Application note:
Low noise voltage PWM chopper with TMC236/TMC239 driver family

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This application note shows a chopper principle which can be used for high resolution drives, where extremely quiet and smooth motion a low velocities (below the first motor resonance frequency) is desired. The scheme uses a processor for driving the motor via two of its internal PWM units, rather than using the driver's internal cycle based chopper system. This low noise driving scheme is also used by the TMC332 for two- and three phase motors as well as on TRINAMIC modules TMCM-013, IDX and TMCM-078. A simple implementation can easily be done by a programmer on a microcontroller as described here.

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2 Basic Concept of Voltage PWM Chopper

Most stepper motor drivers use a cycle-by-cycle based chopper system, because it brings the best performance over a wide range of velocities. It regulates the current by terminating each chopper cycle as soon as the target current has been reached. This direct current regulation provides best dampening of motor resonance, lowest motor power loss and best velocity independently maximum torque using a modern chopper principle like TRINAMICs spreadCycle™. On the other hand, chopper stability requires good decoupling between both motor coils and it needs a precise layout of the high current paths. Instabilities caused by magnetic coupling in the motor or by coupling of the coil current regulators due to electric coupling can lead to chopper noise and fine vibrations. Under normal conditions, these will not do any harm. In some applications, where the motor moves very slowly or where precise standstill with low mass on the motor axis is required, a voltage PWM chopper is a good choice.

The low noise feed forward chopper principle described in this application note uses a voltage PWM controlled driving principle rather than current controlled driving. This is possible, because the stepper motor has a certain coil resistance. Its resistance converts an externally applied voltage to current. As long as the motor velocity is low, back EMF caused by the motor rotation does not need to be taken into account. At increasing velocities, the motor's back EMF has an increasing influence and influences coil current. This can be compensated for by increasing the driver voltage with increasing velocity. Effects like motor temperature dependency of the coil resistance should be taken into account, in case the motor operates in an increased voltage range. The described compensation principle can be realized in a completely feed-forward way, based on the motor data, or by measuring the effective current and adding a regulation loop.

The chopper principle described generates a certain motor voltage by toggling each motor phase with a certain PWM frequency. Therefore the motor full bridges either switch on the motor current in one direction or in the opposite direction. This way, the duty cycle of toggling the coil polarity produces a certain effective voltage on the coils. A 50 percent duty cycle gives a mean current of zero, while a higher or lower duty cycle gives a positive or negative current. A high PWM resolution will bring high microstep resolution.

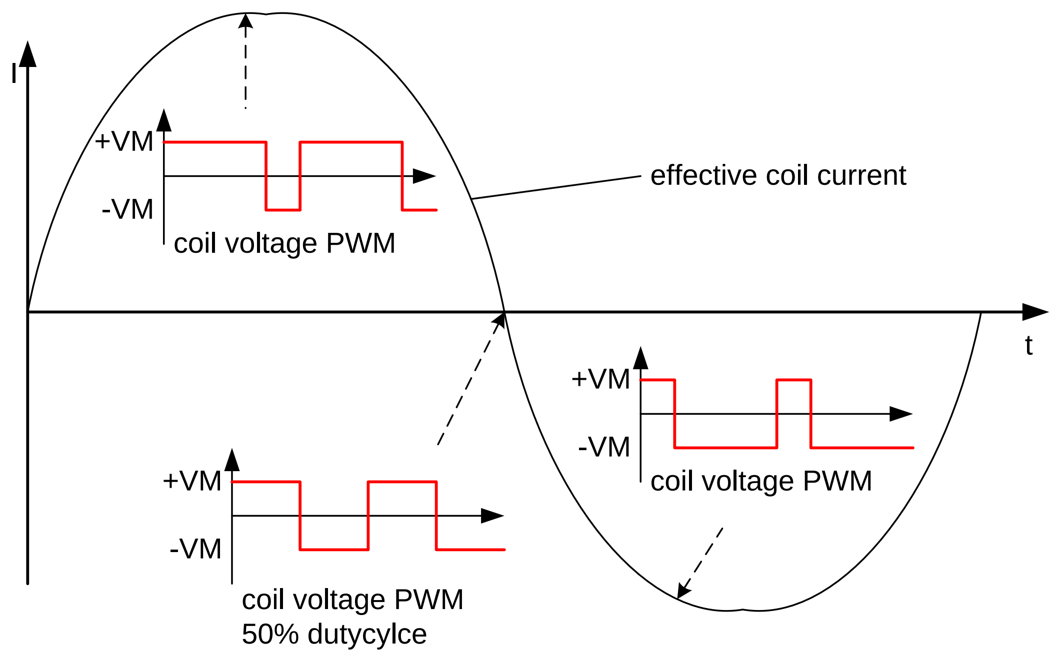

figure 1: Voltage PWM generates motor current

2.1 Understanding relevant motor parameters

As a first step, you should understand which parameters have a direct or indirect influence on the chopper settings, and thus should be selected before starting optimization.

Parameter	Description	Setting
Driver supply voltage	Motors cannot operate well below or above their specific voltage limits. However, in voltage PWM mode, the rated motor voltage should be not much higher than the driver supply voltage, because chopper ripple and power dissipation will increase with higher supply voltage, and at the same time available PWM resolution will decrease.	As a guideline, satisfy: R_{COIL} * I_{COIL} < VS < 5 * R_{COIL} * I_{COIL} and current ripple < 50% (see chapter 3.2)
Motor coil current	Normally, stepper motors work best at their nominal current, as they provide the highest torque and lowest relative torque ripple. However, factors which might lead to operation at reduced current levels are 1. Reduction of power dissipation 2. Standby operation	As a guideline operate a stepper at 50% to 100% of nominal current. A short time increase using coolStep™ will provide for extra torque, while the nominal current can be reduced. In standby, current can be reduced down to zero, depending on mechanics and application.
Velocity	Voltage PWM mode is optimum for low velocities well below the resonance frequency.	A motor velocity from standstill to a few 10 fullsteps per second is optimum. At velocities above 50 or 100 fullsteps per second, severe resonance issues can occur.
Chopper frequency	The chopper frequency is determined by many parameters. Basically, it usually should be outside the audible range, i.e. above 16 to 20kHz, but not too high, i.e. below 50kHz, in order to limit switching losses in the motor and the power driver. In voltage PWM mode, a high PWM resolution is mandatory. This is best, when the PWM frequency is as low as possible. On the other hand, current ripple increases with lower frequency and will cause higher power dissipation in the motor. Due to this, it is best to use a motor with comparatively high inductivity, in order to keep required chopper frequency low.	Try to keep chopper frequency low, but above the audible range.
Waveform	For most stepper motors a sinusoidal waveform is a good approach. Specific applications requiring most equidistant microsteps may profit from an adapted microstep waveform.	The waveform can be best optimized when using a high resolution encoder or a laser pointer attached to your motor and moving the motor at very low velocity.

table 1: Parameters which should be considered before optimizing chopper settings

2.2 Calculating the PWM

A microcontroller or an FPGA can be used for generating the two PWMs required to drive the motor. For 256 microstep resolution, a PWM resolution of 9 to 10 bit is required. Assuming a target chopper frequency of roughly 20kHz, a base clock frequency of 20MHz (=2^{10} x 20kHz) is required to yield a 10 bit PWM. A 16MHz clock frequency will allow realizing a 9 bit PWM with 31kHz, or a resolution of 800 PWM steps with 20kHz. This is a feasible value for most standard 8 bit or better microcontrollers.

Basically, one motor coil is driven with a PWM, which duty cycle is modulated using a sine wave. The other coil with a cosine modulated PWM. Assuming, that the system supply voltage would exactly match the motor voltage required for nominal current, the PWM duty cycle would be altered between 100% for maximum positive current and 0% for maximum negative current. As this is not a typical constellation, the PWM modulation required to match the motor needs to be calculated:

$$PWMAmpl = I_{COILpeak} \frac{R_{COIL}}{(V_M - V_{BEMF})}$$

where

- PWMAmpl is the PWM amplitude required to reach the nominal motor current. Half of this amplitude is applied in positive direction (additional to 50% duty cycle), and half of it is applied in negative direction (subtracted from 50% duty cycle)
- $I_{COILpeak}$ is the nominal peak coil current of the motor, i.e. $I_{COILRMS}$ * 1.41
- R_{COIL} is the resistance of the motor coil
- V_M is the motor driver supply voltage (may be measured in the application)
- V_{BEMF} is the velocity dependent back EMF voltage of the motor. It is measured in V/rad/s. At standstill V_{BEMF} is zero, and it can be ignored for low RPM. For higher velocities, multiply it by the angular velocity of the motor.

Example: A 1A RMS motor with 6.5Ohm coil resistance is to be operated from a 12V supply at low velocity.

$$1A * 1.41 \frac{6.5\Omega}{(12V - 0V)} = 0.76$$

Therefore, the duty cycle needs to be modulated between 0.5+0.76/2=88% for the positive sine wave peak and 0.5-0.76/2=12% for the negative sine wave peak.

3 Practical Solution using the TMC23x / TMC24x family drivers

3.1 Schematics

The TMC236 / TMC239 / TMC246 / TMC249 drivers provide a stand-alone mode, which allows direct control of coil polarity using a digital signal and control of coil current using an analog voltage in the range 0V to 3V. As current control is done by PWM duty cycle in this application, the integrated PWM based analog current control of the IC is not used. Therefore, in principle it would be possible to work without sense resistors. But the analog current limit is good for use as a safety feature, or to allow falling back to classical fullstepping at higher motor velocity, in order to also allow faster movements. During voltage PWM mode the analog current control can be used to limit the motor current in case of an error. Therefore, the current limit must be set at least 20% to 30% higher than the desired maximum motor current for PWM operation (peak current value plus additional ripple). The mixed decay mode must be switched off (MDAN=MDBN=VCC), because it would interfere with voltage PWM operation. Both motor coil limits thus can be set to the same analog current limiting value, both for safety limit and for fullstepping. In fullstepping switching to a lower value may be desired in order to match motor RMS current. Please see the chip manual for calculating the fitting sense resistor and analog input voltages values in order to choose the correct resistor values. The processor controlled PWM uses the polarity inputs (PHA, PHB) for both coils to control motor PWM.

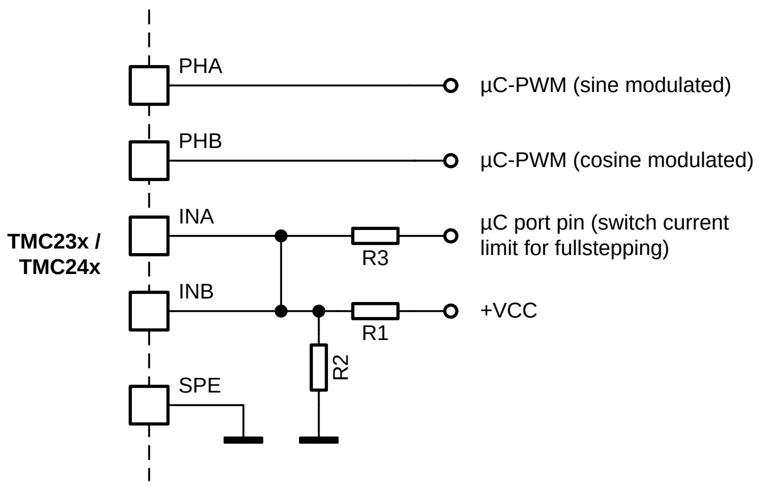

figure 2: Controlling the driver with two PWMs in standalone mode

3.2 Reasonable combinations of supply voltage and motor data

While the lower driver supply voltage limit is given by coil resistance multiplied by coil peak current, experiments have shown that the combination of motor current and inductivity limits the maximum driver supply voltage.

A good chopper frequency range is 18 to 30kHz in order to be safely outside the audible area, while keeping a high PWM resolution. The coil sees a 50% duty cycle at full supply voltage when the coil current is meant to be zero. This is only true for the average, but the motor still sees an alternating current and thus an alternating magnetic field. Assuming 20kHz chopper frequency, the coil is on in a positive direction for 25µs and in a negative direction for 25µs giving a mean voltage of 0V. Now, care has to be taken in order to keep resulting current ripple to a value which is significantly lower than the motor maximum coil current. If it is too high, the motor has significant magnetization losses and coil power dissipation. The motor heats up, even with zero average current. The best possibility to limit this effect is to operate with a comparatively low supply voltage.

Please take the motor inductivity and motor rated full step coil current from the motor's data sheet and calculate motor ripple current for the desired driver supply voltage:

$$I_{RIPPLE} = \frac{V_M * t_{CHOP}/2}{L_{COIL}}$$

where

- t_{CHOP} is the chopper time, i.e. $1/f_{CHOP}$
- V_M is the driver supply voltage
- L_{COIL} is the motor coil inductivity

It should be satisfied:

$$I_{RIPPLE} < 0.5 * I_{COILRMS}$$

This way, the ripple current is not higher than half of the RMS current, which is the acceptable upper limit for most motors. An example for different supply voltages is shown in figure 3. You can look up the motor coil current on the x-axis and find the lower coil inductivity limit for the desired supply voltage. If your motor does not have sufficient inductivity, you either need to use a different motor, e.g. higher voltage type, or use a reduced supply voltage. A velocity dependent supply voltage setting also would be a valid solution.

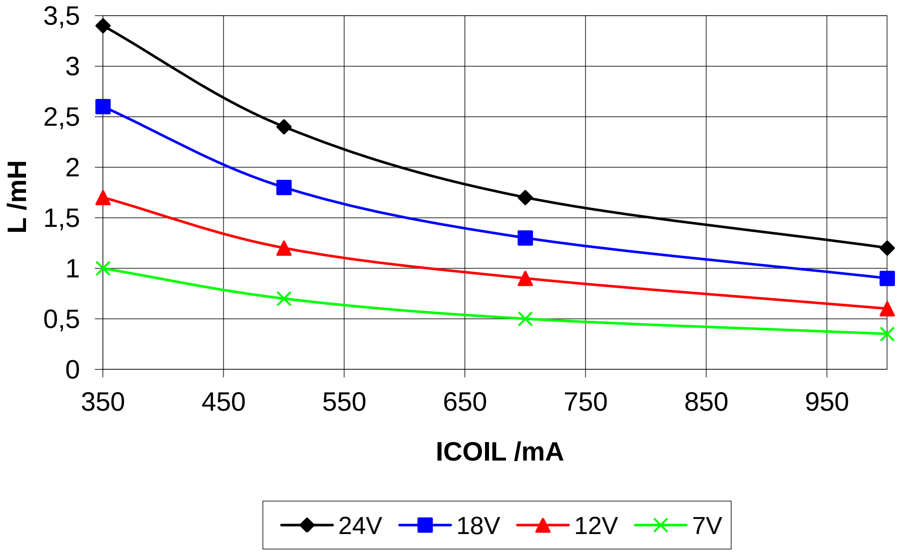

figure 3: Sample current and voltage dependent lower coil inductivity limit for a 20kHz chopper

4 Comparison of Performance to a Native 256 Microstep Driver IC

4.1 Audible noise

A cycle based chopper system most likely generates audible noise even in motor standstill, as there is always any kind of electric noise present when measuring a signal and reacting to it. There is always some electric coupling between motor coil choppers (which optimally should run independently) due to coupling caused by PCB layout, coupling via supply voltage ripple and magnetic coupling of the motor coils. This causes a slight disturbance of both motor coil currents, as they start interacting with each other. The resulting loop may cause a modulation of coil currents with a frequency below the chopper frequency. The coil currents thus see small components of ripple within the audible frequency range and the motor sounds a bit like chirping and whining, mostly barely audible. Finding the best chopper settings helps in keeping this noise as small as possible with a given motor. There is much dependency on the motor type and the application, if the chopper noise is audible.

The low noise chopper avoids these sources of noise, by eliminating feedback paths which are susceptible to noise. This way, the coils see only the base chopper frequency.

4.2 Microstepping performance

It is clear, that absolute microstep performance depends a lot on the motor type when using pure sine wave drive. Generating the PWM in a microcontroller gives you the possibility to adapt the microstep curve to the motor type, or even to the actual motor by eliminating production stray. Therefore, you can modify the voltage wave as required to give best microstep equidistance. This gives some advantage over using the TMC26x family in step & direction mode, where the wave cannot be modified except for adding an offset. The sample setup compares a voltage PWM mode drive (TMCM-078) with a TMC260 board, using the same motor attached to an encoder.

In figure 4 a trace of the motor coil current in one coil in slow motion is shown. The waveform used is a sine wave, but the resulting coil current shows distortion in zero crossing. This distortion results from break-before make times of the driver stage altering the PWM duration slightly. The change in PWM duration depends on the actual current direction, thus zero crossing shows most distortion. A shorter break-before make time in combination with a lower chopper frequency reduces these distortions. But still, the motor moves smoothly. When comparing microstepping equidistance of the low noise chopper (figure 6) to a spreadCycle driven motor (figure 7) it becomes clear, that the current impurity visible in figure 4 causes some ripple in microstepping equidistance, as it deviates from the optimum, diagonal straight curve. This ripple could be eliminated by adapting the waveform.

In figure 5, chopper events are shown and the resulting ripple on the coil current becomes visible (zoomed).

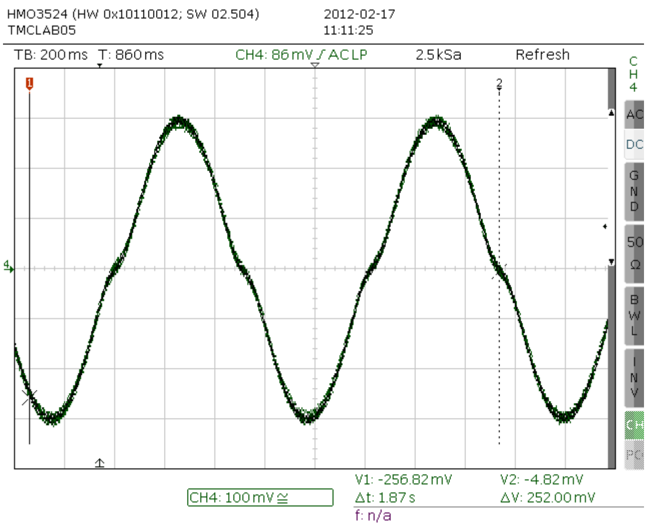

figure 4: Coil current (3A peak)

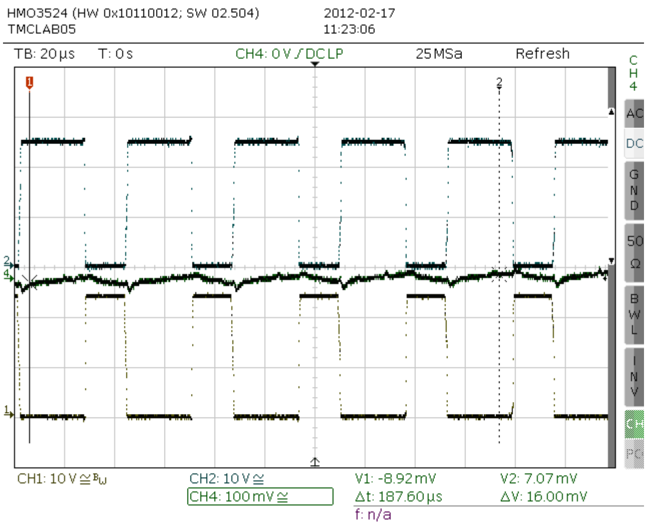

figure 5: Coil current and voltages on coil

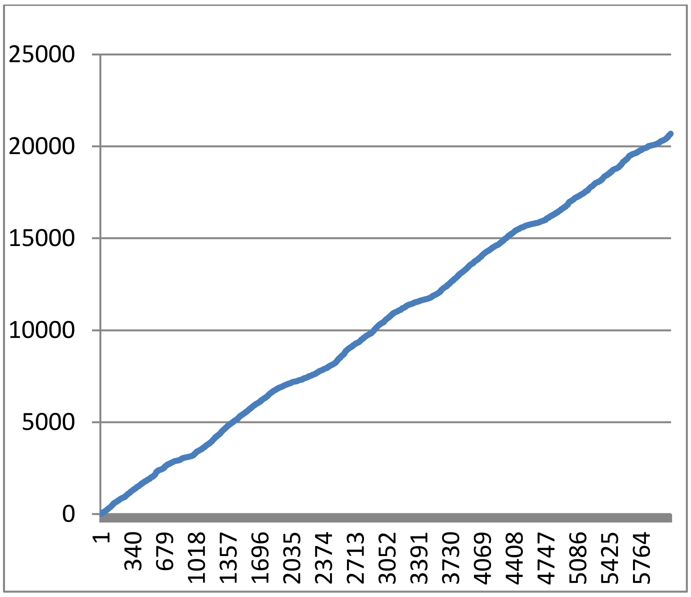

figure 6: Microstepping performance (position over 5 fullsteps) with low noise voltage controlled PWM

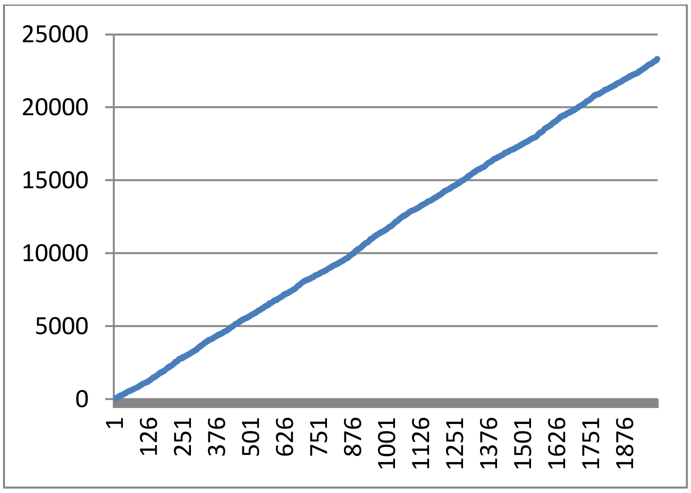

figure 7: Microstepping performance (position over 5 fullsteps) with TMC262 spreadCycle chopper

5 Conclusion

The described chopper principle has the major benefit of generating no chopper noise (see table).

Chopper principle	Low velocity	Medium velocity	High velocity	Motor choice
Voltage controlled PWM	+ Absolutely quiet - Steps not equidistant	- High resonance should switch to different chopper mode	- not possible	- Only high inductive motor
spreadCycle	+ Equidistant steps - Chopper noise and slight vibrations can occur (reduce with chopSync)	+ Best performance	+ Best performance	+ All motor and voltage combinations

6 Revision history

6.1 Documentation revision

Version	**Date**	**Author** **BD=Bernhard Dwersteg**	**Description**
0.1	2012-FEB-24	BD	First version

table 2: Documentation revisions