottom) compared to mixed decay (top)

smart tune finds the optimal decay solution for both large and small currents. This eliminates any distortion in the sinusoidal micro-stepping current profile. Figure 12 shows distortion at low-current levels with mixed decay



Fixed-decay with Tfast = 30 percent is unable to regulate small current, resulting in distortion near zero cross.

Smart Tune finds the right decay solution for both large and small currents. There is no zero cross-distortion present with AutoTune.

Figure 12. Distortion at low current eliminated in smart tune

At the heart of smart tune is the decay-locked loop, which automatically and optimally regulates any current, regardless of supply voltage variation, load changes, and varying BEMF. This results in a smoother, quieter and more efficient operation of the motor.

11 Summary

Tuning a stepper motor is time-consuming and involves making trade-offs between parameters such as ripple, step response, ability to regulate small current and efficiency. Fixed-decay schemes have limitations – audible noise, inability to handle BEMF well, and the need to re-tune if system parameters change or when a motor ages. smart tune, a dynamic plug-and-play scheme discussed in this paper, incorporated into TI’s new generation of stepper parts like the DRV8880 eliminate the need for tuning the motor entirely

12 References

- DRV8880 2-A Stepper Motor Driver With smart tune, datasheet
- Motor drivers Product Tree

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