APPLICATION NOTE

AN1221
Switched-mode drives for DC motors

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ABSTRACT

The purpose of this paper is to demonstrate the use of integrated switched-mode controllers, generally used for DC power conversion, as the primary control and excitation element in practical PWM drives for DC motors. Basic principles, related to motor specifications and drive frequency, are discussed.

Finally, a series of circuit configurations are shown to illustrate velocity and position servo applications in addition to ideas on constant speed and constant torque using the NE5560 switched-mode controller integrated circuit.

PRINCIPLES OF THE PWM MOTOR DRIVE

THE MOTOR

Pulse-width-modulated drives may be used with a number of DC motor types; however, our discussion will be limited to permanent magnet field motors. This does not impose a severe restriction since PM motors are available today in a large variety of sizes, shapes, and power ratings from fractional to integral HP ranges. The PM motor, however, does have definite advantages for PWM drive as will be made evident in our discussion.

To begin with, let us look at some of the characteristics of DC motors in general, and see how these affect the design of a pulse-width motor drive.

The permanent magnet field motor may be represented in terms of a simplified equivalent circuit as shown in Figure 1.

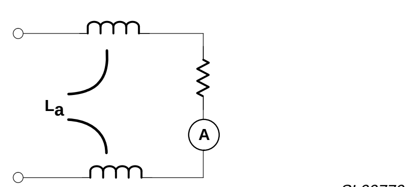

Figure 1. Typical Motor Circuit

L_A represents the total armature inductance, R is the equivalent series resistance, and E the back emf which represents that portion of the total input energy which has been converted to mechanical output. When the armature is not rotating, E=0 and the motor is limited simply to the series armature R and L components.

Inductance, which may vary from tens of μH to mH, will have a significant effect on PWM drive designs. This is due to the fact that average motor current is a function of the electrical time constant of the motor, τ_E. Specifically, pulse current will depend upon the ratio of the pulse-width, $\delta^\bullet T$, to the motor electrical time constant, τ_E. A motor which has high armature inductance will require a lower PWM drive frequency in order to develop the necessary torque in most instances.

As we examine the motor current waveform (shown in Figure 2) for fixed period excitation and two different motor electrical time constants, the effects are obvious. A low inductance motor allows the use of higher switching drive frequency which results in faster response.

In general, then, to achieve optimum efficiency in a PWM motor drive at the highest practical frequency, the motor should have an electrical time constant, τ_E, close to the duration of the applied waveform, T. (τ_E=kT for k small.)

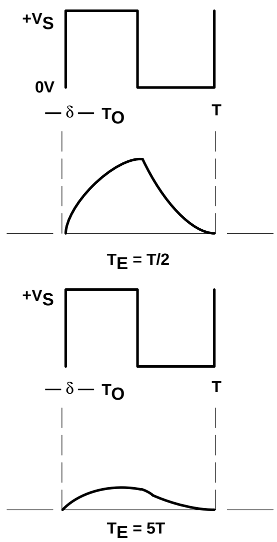

Figure 2. Typical Motor Circuit

The printed circuit motor is probably the lowest inductance motor available since the armature is etched from a flat disc-like material much like the standard double-sided printed circuit board. These motors also exhibit very fast response and high torque. Electrical time constants in the order of 100μs allow these motors to be used with switching rates as high as 100kHz, with typical drive circuits being operated at 10kHz.

MOTOR TORQUE

Now that we have discussed the role played by PWM frequency in gaining a high enough average motor current, the control of motor torque output as it relates to motor current is required. How is torque controlled in a PWM system? The answer is by controlling the duty cycle. Frequency is held constant so pulse-width relays torque control information to the motor. Torque is dependent on average motor current which, in turn, is controlled by duty cycle (I_{ave} aδ). The on-time of the voltage waveform to the motor is represented by the symbol "δ". Obviously, mechanical transient response depends on an input current.

To illustrate the general theory, a typical starting sequence will be simulated using the block diagram as reference with a manually adjusted DC level controlling the duty cycle. (Figure 3)

PWM MOTOR CONTROL

At initial start-up, the duty cycle is adjusted to be long enough to give sufficient starting torque. At zero rotational velocity (ω=0), the back emf ε=0V which causes full step voltage across the motor terminal to appear across the inductor series impedance. The initial motor current determined according to the equation:

EQ1

$$Ldi/dt+Ri=V_S[u(t)-u(t-t)],$$

where the drive signal is a variable duty cycle rectangular voltage wave with peak amplitude V_S and on-time δ (%). Motor current prior to armature rotation is shown by Equation 2.

EQ2

$$Im(t)=V_S/R[1-e^{-t/\tau}E]$$

(for $t=\delta^{\bullet}T$),

where τ_E equals L_m/R_t, the motor electrical time constant. Current now rises in the motor windings exponentially at a rate governed mainly by average supply voltage and motor inductance. If the pulse width is close to the τ_E of the motor as shown previously, motor current at the termination of the first pulse will reach nearly 60% of $I_{max}=V_S/R_t$. For the remainder of the PWM cycle, switch S1 is off and motor current will decay through the diode at a different rate, depending upon the external circuit constants and internal motor leakage currents, according to the equation:

EQ3

$I(t)/decay=-I_O e-(t-t_O)/\tau E'$

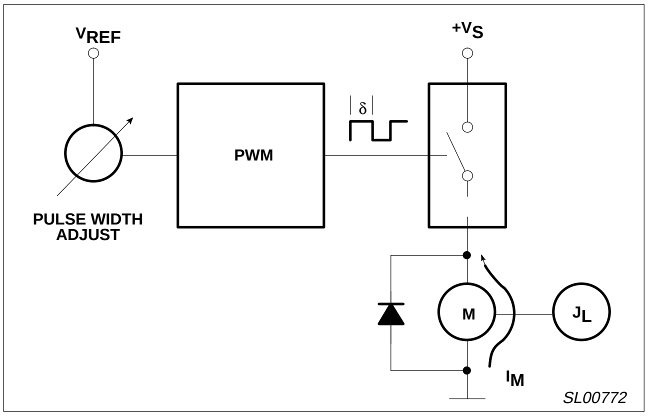

Figure 3. Simplified PWM Motor Control

The simultaneous solution of Equations 1-3 over many cycles will result in a figure for the average motor current, I_{ave}. This magnitude is much higher prior to armature rotation.

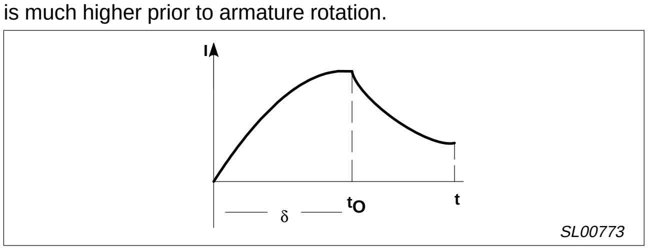

Figure 4. Motor Current Waveform

Note that motor current at the end of the cycle time, T, remains at a level, I_1, which is the starting current of the next cycle. As this sequence repeats, adequate current soon flows to cause armature rotation. As soon as rotation begins, back emf is generated which subtracts from the supply voltage. The general motor equation then becomes:

EQ4

$L_A di/dt+R_T i=V_S(t)-\varepsilon$

For a given PWM duty cycle, δ, the motor reaches a quiescent speed, ω-rpm, governed by the negative load torque and damping friction. With the end of the starting ramp, duty cycle is reduced because less current is required than was necessary for accelerating the motor and load inertias. The torque available from the motor is now lower due to the reduced I_{ave} level and a constant rpm is reached governed by average friction and loading. Torque is related by:

EQ5

$Torque=I_{ave}K_T$,

where K_T=Motor Torque Constant

For a low inductance motor where the electrical time constant is much less than the

duty cycle, δ, average current will be nearly equal to:

EQ6

$I_{ave} \cong (V_S-\varepsilon)\bullet\delta/R_T$

For a motor time constant, τ_E, close to the switching period, the current will be proportionately lower as determined by the exponential current equations, (Equations 2 and 3 where,

$V_S=((V_t)-\delta).)$

In summary, the principle control variable in the PWM motor control system is "duty cycle', δ; by changing δ, motor torque and velocity may be tightly controlled. Next we shall discuss the integrated controller.

THE SWITCHED MODE CONTROLLER

For the remaining portion of the paper, the NE5560 will be the principle integrated switched-mode controller referred to. Let us examine some of its features and then see how they fit into a number of motor drive designs. The device (see Figure 5) contains an internal voltage reference of 3.72V connected to the non-inverting input of the error amplifier. The feedback signal from the motor tach or other monitoring element must be scaled to center about this positive input level. The error amplifier output, in addition to being available for gain adjustment and op amp compensation, is connected internally to the pulse-width modulator.

Frequency may be fixed at any value from 50Hz to 100kHz and duty cycle adjusted at any point from 0 to 98%. Supply is either voltage fed 11 to 18V, or current fed from 10 to 30mA. Automatic shut-down of the output stage occurs at low supply threshold -10.5V. The error amplifier has 60dB of open loop gain, is stable for closed loop gains above 40dB. It is compensated for unity gain by adding an external .02µF capacitor from Pin 4 to ground. The switching output is single ended from either emitter (+5V max) or collector output saturated during duty cycle on-time. The device has protective features such as high speed overcurrent sense on Pin 11, which works on a cycle-by-cycle basis to limit duty cycle, plus a second level of slow start shutdown. It is this input which can be adapted to act as a motor torque limit detector.

THE OPEN LOOP PWM CONTROLLER USING THE NE5560 FOR SWITCHED MODE MOTOR DRIVE (SMMD)

For a given motor characteristic the switched-mode controller frequency should be set to allow best dynamic response considering starting current and motor electrical time constant, as discussed previously. The drive transistors must be capable of carrying peak motor current and, particularly if voltage above 50V is to be switched to the motor, these devices must be protected by snubber networks and diode transient suppressors. The new power MOS FETs provide an excellent solution to many DC drive designs since very low drive current is needed and they are self-protected from reverse transients by an internal intrinsic diode. These devices may be paralleled for added power handling capability.

Figure 6 shows a simple unipolar drive capable of driving a low voltage motor controlled by an external DC voltage to the PWM.

CONSTANT VELOCITY SERVO

Figure 8 shows in block form the general circuit used to obtain a constant speed SMMD servo. Figure 8a shows a unipolar drive using DC tachometer feedback to the PWM error amplifier. Starting torque is limited by the slow start circuit which limits duty cycle at power on. Average motor current is determined by the duty cycle which, in turn, is governed by the speed torque characteristic of the motor as was shown in Figures 7a-7c.

Figure 8b shows a bi-directional drive in a half-bridge configuration. In this case the duty cycle controls the direction of motor rotation. If the average duty cycle favors the CW switch, the motor turns CW, and vice-versa for the CCW switch. This circuit form can actually be used for both velocity and position servo-designs. The reversing switch allows tach output to match the polarity of the PWM reference which is always positive.

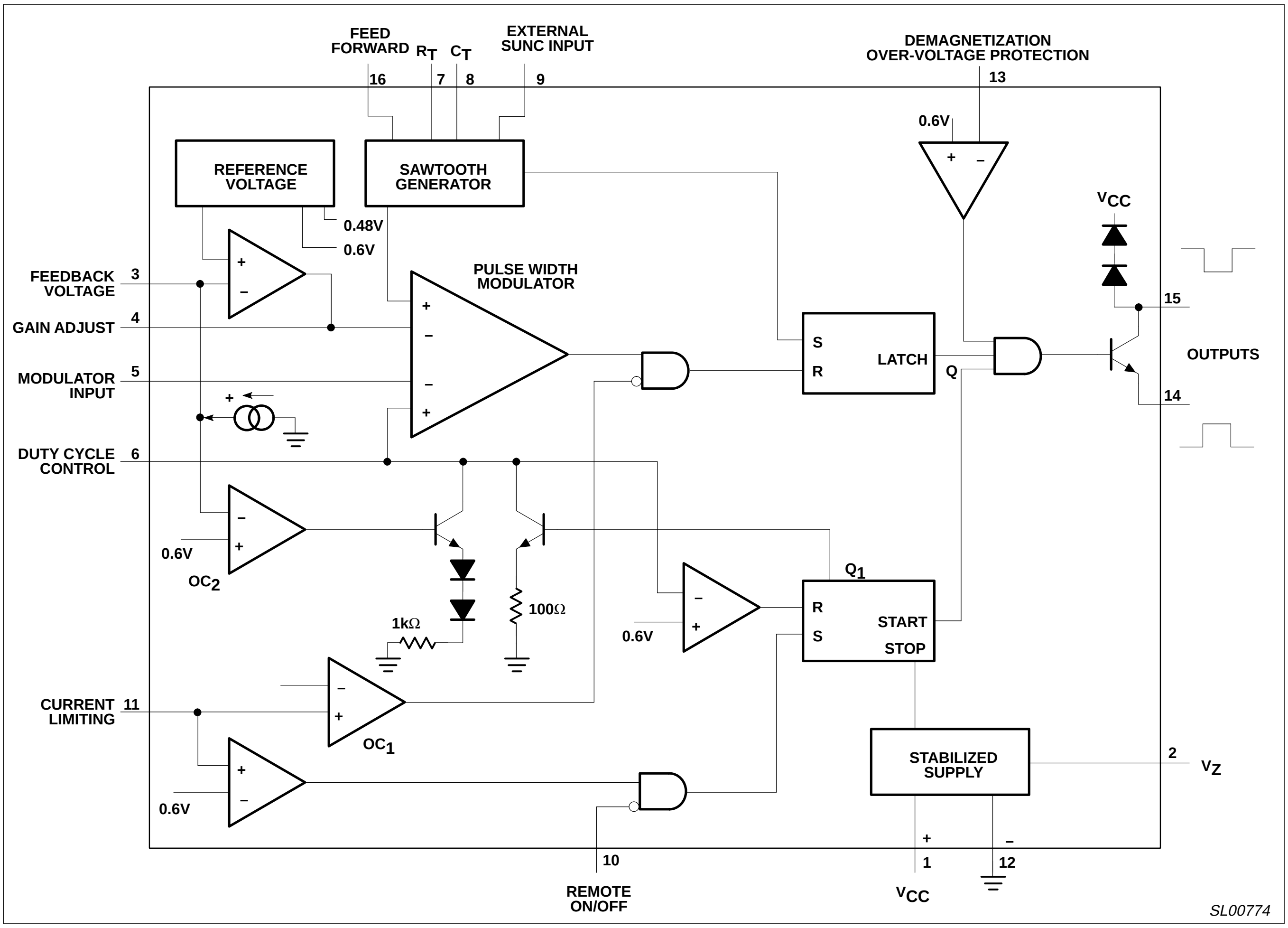

Figure 5. NE5560 Block Diagram

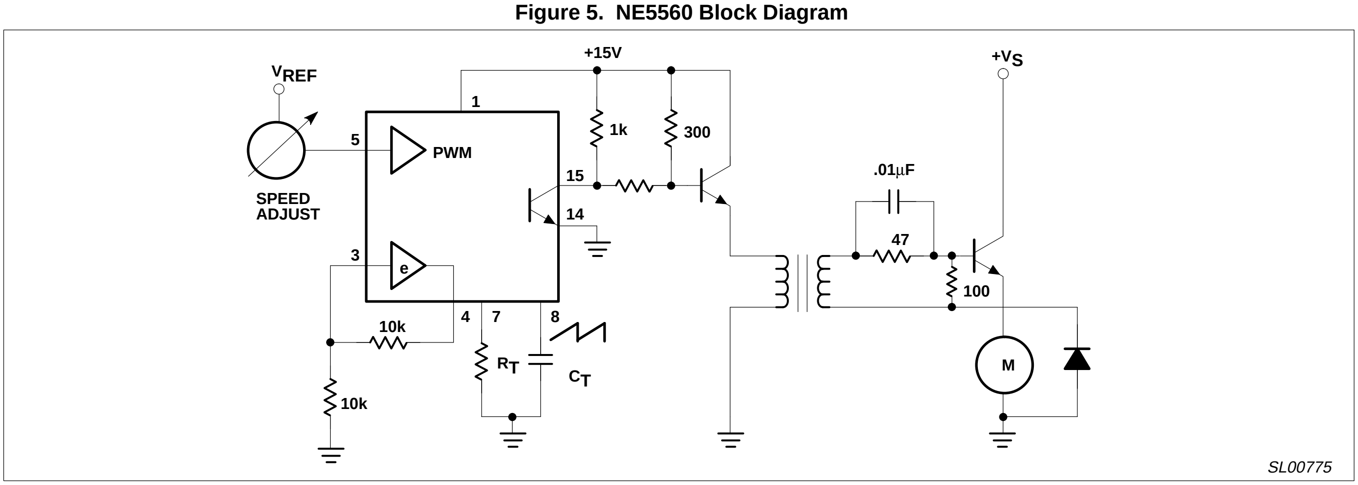

Figure 6. Unipolar Drive

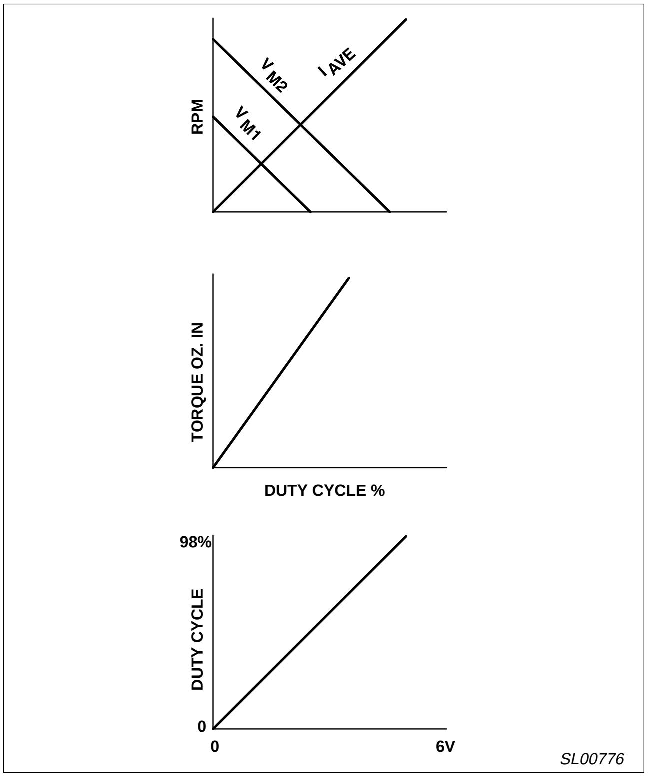

Figure 7. PWM Duty Cycle vs Motor Speed and Torque

FIXED SPEED SERVO

The unipolar drive circuit in Figure 9 uses the NE5560 to develop a switched-mode motor drive (SMMD) with constant speed control suitable for small 20V motor operation. The switching drive is developed by a single IRF130 power Hex FET capable of 12 amps continuous current with a voltage rating of 100V drain to source. The PWM drive from the NE5560 is applied to the gate at a nominal 10kHz, although much higher frequencies are possible. Peak gate to source (V_{GS}) is 10 to 15V to provide minimum R_{on}. A shunt return resistor is placed in the source lead to monitor motor drive current on a cycle-by-cycle basis with resistance value set to develop +0.48V at the desired maximum current. The NE5560 then automatically limits the duty cycle, should this threshold be exceeded. This may be used as an auto torque limit feature in addition to protecting the switching device.

The network from Pin 2 (V_Z) to Pins 5 and 6 provides a simple slow start by gradually ramping up the duty cycle at power on.

DYNAMIC VARIABLE DUTY CYCLE BRAKING

R_3, R_4 sets fixed braking duty cycle control by forcing Pin 3 to remain at ≅ +3V, thereby causing a relatively long duty cycle for braking communication. The higher V_B is set, the shorter is the duty cycle, which results in slower braking rate. Over-current circuit is still active.

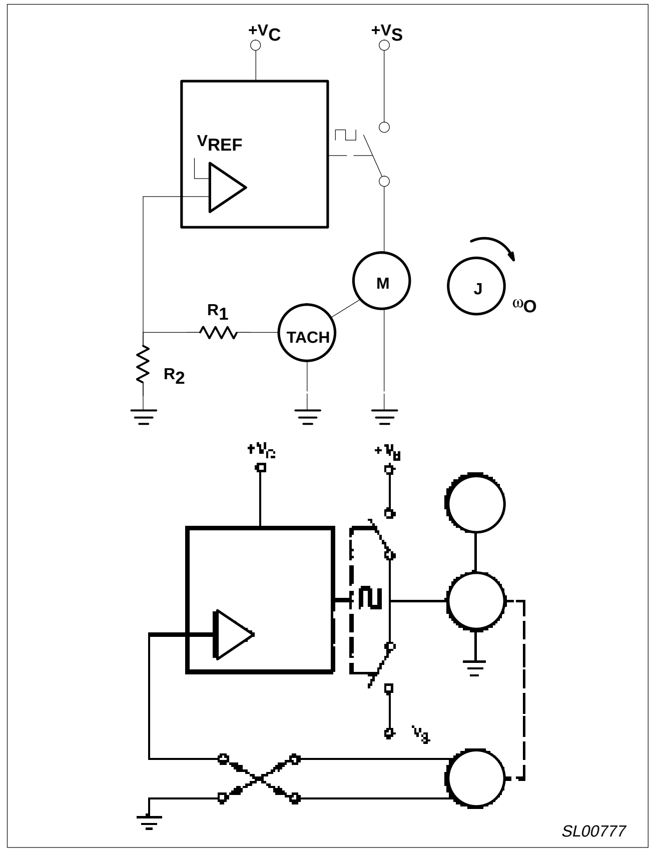

Figure 8.

POSITION SERVO USING SMMD WITH ΜP CONTROL

By coupling the switched motor drive in a bi-directional drive as shown in Figure 10, and then sensing linear position with a potentiometer or LVDT connected to a lead screw, for instance, the loop can be closed on a position servo. The input to control position of the mechanical stage may be fed as a DC offset to a summing amplifier whose output is fed to Pin 5 of the NE5560, as shown. Forward lead-lag compensation may be combined with the summing amplifier function to achieve a stable response. A velocity loop may be closed through the error amplifier at Pin 3.

Note that Pin 5 may easily be interfaced to a microprocessor by means of a unipolar D/A converter working in the 1 to 6V output range.

CONCLUSION

The switched-mode motor drive, SMMD, using small, easily available, monolithic integrated control devices designed for switched-mode power, SMPS, applications may easily be adapted to perform a number of useful and efficient torque, velocity and position operations. The ready availability of good quality switching power devices in both bi-polar and power FET technology makes such designs even more effective and easily attainable by the controls systems designer.

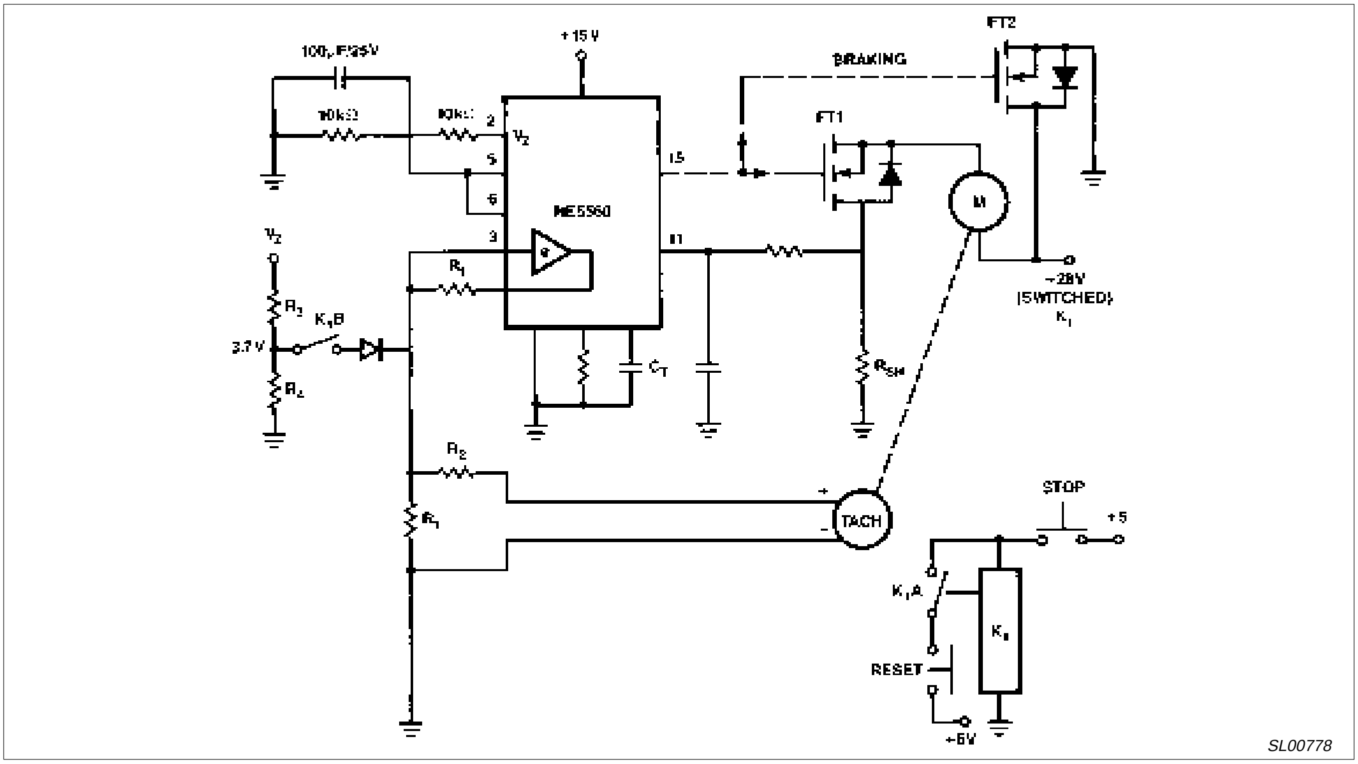

Figure 9. Basic Unidirectional Drive with Dynamic Braking

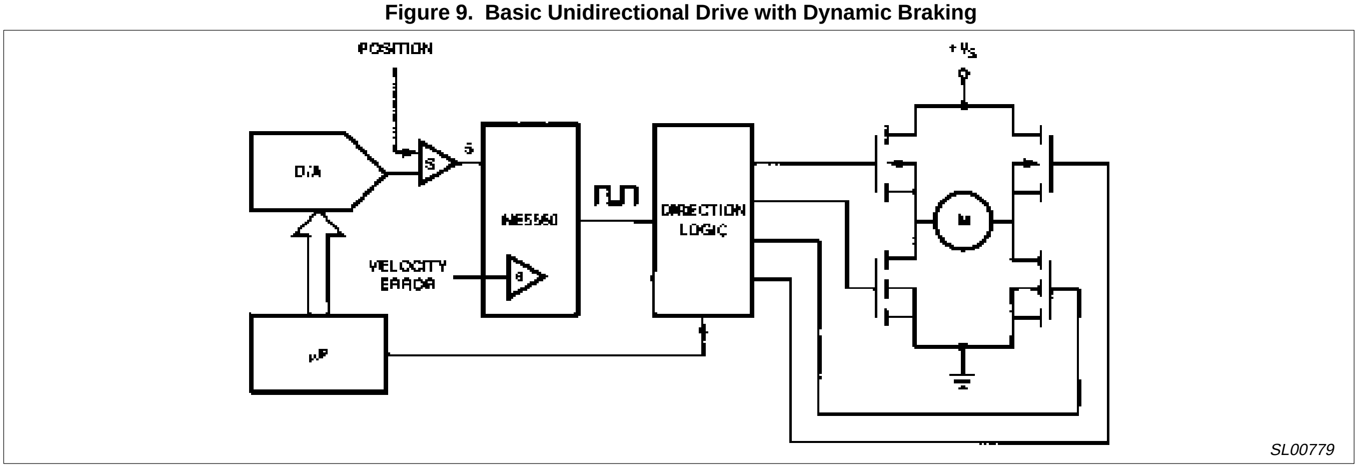

Figure 10. Microprocessor Control of PWM Drive with Four Quadrant Output

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