Application Note AN2229

Multi-Functional Stepping Motor Driver

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Abstract

This Application Note demonstrates how to use the PSoC^{TM} device to build a universal stepping motor controller with minimal external components. This offers a cost-effective solution for many applications.

Introduction

A stepping motor is an electro-mechanical device that converts electrical pulses into discrete mechanical movement. Stepping motors have the following advantages:

- The rotor's turning angle is defined by the number of pulses delivered to the motor.
- A stepping motor provides full torque in stop mode (if windings are powered). This is in contrast to brushed DC motors, which cannot provide full torque.
- Stepping motors have precise positioning and repetition. High quality stepping motors have three to five percent step size precision. This error doesn't accumulate from step to step.
- Stepping motors have quick start/stop/reverse capability.
- Because there is no need for a brush, stepping motors have high reliability. The life span of a stepping motor is dependent on the performance of the bearings.
- The pulse output provides precise positioning of the rotor without feedback.
- Microstep mode at low speeds while directly connecting to the rotor loading does not require an intermediate gear.
- The stepping motors provide a wide speed range. The speed is proportional to the input pulse frequency.

Stepping motors have many advantages, which make them ideal solutions for many applications. However, stepping motors have some drawbacks such as:

- Resonance is inherent for stepping motors.
- It is possible to lose positioning control, in some situations, because no feedback is used.
- Power consumption does not decrease even if load is absent.
- Duration has limitations at high-speeds for stepping motors.
- Stepping motors have low power density.
- Stepping motors have a complex control method.

DC stepping motors are collector free motors with a direct current and have high reliability and long life spans. But stepping motors need more complex controls to compensate for all of their restrictions, which are not present in usual DC brushed motors. Previously, microcontrollers, which are just as complex as stepping motor drivers, were used to control stepping motors.

A significant advantage of stepping motors is accurate positioning and potential rotation speed control without a feedback sensor. This is only advantageous for systems that use low accelerations and fixed loading.

For high acceleration systems that require variable loading feedback, stepping motors are not ideal because the rotor position information could be lost due to stator magnetic field rotation without corresponding rotor position variation.

If the stepping motor's loading is higher than its torque, information about rotor position can be lost and the system must be built with a terminal switch or another sensor. A system with feedback does not have this disadvantage.

Stepping motors are used when precise positioning and speed control are needed and the required torque and speed are within acceptable ranges. Gears can be used to increase torque, but this is not always an acceptable solution. In contrast to common collector motors, where torque increases at higher speeds, torque of stepping motors increases at lower speeds and decreases at higher speeds. Furthermore, stepping motors have lower maximum speeds than collector motors, in which the maximum reduction ratio decreases as the torque and gears increase.

Stepping Motor Types

There are several basic types of stepping motors:

- Motors with Variable Reluctance
- Motors with Constant Magnets
- Hybrid Motors

Motors with Variable Reluctance

Stepping motors with variable reluctance have several phases on the stator and the toothed rotor, made with m-metal. The rotor is not magnetized. A simplified variable reluctance stepping motor is shown in Figure 1. In this figure, the rotor has four teeth and the stator has six phases. The motor has three independent windings on two opposite phases. This motor has 30-degree steps. When the current flows in one winding and the flux is closed (that is, the rotor's teeth are placed opposite to the phases of the powered winding), the rotor tries to occupy the flux position. If a winding is turned off and the next winding turn on, the rotor changes its position to the closest flux. So, the phases need to be turned on alternately to provide continuous rotation. Real motors commonly have more stator phases and more rotor teeth, which provide more steps per revolution.

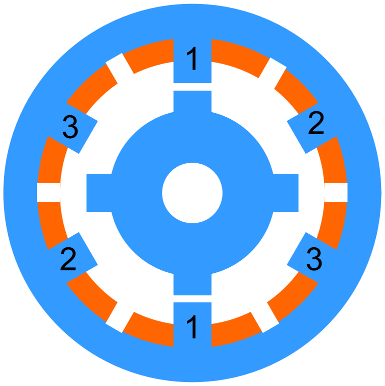


Figure 1. Variable Reluctance Stepping Motor

Motors with Constant Magnets

A motor with constant magnets consists of a stator with windings and a rotor with constant magnets. Alternate rotor poles have rectilinear forms parallel to the motor axis. Motors with rotor magnetization provide greater flux and greater torque than motors with variable reluctance. The motor, shown in Figure 2, has three rotor pole pairs and two stator pole pairs. The motor also has two independent stator windings, which are placed on two opposite stator poles. This type of motor has 30-degree steps. When the current in one winding is turned on, the rotor tries to occupy position where the opposing rotor and stator poles are placed. To obtain continuous rotation, the phases must be turned on alternately.

Motors with constant magnets are subjected to influence of back-EMF from the rotor, which limits the maximum speed. Therefore, when high speeds are required, motors with variable reluctance are preferred over motors with constant magnets.

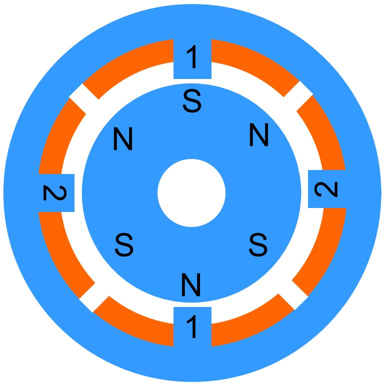


Figure 2. Stepping Motor with Constant Magnet Motors

Hybrid Motors

Hybrid motors are more expensive than motors with constant magnets, but they use smaller steps, have greater torque, and have greater maximum speeds. Hybrid motors combine the best features of motors with variable reluctance and motors with constant magnets. A hybrid motor rotor has teeth, placed on directional axes. The rotor is divided into two parts. Between the two parts is a constant magnet. One rotor part is called the North magnet pole and the other is called the South magnet pole. Furthermore, upper and lower rotor parts are turned on half of an angle of teeth step. The number of rotor pole pairs is equal to the number of teeth on one of the rotor's parts. The hybrid motor stator has teeth too, for creating more poles than just the main poles, which contain windings. The rotor teeth provide a smaller magnetic circuit resistance in some rotor positions, which improves static and dynamic torque. This is provided by corresponding teeth positioning; some parts of the rotor teeth are placed opposite to the stator teeth and the remaining rotor teeth are placed between the stator teeth. Dependence between the rotor pole's number, the stator equivalent poles and the phase number define step angle size S:

$$S = \frac{360}{\left(N_{ph} \bullet Ph\right)} = \frac{360}{N} \qquad \textbf{(1)}$$

Where…

- N_{ph} is equivalent poles number per phase
- Ph is phase number
- N is pole's number for all phases

The hybrid motor is depicted in Figure 3. Its rotor has 100 poles (50 pares) (N_{ph}) and the motor has two phases (Ph), so the pole's number (N) is 200 and the step size is 1.8 degrees.

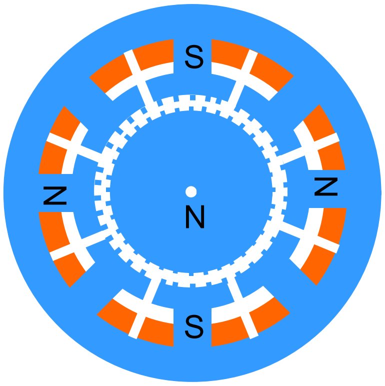


Figure 3. Hybrid Stepping Motor

Stepping Motor Control

A step motor is a synchronous electric motor. Its fixed rotor equilibrium position concurs with the stator magnetic field. When the stator changes position, the rotor rotates to occupy a new equilibrium position. The correct current direction in the windings and correct current dependence are both needed to obtain the appropriate magnetic field direction.

There are several operational modes of stepping motors such as: Full Step mode, Half Step mode and Microstep mode. Each of these modes controls stepping motor phases in different ways:

- **"One Phase On" Full Step (or Wave Drive Mode)**: Uses variable phase switching, which is only when one phase is turned on at a given moment. The rotor's balance points for each step are the same as for the turned off motor. For this given mode, only 50 percent of motor coils are used at a given moment, so we cannot obtain full torque.
- **"Two Phase On" Full Step (or Full Step Mode)**: Uses two phases at a time. When this mode is used, two phases are turned on at the same time, which provides up to 40 percent more torque than when one phase is turned on at the same time. The rotor's position, when two phases are turned on, is between stator poles.
- **"One and Two Phase On" (or Half Step Mode)**: Uses a combination of two of the modes previously described. When this controlling mode is used, the motor's step is one half of a step in full step mode. One phase is turned on during each first step and the other phase is turned on during each second step. The Half Step mode does not provide constant torque without special controls. Some drivers realize constant torque for this mode as long as dissipated power does not exceed nominal value.
- **"Microstep Mode:"** Due to a torque rippling and resonance condition present in the aforementioned modes, Microstep mode is needed in many situations. When used, the current is changed by small steps that split each step into microsteps. When two phases are turned on and the current on each phase is not equal, the rotor position is determined by the current phase ratio. Ratio changing produces a number of microsteps inside each full step. Microstep mode requires a more complex controlling method.

For example, various current levers need to form in the coils.

Half Step Mode

The basic principle of stepping motor function is revolving flux formation, which causes rotor rotation. The revolving flux is formed by the stator that powers various phases.

For motors with a single powered phase, the torque change on sinusoidal form is ideal. But in real motors, this dependence is not ideal sinusoid, which is explained by non-ideal geometry of the rotor and the stator. The peak torque value is called the “keeping“ torque. Equation (2) describes the dependence of torque from a rotor rotation angle:

$$T = -Th \cdot \sin\left(\frac{\left(\pi/2\right)}{S}\right) \cdot \Phi \qquad \textbf{(2)}$$

Where…

- T is torque
- Th is keeping torque
- S is one step angle
- Φ is rotor rotation angle

The rotor can change its position when the external torque, which is larger than the keeping torque, is applied to the rotor. If the external torque is less than the keeping torque, the rotor will balance in one step angle range. When the motor is not powered, its keeping torque is not zero, because the rotor’s constant magnets create a torque of about ten percent of the maximum motor torque.

Two terms are used: mechanical rotor’s rotation angle and electrical rotor’s rotation angle. The mechanical angle is calculated by taking into account that a full rotor revolution is 2*Pi radians. For electrical angle calculation, one period of the torque angle dependence is considered one revolution. In Equation (3), the electrical angle, for a motor with four steps on one period of torque dependence is:

$$\left(\frac{pi/2}{S}\right) \bullet \phi \text{ or } \left(\frac{N}{4}\right) \bullet \phi \qquad \textbf{(3)}$$

Where…

- N is steps number per revolution
- Φ is the mechanical rotor rotation angle

The electrical angle determines the stator’s magnetic field rotation angle. When two motor windings are powered, the resulting torque can be calculated as the vector sum of torques, provided by each winding (see Figure 4).

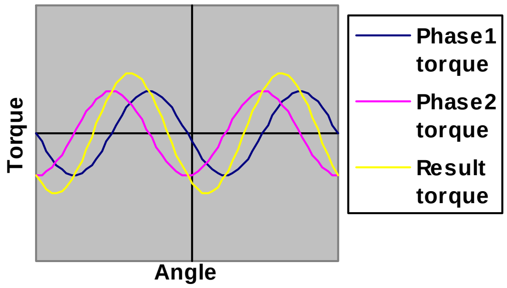


Figure 4. Torque Dependence from Rotor Rotation Angle for Two Powered Windings

The maximum point and rotor balance point shift on half step when the windings’ currents are equal. The torque maximum value (keeping torque) for two powered windings is larger on $\sqrt{2}$ than for one powered winding.

$$Th_2 = \sqrt{2} \cdot Th_1 \qquad \textbf{(4)}$$

Where…

- Th_2 keeps torque for two powered windings
- Th_1 keeps torque for one powered winding

The magnetic field value and direction are shown in Figure 5.

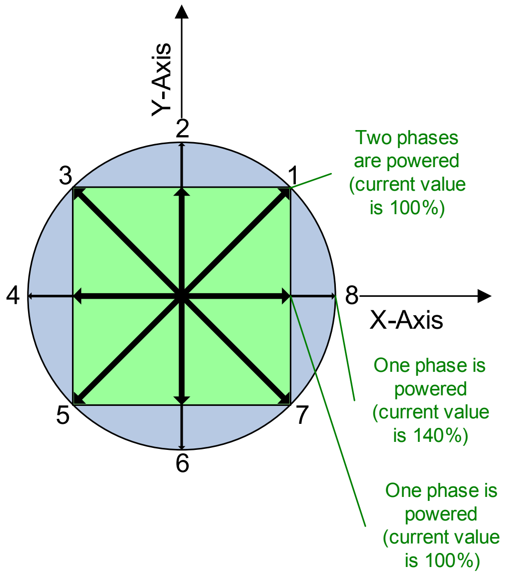


Figure 5. Magnetic Field Value and Direction for Different Powering Modes

The X and Y axes run the same direction as the magnetic field, created by the motor's first and second phases. When the motor functions with one phase switched on, the rotor occupies the 1, 3, 5, 7 positions. When two phases are switched on, the rotor occupies the 2, 4, 6, 8 positions. The torque is larger for this mode, because it is proportional to vector length on the figure. Both control methods provide full step, but the rotor balance points are shifted on half of a step. The half step can be obtained, if both methods are combined and the appropriate pulses are routed to the windings. In this case, the rotor occupies the 1, 2, 3, 4, 5, 6, 7, 8 positions, which correspond with Half Step mode. Half Step mode has the following advantages:

- Higher resolution without using the more expensive components needed for Full Step mode.
- Greater resonance simplicity.

One disadvantage of the Half Step mode is significant torque fluctuation from step to step. In the positions, where one phase is powered, the torque is 70 percent of the torque created when two phases are powered. This fluctuation creates vibrations and noise. To minimize the torque fluctuations and the resonance effects during motor operation, the windings' current is intermittently reduced, when both windings are powered. To maintain a constant torque, this current should be 70.7 percent of the nominal. This technique for Half Step mode is used in Allegro Motor Driver A3955.

Because Half Step mode uses one and two phase powering, the transition into state with a single powered-off winding is very important. Current in the powered-off winding should quickly be decreased in order to move the rotor to the appropriate position. The duration the current decreases depends on the winding voltage when it loses stored energy. The maximum voltage can be reached when the winding is abridged to the power source, so the maximum voltage of the system should be applied to the winding.

Microstep Mode

Microstep mode is obtained by rotating the stator magnetic field more smoothly than if it was in either Full Step or Half Step mode. Less vibration and noiseless operation for a wide rotation frequency range are the result. Smaller step angles provide more precise positions.

Torque calculation for a motor with both powered windings and with non equal currents is shown in Equation (5):

$$Th = \sqrt{a^2 + b^2} \tag{5}$$

The rotor's equilibrium position shifts:

$$X = \frac{2S}{\pi} \arctan\left(\frac{b}{a}\right) \tag{6}$$

Where…

- a and b are torque, created by first and second phases, respectively
- Th is total keeping torque
- X is rotor equilibrium position in radians
- S is step angle in radians

The rotor's equilibrium position shift provides the potential to fix the rotor at any position. This is needed to set correct current dependence. Microstep mode provides smooth rotor rotation at low frequencies. However, due to the rotor and load inertia filtering action, there are no significant advantages for Microstep mode when the rotation frequency is two to three times larger than the rotor or loaded rotor resonance frequency. The step motor acts like a low-pass filter. During acceleration and slowdown, the motor operates in Microstep mode. During the remaining time, the motor operates in Full Step mode. When shifting from Full Step to Microstep mode, the rotor does not temporarily stop at a new position and perform relaxed oscillations. These oscillations are undesirable and Microstep mode helps eliminate them. Figure 6 shows the rotor moving in Full Step and Microstep modes.

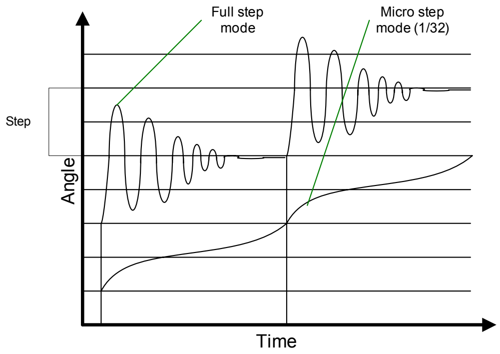


Figure 6. Rotor Moving in Full Step and Microstep Modes

As can be seen in Figure 6, oscillations and surges are present in Full Step mode and are not in Microstep mode. However, in Microstep mode, the rotor's position graph is not a straight line because of motor detail inaccuracy. When the phases of an ideal stepping motor are powered by sine and cosine currents, the rotor should rotate with constant speed. In real motors, speed fluctuations are present. This is caused by the instability of the rotor-stator air-gap and the presence of a magnetic hysteresis. It invokes an error in the magnetic field value and direction. So, equilibrium positions and torque have some errors. Errors are caused by deviations in the tooth form and from typical variations in the magnetic material. Deviations can be divided into two types:

- Magnetic field value deviations, which force torque deviations in Microstep mode.
- Magnetic field direction deviations, which cause equilibrium position deviation.

Keeping torque deviations in Microstep mode are near 10-30 percent of maximal torque. Deviations of keeping torque can also be 10-20 percent in Full Step mode, which is caused by rotor and stator geometry distortion.

There are physical limits that decrease positioning accuracy in Microstep mode:

- Friction torque and moment of inertia causes decrease in positioning accuracy.
- Dead spaces, caused by friction, limit positioning accuracy.

Dependence between the torque and rotor rotation angle is not a distinct sine for most commercial motors. That is why the dependence between power sine signal phase and rotor rotation angle is not linear.

As a result, the rotor will pass each step and half step position; however, between positions, significant deviations will be present.

Many stepping motor drivers use a digital-to-analog converter (DAC) to set winding currents in Microstep mode. A DAC has a DAC quantization error, which decreases accuracy. Due to this limit, Microstep mode provides a smooth rotation (important at low speeds) and eliminates noise and resonance. Microstep mode can decrease setup time, because pulses and oscillations are not present. But for most motors, precise positioning cannot be guaranteed due to deviations in rotor and stator geometry.

Torque decreases motor noise when some value of phase commutation frequency is reached. There are two graphs in Figure 7 that depict torque from speed dependence for stepping motors.

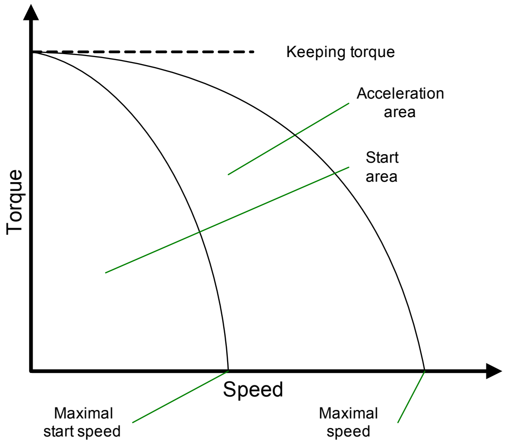


Figure 7. Torque from Speed Dependence

The internal curve (pull-in curve) shows maximum friction torque for a given speed when the motor starts moving. This curve crosses the speed axis at the maximum start frequency. It defines the maximum speed to pickup the unloaded motor. The loading inertia significantly influences the pull-in curve.

The external curve (pull-out curve) shows the maximum friction torque for a given speed on which the stepping motor can support rotation without losing steps. This curve crosses the speed axis at the maximum acceleration frequency, also known as the maximum motor speed without loading. Torque can be on a resonant frequency. The area between the curves is the acceleration area.

Motor rotation must start at low speed (from start area) and during acceleration. To stop the motor, we need to decelerate the rotation speed back to the speed used in the start area so that the control pulses can be stopped on the motor windings. Otherwise, synchronization in rotor positioning will be lost. The stepping motor should not be used for long durations at high-speed rotations because overheating can occur. The stepping motor is ideal for short durations at high speeds (in a drilling machine, for example).

Note the motor's windings inductance, when the high speed stepping motor drivers are designed. This inductance determines the current's pulse increase and decrease. So, when the rectangular voltage pulses are supplied to the winding, the current wave will not be rectangular. The variation of the current pulse does not affect torque at low speeds, but decreases torque at high speeds. It is caused by the current's impossibility to reach nominal value at high speed. This process is depicted in Figure 8.

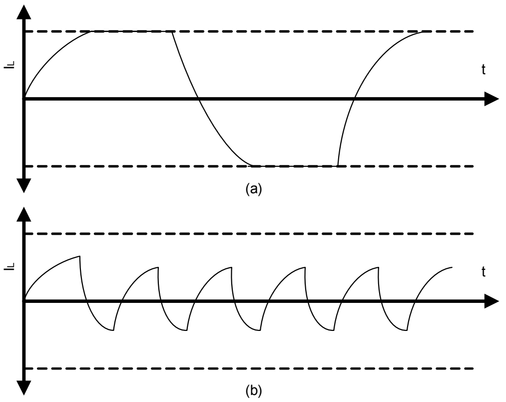
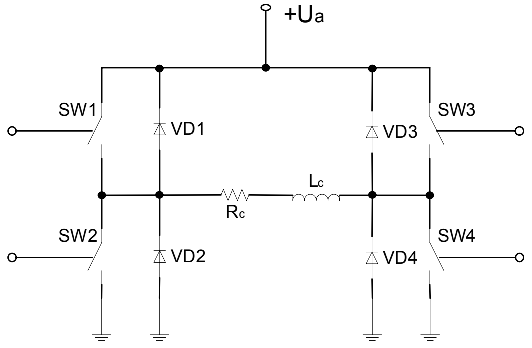


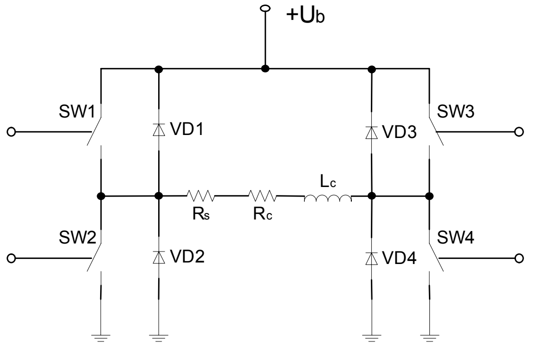
Figure 8. Windings' Current Wave
(a) Low and (b) High Pulse Frequency

Stepping Motor Powered by H-Bridge

In bipolar motors rotation direction is changed by reversing the poles of the motor windings. For such pole reversal, a full H-bridge is needed. It is shown in Figure 9. This control method recognizes switch controlling and prevents power from short-circuiting.



a) Ic=U/Rc;
t_1=Lc/Rc



b) Ic=U/(Rc+Rs);
t_2=Lc/(Rc+Rs)

$U_b > U_a$ for voltage dropping
on R_s compensation

Figure 9. Bipolar Stepping Motor Winding Powered by (a) Nominal Voltage Level and (b) Using Limiting Resistor: $t_2 < t_1$

Because motor windings have inductance, the winding current cannot quickly increase and decrease infinitely. When the winding power is switched on, the current increases with some speed and when the power is switched off, a voltage surge takes place, which damages the switches. Special protective chains are used to protect the switches from induction surges. In Figure 9, these chains are formed by diodes. High-speed current increases are needed in motor windings to minimize torque decreases as the rotation speed increases. This can be accomplished with distinctive power designs that are described as follows.

Current Control

Current control is needed for torque regulation. Just as motor torque is directly proportional to windings' current, current control should be used to provide demanded torque level at various rotation speeds. Also, the current should be limited to avoid exceeding the motor's winding dissipation power limitations.

The simplest way for motor powering is to use a DC voltage supply. In this case, the current is limited by the windings' resistance and supply voltage value. This powering method is called Inductance/Resistance powering, also known as L/R-powering. The windings' current increases by exponential law and is dependent on the winding inductance, active resistance, and applied voltage. When the phase switching frequency increases, the current will not reach the nominal value, causing the torque to decrease. Therefore, L/R-powering is applicable in low speed modes and is commonly used for low-power motors (Figure 9a) such as one that controls the pointers on automobile dashboards.

For high-speed modes, the current set time should be reduced, which is achieved by increasing the power supply voltage level and reducing the LR network characteristic time constant. In this case, the windings' maximum current should be limited by a resistor. This powering mode provides quick increases in current, but dissipates additional power on the resistors (Rs) as shown in Figure 9.

A better technique is to use pulse-width current regulation. A switching regulator provides quick increases in current and low regulation losses. Furthermore, this design independently supports the constant motor torque from the power voltage fluctuations commonly seen in low-priced, unregulated power supplies.

To ensure an increase in the high speed current, a power supply several times larger than the nominal voltage value should be used. The simplest approach is to use a programmable voltage reference comparator (Uref), a pulse generator and an RS-trigger (Figure 10). This module operates the following way: the generator sets the RS-trigger, which closes the transistor switch. Current via the inductor starts rising. When the voltage drop on the current sense resistor reaches the reference voltage, the comparator resets the trigger that finishes the energy storage state in the inductor during this clock cycle. The current drops via a turned-on diode due to energy dissipation on the diode and the inductor resistance. This process is repeated during next the clock cycle. Therefore, the switching current source regulates the peak value in the inductor. Applying various reference voltage Uref values permits the different inductor current values that are required to obtain smooth rotor rotation in Microstep mode.

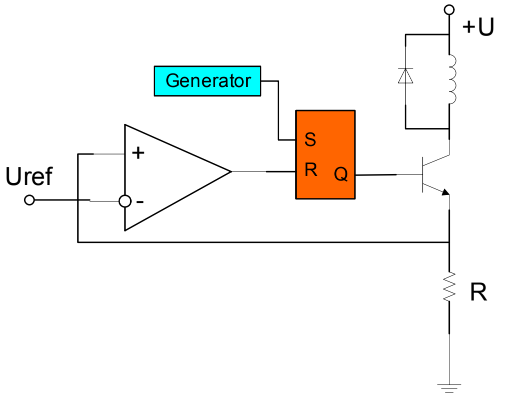
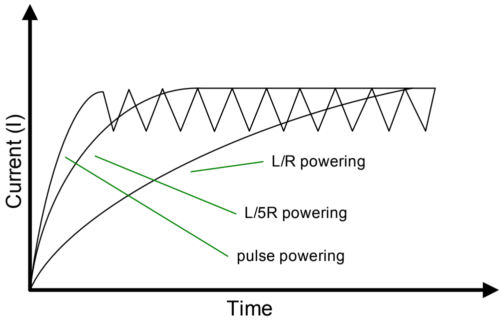


Figure 10. Current Switching Regulator



Power supply
voltage level:
L/R powering – Us
L/5R powering - 5Us
pulse powering - 5Us

Figure 11. Winding Current Form for Different Power Methods

Figure 11 shows the winding current form for three coil powering methods. The switching current regulation method is efficient and provides an easy-to-control current value technique.

Quick and Slow Decrease in Current

Due to the nature of inductive winding, winding current cannot change rapidly. This limits maximum rotation speed for stepping motors. Moreover, the rotating magnet induces the voltage signal, which also influences the current value. To obtain maximum rotation speed, increase and decrease the winding current as quickly as possible. Increasing current speed was discussed in the previous section. Different modes to decrease current are discussed as follows.

Figure 9 shows an H-bridge switch configuration for different winding current directions. For the fastest current decay, all switches can be opened. After disconnecting inductance from the power supply, the current cannot immediately stop. Self-induction voltage appears and is opposite in direction to the power supply. When transistors are used as switches, two pairs of shunting diodes are needed to provide conductivity in both directions. The first pair provides the decrease in inductivity energy after the inductivity current flows through in one direction. The other pair provides decrease in energy after the inductivity current flows in the reverse direction. The change to current speed is proportional to applied voltage. This is true for both increasing current and decreasing current.

Figure 12a shows the state of the H-bridge switches when the winding is powered. Switches SW1 and SW4 are closed and the current direction is indicated by an arrow. Figure 12b depicts situations in which inductance is powered off, but switch SW1 is closed. Self-induction voltage is abridged through this switch and the VD3 diode. In this case, a low voltage level is present on the winding. This voltage is equal to the direct diode voltage plus the dropping switch voltage (transistor saturation voltage for bipolar transistor or channel voltage drop for MOSFET).

Because the winding voltage is small, the current change speed is small as well. As a result, the decreasing magnetic field is also small and the stator creates an undesirable magnetic field, which slows down the rotor. This prevents normal operation at a high rotation speed. Quickly decreasing current is very important for high-speed controllers, which work in Half Step mode.

In another method to switch current off, all H-bridge switches are opened (Figure 12c). The self-induction voltage abridges through the VD2 and the VD3 diodes to the power source. As a result, the winding voltage is equal to the power source voltage plus the direct voltage drops on both diodes. This method provides a quick decrease in the current and magnetic field.

Frequently, with step motor applications, there are instances when slow decay fails to properly control the phase current and fast decay induces excessive ripple in the load current. In this case, a mixed decay mode can be used. Mixed decay splits the PWM off-time interval into two segments. During the first segment, fast decay is used (when all bridge transistors are off) and during the second segment, slow decay is used (when the coil is shorted). Mixed decay permits reduction of current ripple, whereas, fast decay cannot. Furthermore, using mixed decay can increase maximum rotation speed and provide better current wave when compared to only using slow decay. Mixed decay is a compromise between slow and fast decay modes; it provides a good combination of current level ripples and a suitable current wave during motor rotation at high speeds.

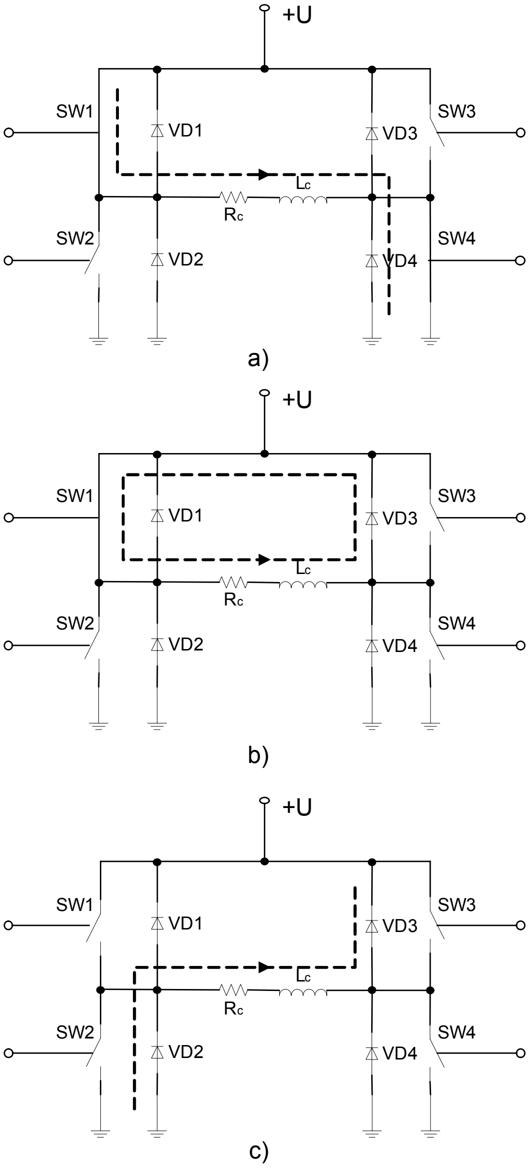


Figure 12. Current Flows During
(a) Current Excitation Phase
(b) Slow Current Decay
(c) Fast Current Decay

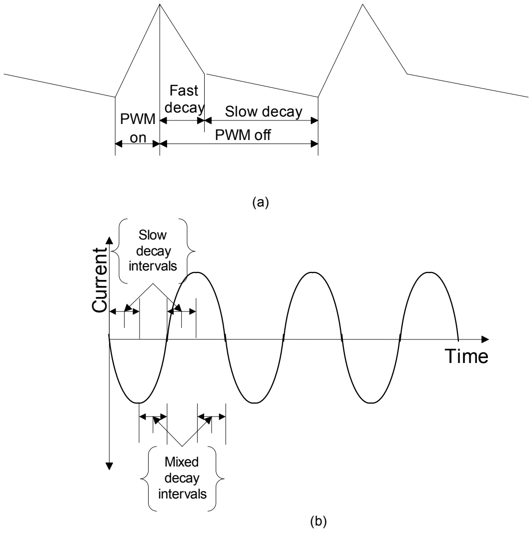


Figure 13. (a) Mixed Current Decay
(b) Slow and Mixed Decay Combined

Figure 13a depicts current change for mixed decay. In authentic motor applications, slow and mixed decay are combined. During the period of increasing winding current, slow decay is used and during the period of decreasing winding current, mixed decay is used to provide a good phase current wave. This combined approach, shown in Figure 13b, provides improved current waveform quality at high motor rotation speeds (typically 50-150 full steps per second).

PSoC-Based Driver Description

The driving motor is easily formed with two analog quadrature sin/cos currents using two digital-to-analog converters (DACs). However, we should determine how motor rotation speed changes in time. There are several strategies to control motor speed using constant or variable speed operation.

As can be seen in Figure 7, the maximum startup frequency is less than the maximum operation frequency. Therefore, the constant speed profile does not provide the minimum rotor positioning time. The variable speed driving profile is free from this limitation, permitting full motor possibilities and obtaining minimal rotation angle positioning time.

There is a limitation for maximum rotation acceleration, which determines the motor speedup and brake times. This limitation comes with a restricted magnetic force value.

Note that if the stepper motor control frequency (both during startup and operation) exceeds the predefined limit, the motor loses the steps and the rotor angle is no longer synchronized with the controlling sequence that was sent. Therefore, the acceleration and startup/operation rotation speeds should never exceed the maximum limit.

During the stepper motor driver design, we can select different motor acceleration and deceleration methods. One possible solution is to use the digital low-pass filter to gradually increase the rotation speed during motor acceleration phase and apply the same filter when the speed is decreased near destination point. When this method is used, the absolute value of acceleration should not exceed the predefined threshold limit.

Another method is to use a constant acceleration profile where the rotation speed is increased with constant acceleration during the speedup phase with the same deceleration during the speeddown phase. The rotation speed is constant when the speed reaches the predefined threshold limit. The proposed motor driver uses the constant acceleration drive profile. This profile is sometimes referred to as a trapezoidal profile, because the speed shape is a trapezoid.

This driver can be implemented on the device, which removes all previously mentioned limitations. The following components are required to build the driver:

- Double DAC for creating the phase coil quadrature signals.
- Variable frequency generator that forms the phase current values to update events, thereby determining the existing rotation speed.
- Speed control system to provide rotation acceleration/deceleration.

Modern microcontrollers have PWMs, where the programmable interval timer can be used as a variable frequency generator. The changing linear motor rotation speed corresponds to the hyperbola timer period curve that requires use of a high-resolution timer. The PSoC device provides a great solution, thanks to the flexible internal analog user modules. The voltage-to-frequency converter together with the DAC can be used as a programmable signal generator with a constant frequency step. This approach is used in this design.

Figure 14 illustrates one possible microcontroller-based driver implementation.

Note that the conventional Unified Modeling Language (UML) notation was used to mark the relations between blocks.

The driver is connected to the PC via the COM port. The PC host interface receives the data via the EIA232 (RS232) Interface. It then decodes, parses, and executes the received commands.

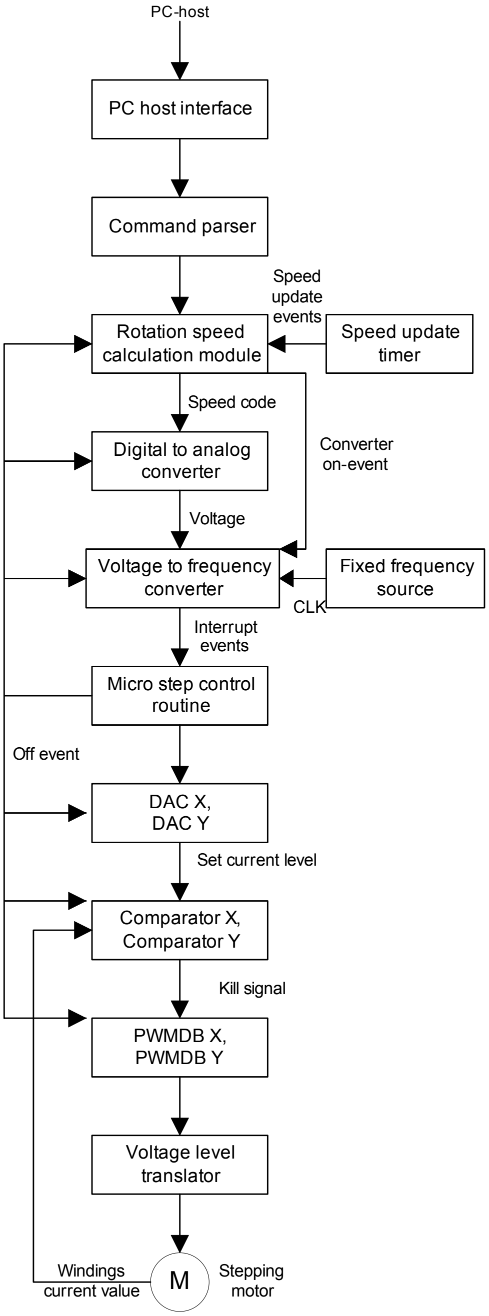


Figure 14. Motor Driver Cooperation Diagram

The speed calculation module analyzes rotation mode (continual rotation or predefined microstep-number rotation) to form the actual motor rotation speed; the speed adjustment is periodically initiated using a dedicated interval timer. The current motor rotation speed value is calculated using the following formula in each timer update event:

$$v_i = v_{i-1} + a_i \qquad a_i = \{a_0, 0, -a_0\} \tag{7}$$

Where…

- v_i, v_{i-1} is speed value for *i* and *i-1* iterations.
- a_i is current acceleration value, which can accept only three possible values: fixed positive during acceleration stage, zero during constant rotation speed stage, and fixed negative during deceleration stage.

At the start of motion, positive acceleration is selected and half of the rotor movement distance (in predefined microstep-number rotation mode) is used to mark the initial switching upon the moment of deceleration. In continual rotation mode, acceleration step numbers are calculated and then used to correctly apply the rotor brakes when the STOP command is received. When the rotor speed reaches the predefined threshold, the acceleration drops to zero and the constant speed stage begins. At this moment, the current rotor step number overrides the previously calculated value in order to determine the rotor braking start position. The braking stage begins when the distance-to-destination position is less than the previously calculated value or the STOP command is received; the acceleration is set negative for this stage. The proposed algorithm provides a symmetric acceleration/deceleration profile for both small and large rotor displacements, even if the rotation speed reaches the maximum allowed value.

Figure 15 illustrates the driver speed control state diagram. *Ready* is the default stage. When the new position command is received, the driver enters into *Initialization* stage, where the internal control variables are initialized. Next is the *Acceleration* stage, when motor rotation speed increases linearly. When rotation speed reaches the predefined maximum value, the driver enters constant speed rotation. If the rotor is close to the demanded position or the STOP command is received, the driver enters the *Deceleration* stage, where speed drops linearly.

Note that the driver enters *Deceleration* stage immediately after *Acceleration* stage, when the rotor completes half of its demanded rotation angle and the speed is less than the predefined maximum value. This corresponds with minute rotor displacements.

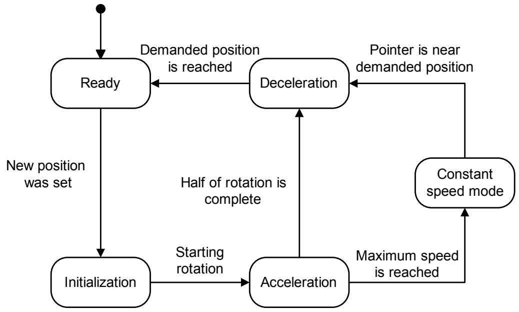


Figure 15. Speed Control State Diagram

The voltage-to-frequency converter is used to form variable frequency interrupts for calling Microstep mode. The input voltage is calculated using the following formula so that the interrupt frequency is proportional to the estimated frequency of the speed value:

$$U_i = \frac{v_i}{K_s} \tag{8}$$

Where the K_s is scale coefficient.

The Microstep mode routine accomplishes several things:

- Changes programmable current source DAC value to obtain rotor rotation.
- Switches current direction in the motor windings and determines the stop condition.
- When stop rotation condition is detected, the voltage-to-frequency converter and programmable current source are stopped and rotor movement is considered complete.

The motor control system was simulated in Simulink to study the calculus quantization effects and optimize parameters in control algorithms, Figure 16 illustrates the top-level control system model and the simulation results for various rotor displacements. The simulation results correctly displayed the control algorithms and were later replicated by driver experimental testing.

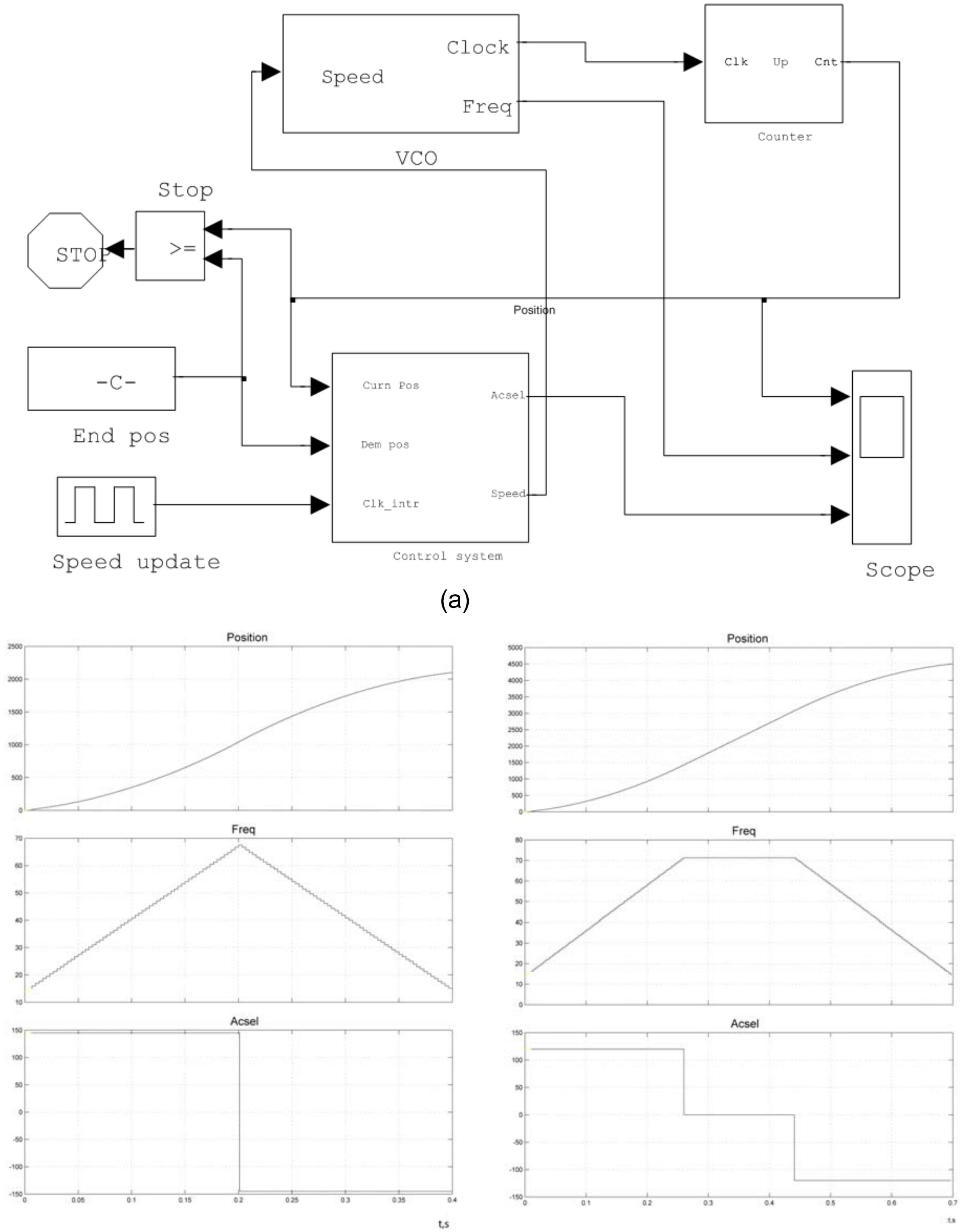


Figure 16. Motor Driver Simulation
(a) Driver Simulink Top-Level Model (b)-(c) Simulation Results for Various Rotor Displacements

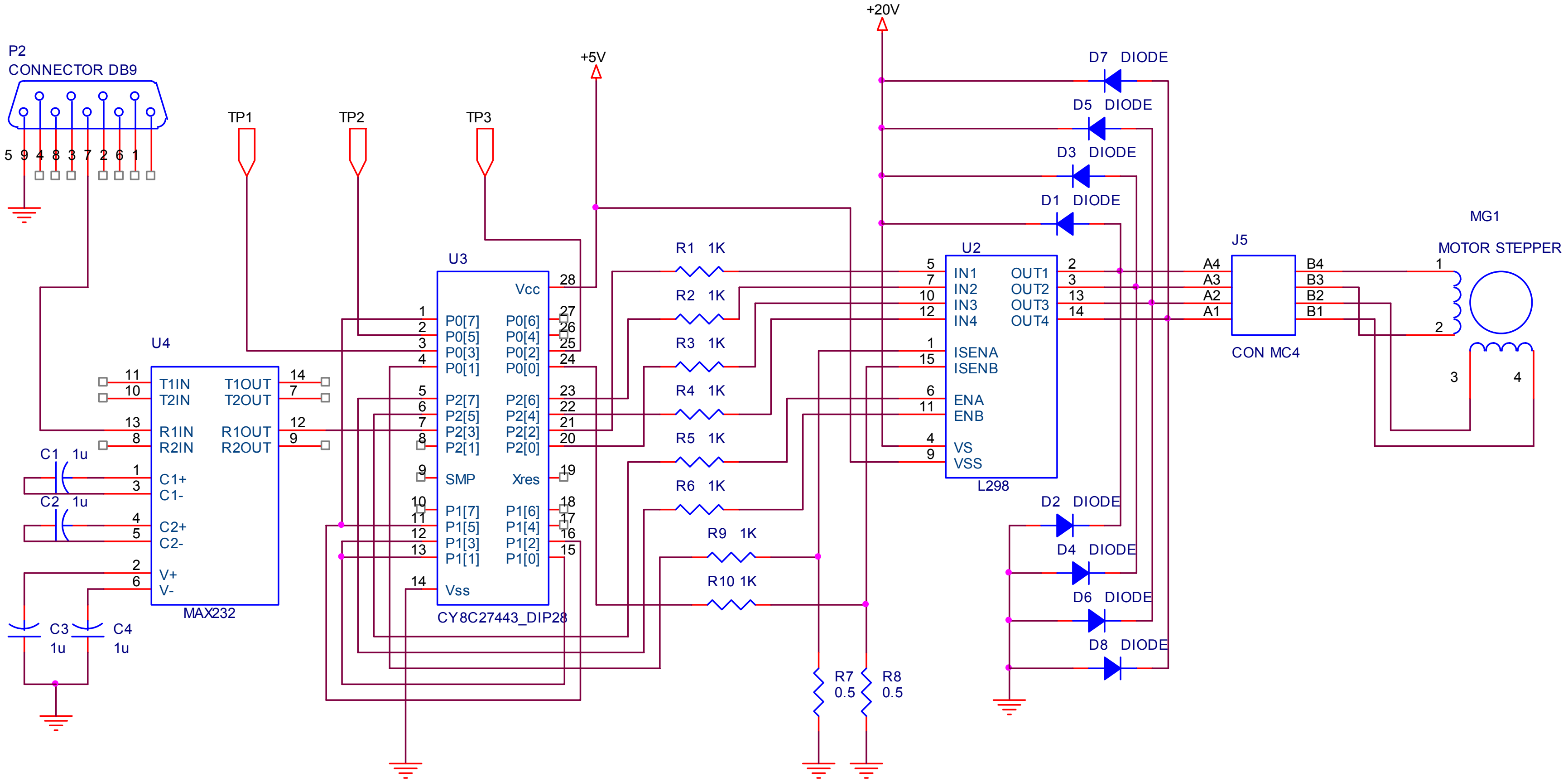


Figure 17. Driver Schematic

Driver Schematic

This driver was designed for stepping motors with a 12V supply voltage and a control from the host PC. The 28-pin PSoC mixed-signal array CY8C27443 was used for the prototype.

The driver consists of a microcontroller U3, a motor driver U2, and an EIA232 (RS232) voltage level converter U4. The motor driver U2 is used to drive the motor by driving the motor windings.

The EIA232 (RS232) voltage level converter U4 is used to connect the driver board to the PC via the COM port, which sends the commands and the rotation parameters. The microcontroller U3 is used to form the correct pulse sequences to rotate the rotor.

There are test points on the schematic:

- TP1 is amplified by the PH1PGA voltage drop upon current sensing resistor R7.
- TP2 is amplified by the PH2PGA voltage drop upon current sensing resistor R8.
- TP3 is rotation speed of the DAC output.

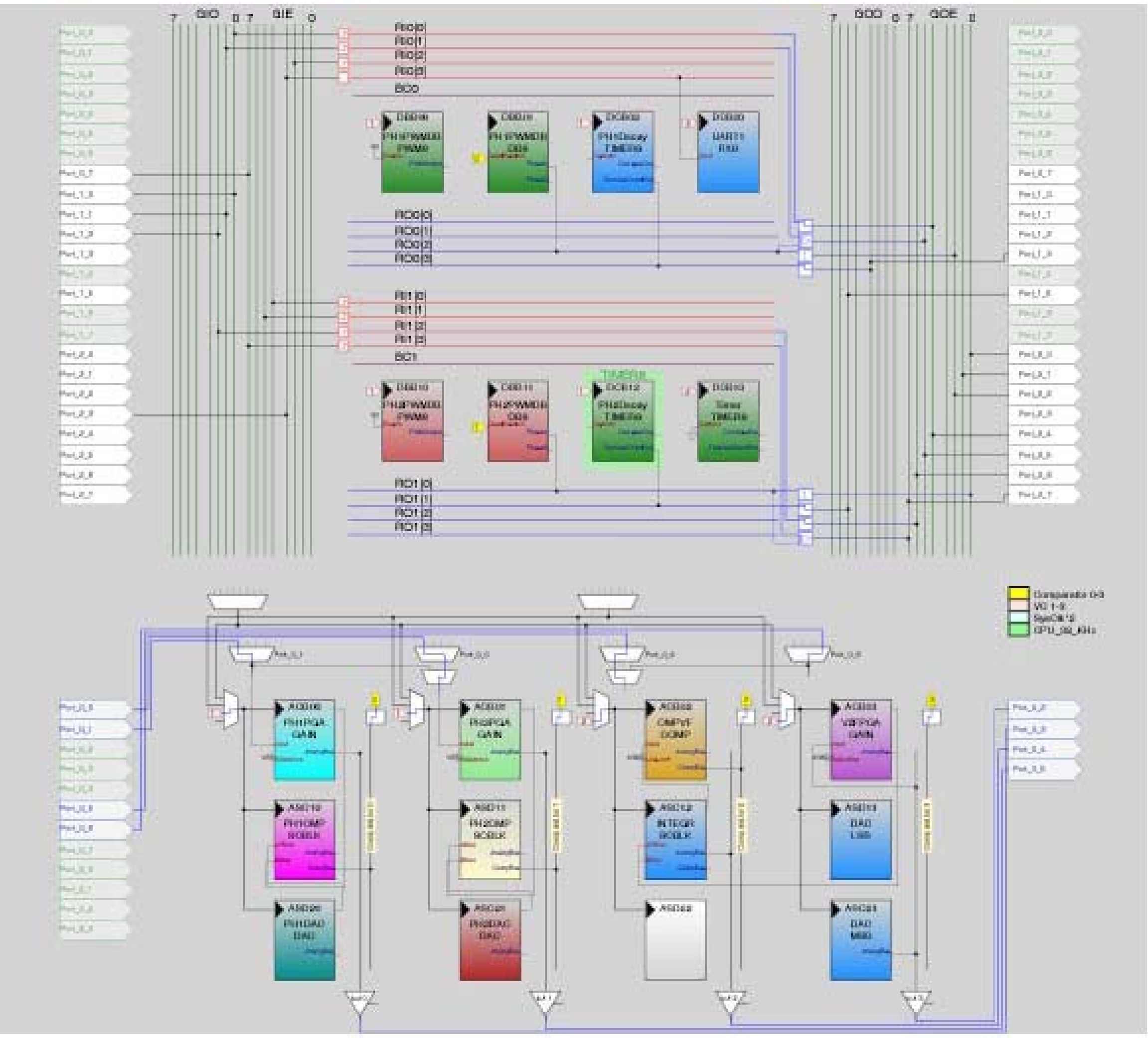


Figure 18. User Module Placement in PSoC Designer

PSoC Device Internals

The PSoC device internal structure is illustrated in Figure 18.

Programmable current source for each motor winding consists of following the blocks:

- PWMDB (PWM User Module with deadband).
- DB (DB User Module without dedicated PWM, which uses previous block output as input).
- PGA User Module (programmable gain amplifier).
- Generic SCBLOCK User Module (this block is configured as a comparator).
- DAC User Module (6-bit).

For X phase, the following blocks are used to form the winding current:

- DBB00
- DBB01 (PWMDB)
- DCB02 (DB)
- ACB00 (PGA)
- ASC10 (SCBLOCK/Comparator)
- ASD20 (DAC)

For Y phase, the following blocks are used to form the winding current:

- DBB10
- DBB11 (PWMDB)
- DCB12 (DB)
- ACB01 (PGA)
- ASD11 (SCBLOCK/Comparator)
- ASC21 (DAC)

Current sources are used to form the motor windings' current with proper direction and value to provide rotor rotation. Figure 21a depicts current source functional method for one motor phase. As noted in the figure, the current source consists of:

- DAC
- PGA
- CMP
- PWM
- DB1
- Delay line (DB2)
- The logical function method shown in Figure 12 (LUT is used to form logical functions).
- The switching method, which is intended to form big current values for motor windings.
- Current sensing resistor R_s (R7 and R8 on Figure 17), which is used to control current winding current value. This resistor is attached between motor winding and ground. Voltage drop on this resistor is proportional to current through winding.

The programmable current source functions as follows. The DAC is used to set the current value through the motor winding. The voltage value, set by the DAC, is compared with the voltage on the PGA. The PGA voltage is an amplified voltage drop upon current sense resistor Rs. This voltage drop is proportional to the current through the winding. So, if the DAC voltage level is smaller than the amplified PGA voltage drop upon the current sense resistor, the current through the winding should be decreased. When this situation takes place, the KILL signal, formed by a comparator (CMP) is asserted to the deadband user module. It resets the PWMDB User Module DB1PH1 signal to zero and sets the DB2PH2 signal to '1' after a dead time interval. This dead time interval is set by the user through PC-controlled software. During the dead time interval, when both the DB1PH1 and the DB2PH2 signals are in zero state, '0' state will be in the 'Enable' pin of the current driver (U2 on Figure 17). It opens all of the switches and, as a result, starts fast decay. After the dead time interval is complete, the DB2PH2 is set to '1' state, which sets the "Enable" pin of U2 to '1' state signal. Then, one of the top switches (SW1 or SW3) closes and the corresponding bottom switches stay open because the DB2PH2 signal is set to '1'. As a result, slow decay starts.

Resetting the DB1PH1 to zero and starting fast decay causes the winding current to decrease. When the amplified voltage drop on the current sense resistor is smaller than the voltage formed by the DAC, the CMP negates the KILL signal and the PWM restarts operation (because synchronous restart KILL mode was chosen for PWMDB). The PWM output signal has a duty cycle close to 100 percent. The DB1PH1 signal will be in zero state, while a short zero insert takes place. As a result, the DB2PH2 signal stays in '1' until the DB1PH1 changes from '0' to '1'. After the short zero insert on the PWM signal and the small dead time period, the DB1PH1 signal sets to '1' and DB2PH2 sets to '0'. This starts the current increasing interval. This increase will take place until the amplified voltage drop on the current sense resistor is greater than the voltage generated by the DAC. Then, the previously described routine restarts.

Switching current source drives in the winding current with a maximum value, set by the DAC, provides a combination of fixed-time fast decay and variable time slow decay. The user can reprogram the module to get only fast or slow decay modes according to given requirements.

The proposed current source method implements fast decay during a defined time interval and then implements slow decay, so mixed decay provides better winding current wave control.

Phase switching is realized by switching the row output RO lines between the lines of the global output bus. For example, GOE[2] and GOE[6] are used to control the first phase. RO0[2] is connected to GOE[2] and RO1[2] is connected to GOE[6] for direct current flow. For reverse current flow through the winding, RO0[2] is commutated to GOE[6] and RO1[2] is commutated to GOE[2]. Therefore, the current flow through the winding is provided in both directions and, as a result, the rotors rotate in both directions. This process is depicted in Figure 19.

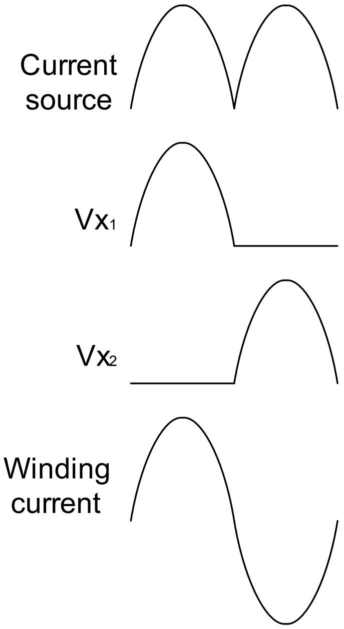


Figure 19. Current Source Phase Change

Signal diagrams are shown in Figure 21b. To achieve slow decay during the winding current increase period, as shown in Figure 13c, the fast decay time interval is set to minimum value in software.

The timer, placed in DCB13, is used to form periodic interrupts to generate speed update events. The interrupt frequency is set to 4800 Hz. The speed update event is triggered one time every 16 interrupts, and therefore the rotation speed value is recalculated once per 3.3 ms.

The voltage-to-frequency converter and DAC are placed in ACB02, ASC12, ACB03, ASD13, and ASC23.

The converter output generates periodic interrupts using the comparator bus interrupts. The converter operation is described in Application Note AN2161 – Standard – “Voltage-to-Frequency Converter.” The 9-bit DAC is used as a voltage-to-frequency signal source. Because the DAC internal output alternates between AGND and the required level of each column clock cycle, the output is passed to the analog bus and later, through the PGA, which is routed to the AMux input of the voltage-to-frequency converter.

The UART receiver, placed in DCB03, is used to host PC commands and receive rotation parameters. VC3 is the source clock for the receiver. The receiver works at the speed of 115,200 bits per second. The PC host sends the command for the driver to start and stop rotation, to change rotation mode (Full Step, Half Step or Microstep mode), to change rotation direction, and to set such parameters as maximum speed, acceleration and decay duration.

The Software

The driver software consists of:

- PC Host Interface
- Command Parser
- Rotation Speed Control
- Rotor Position Control

The PC host interface receives data from the host PC that consists of an interrupt service routine, which provides data buffering received from the host PC. Communication is realized via the EIA232 (RS232) interface.

The command parser is used for parsing PC data to commands and transmitting these commands to the motor driver routine.

Rotation speed control is used to correct motor acceleration and braking according to Figure 7.

Rotor position control provides rotor rotation in two possible modes: continual and predefined microstep-number rotation.

The proposed motor driver implements several rotation modes that can be selected using the host PC application. Three rotation modes are recognized: Full Step, Half Step and Microstep mode. In each of these modes, continual rotation or predefined microstep-number rotation can be selected. If the step number is 0, continual rotation takes place. If the step number is from 1 to 65535, the rotor changes position to the given step number. The following rotation parameters can be set from the PC: maximum rotation speed of either acceleration or current decay duration.

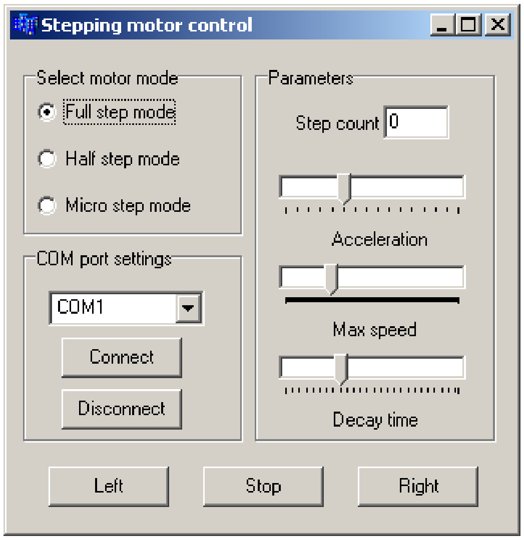
The PC host software and motor driver firmware provide a large range for parameters, but not all motors work properly in the proposed ranges. These parameters should be selected individually per motor.

Figure 22a illustrates implementation of the speed control algorithm, previously described. The speed algorithm uses the voltage-to-frequency converter (described in Application Note AN2161) to form rotor rotation events. The voltage-to-frequency converter is used to convert voltage level, which is set by the firmware used by DAC, to frequency, which is used as an interrupt source for the motor position interrupt service routine. The minimum output frequency is about 100 Hz (limited by the offset voltages and the DAC output voltage limitation). This achieves low rotation frequencies used by the added software counter. This also allows a low rotor positioning speed that can be used for unique applications. The current implementation even permits a minimum rotor rotation speed of less than 1 RPM! The number of skipped interrupt events is calculated in the speed control routine.

Figure 22b shows the motor change position interrupt service routine. This routine checks the ‘Skip‘ value that is used to decrease the minimal operational frequency. If this value is not equal to zero, rotor position change does not take place. If this value is equal to zero, the rotor changes position by one step and ‘Skip’ is set to a defined value. Changing the rotor position is done by setting a new voltage level in PH1DAC and PH2DAC (Figure 18) and the correct phases’ commutation. This is made via ‘Update phase switching’ and ‘Load new DAC value’ as shown in Figure 22b. The current step numbers increase. If no additional rotation is needed, the driver clears the current steps’ number and turns off all unusable modules.

PC Test Software

To send commands to the motor driver, the test software was written using Borland C++ Builder 6, which runs under Microsoft Windows. It sends commands to start rotation left, start rotation right and to stop rotation. The software sets different rotation parameters. These parameters are: rotation mode (Full, Half or Microstep), step count (0 for continual rotation and any other value for rotating to given number), acceleration, and maximum speed and decay duration. The PC COM port can be set to motor driver communication.



● Full step mode
○ Half step mode
○ Micro step mode

Step count 0

COM1

Figure 20. PC Software View

Possible Design Modifications

The proposed driver recognizes the mixed current decay mode. If the mixed decay mode is not needed, two digital blocks are freed and can be used for other purposes. For example, a full (bidirectional) UART could be used to send status messages from the driver to the PC.

If the I2C bus can control the driver, a UART is no longer necessary, which therefore frees up one more digital block.

Summary

The stepping motor driver utilizing the PSoC device is described in this Application Note. With the assistance of the PSoC device, the stepping motor driver provides different operational modes and allows driver function parameter changes for different stepping motors.

References

1. Technical paper STP 97-5A; Allegro MicroSystems Inc.
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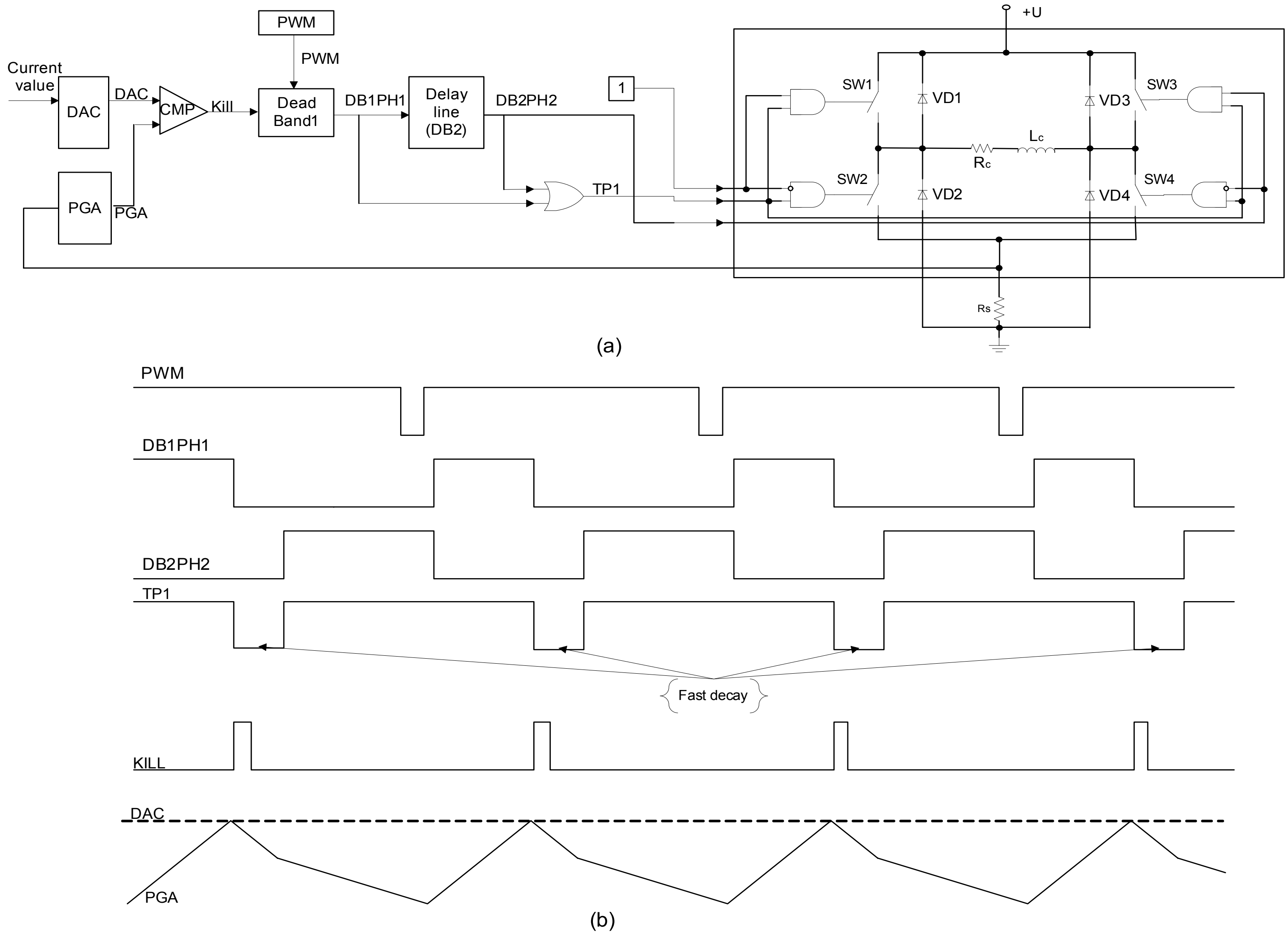
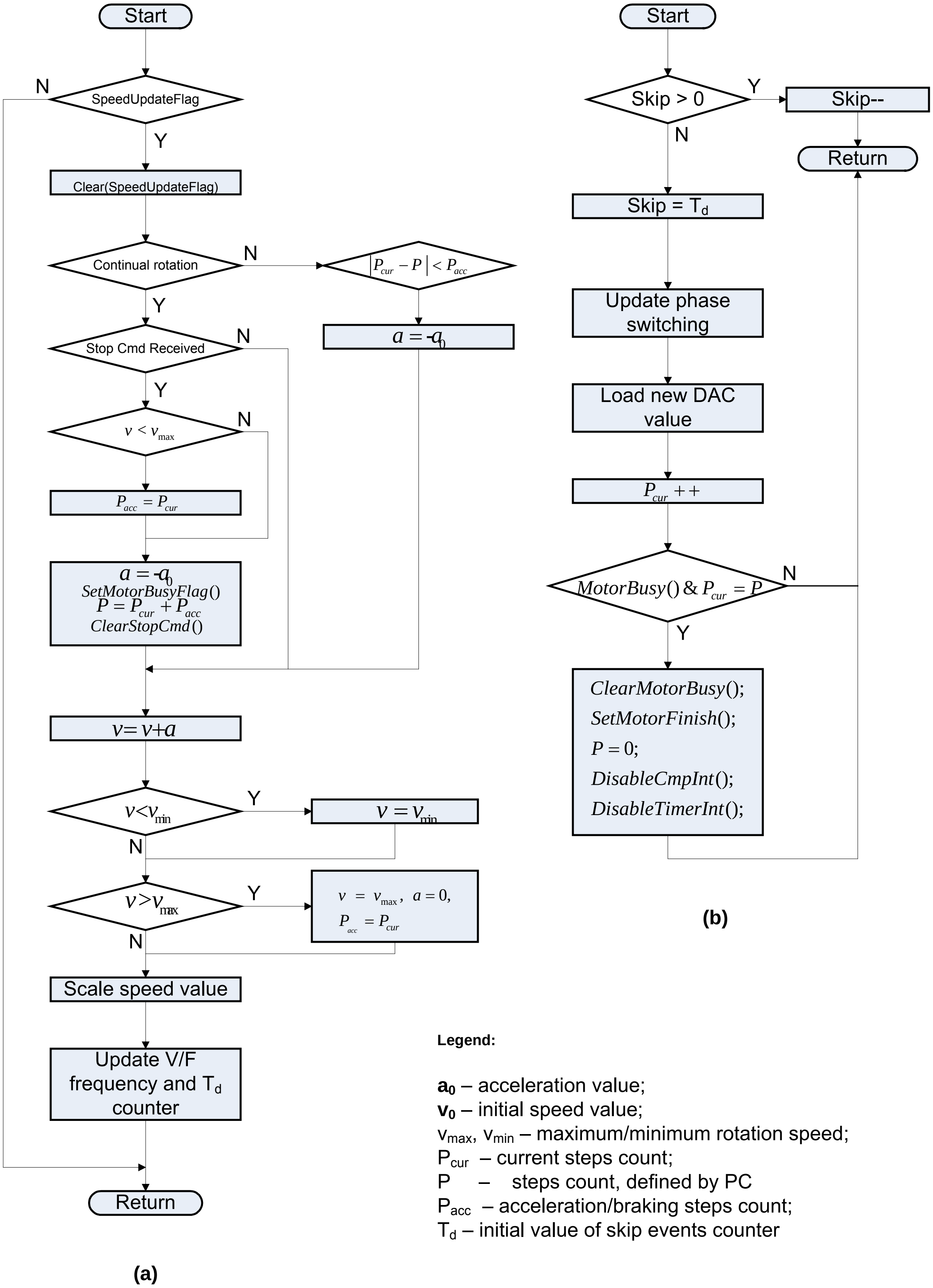
3. Technical paper STP 98-9; Allegro MicroSystems Inc.
4. Technical paper STP 99-11B; Allegro MicroSystems Inc.
5. “Handbook of Small Electric Motors,” William H. Yeadon, Alan W. Yeadon, McGraw-Hill, 2001.



(a)

(b)

Figure 21. (a) One Motor Phase Function Method and (b) Driver Function Diagram



Legend:

a_0 – acceleration value;
v_0 – initial speed value;
v_{max}, v_{min} – maximum/minimum rotation speed;
P_{cur} – current steps count;
P – steps count, defined by PC
P_{acc} – acceleration/braking steps count;
T_d – initial value of skip events counter

Figure 22. (a) Speed Adjustment and (b) Microstep Control

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