



a technical paper from Bodine Electric Company

Selecting DC Motor Speed Controls for PMDC Gearmotor or Motor Applications – SCR vs. PWM, Filtered vs. Unfiltered

Basic DC motor speed controls accomplish the conversion of AC power to DC with varying degrees of DC voltage “purity.” For proper control selection you’ll need to identify which performance criteria are important to your application. We’ll review how different speed controls affect the quality of DC output and consequently, the performance of your DC gearmotor or motor. In addition, we’ll discuss how to evaluate whether filtered or unfiltered DC motor speed controls are best for your permanent magnet DC (PMDC) motor application.

To better understand DC output characteristics, and how they affect motor performance, we’ll compare the output waveforms of four common speed controls.

1. The unfiltered half-wave Silicon Controlled Rectifier (SCR) control is the most basic speed control available. Very simply, it places a single SCR in series with the DC motor’s armature winding as shown in Figure 1A (see page 2). This converts the AC into DC by simply blocking the negative half cycle of the AC sine wave. As can be seen in Figure 1B, this produces a fairly choppy output for the motor and only faintly resembles a true DC current.

2. The unfiltered full-wave SCR control improves on the unfiltered half-wave SCR control by adding another SCR and two diodes to form a bridge rectifier as shown in Figure 2A. Instead of just blocking out the negative half cycle of the AC sine



wave, the unfiltered full-wave SCR control inverts it into another positive half cycle. As can be seen in Figure 2B, this output still looks choppy, but it’s getting closer to looking like a smooth DC current.

3. The filtered full-wave SCR control design utilizes a large filter capacitor that is placed across the output of the control as shown in Figure 3A. Since a capacitor stores energy during the rising portion of the AC sine wave and then discharges it slowly during the falling portion, it effectively smoothes out the choppy output current created by the switching of the SCRs. As a result, a smooth output current is produced that approximates pure DC, as shown in Figure 3B.

Four common speed controls and their output waveforms

Unfiltered Half-Wave SCR Control

Figure 1A
Simplified circuit diagram

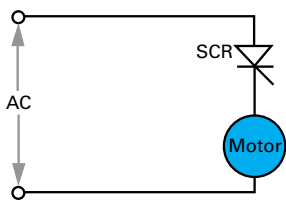
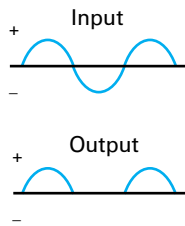


Figure 1B
AC input voltage versus
DC output voltage



Unfiltered Full-Wave SCR Control

Figure 2A
Simplified circuit diagram

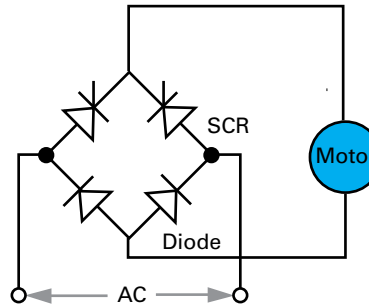
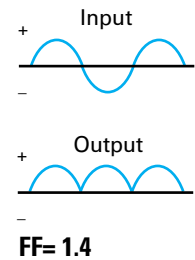


Figure 2B
AC input voltage versus
DC output voltage



Filtered Full-Wave SCR Control

Figure 3A
Simplified circuit diagram

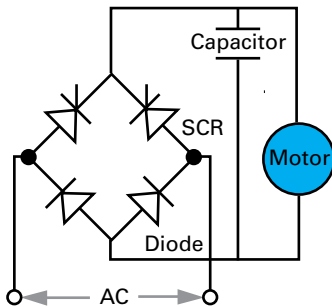
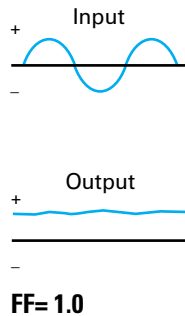


Figure 3B
AC input voltage versus
DC output voltage



Filtered PWM Control

Figure 4A
Simplified circuit diagram

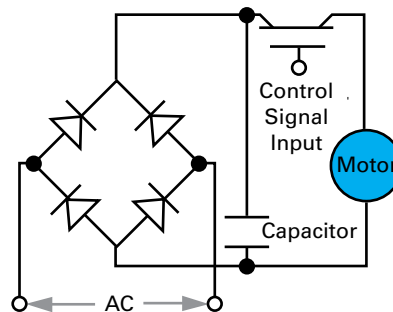
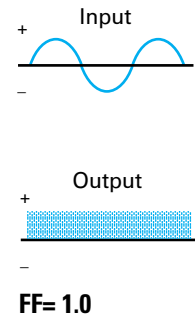


Figure 4B
AC input voltage versus
DC output voltage



4. A filtered Pulse Width Modulation (PWM)

control uses a different method to produce a smooth output current that is comparable to that of a filtered full-wave SCR control. The AC supply is first rectified and filtered before it is switched on and off to vary the output voltage, as shown in Figure 4A. In contrast, the filtered full-wave SCR control simultaneously rectifies and switches the AC supply, then filters it after switching. The output current shown in Figure 4B may look choppy, but due to the rapid switching of the PWM controls and the high inductance of typical DC motors, the current appears to be pure DC.

Filtered versus unfiltered speed controls

As we can see, subtle differences in control design affect the purity, or form factor (FF), of the DC output power and can result in significant performance changes in motor and control operation (See page 3 for definition of form factor). Motor speed range, continuous torque rating, motor operating temperature, brush life, AC current draw and electromagnetic interference (EMI) are among the items that can be adversely affected and can have severe consequences if not taken into account in the system selection process.

Form Factor (F.F.)

Form factor is a measure of departure from pure DC, with pure DC having a form factor of one. It is defined as the root-mean-square (RMS) value of the current divided by the average value of the current. You want to be as close to one as possible for smooth DC output.

The form factor for various types of controls is given in the table below. In general, the higher the form factor from a control, the hotter a motor will run with that control.

Effects of various types of rectification and filtering on form factor

Control Type	Form Factor
Half-Wave Unfiltered	1.6-2.0
Half-Wave Filtered	1.1-1.5
Full-Wave Unfiltered	1.1-1.6
Full-Wave Filtered	1.0-1.1

MOTOR TEMPERATURE. Operating a motor with a higher form factor, unfiltered control can result in motor winding temperatures as much as 30°C higher compared to operation with a filtered control. From page 8-23 of the *Small Motor, Gearmotor and Control Handbook from Bodine (the Handbook)*:

“The form factor is an important consideration with motors designed to operate on direct current. When operated from rectified power versus pure DC, the increase in motor heating for a constant output is approximately proportional to the square of the form factor. For example, a motor operating from half-wave rectified DC current will have approximately 2.5 times the heat rise of the same motor operating on 1.0 form factor DC.”

This is especially important in applications where the motor is located at a place in the machine where people can touch it. Certain safety standards dictate that any parts exposed to human touch can't exceed a surface temperature of 60°C. A

hot motor might also negatively impact other components around it by raising the surrounding ambient air temperature. This effect will be even greater if the motor is located in a sealed enclosure with other temperature-sensitive hardware.

MOTOR LIFE. Besides the safety concerns previously mentioned related to higher motor operating temperature, a hotter motor will also have a shorter life expectancy.

From page 7-34 of Bodine's *Handbook*: “Motor life expectancy is a function of total temperature. Insulation, lubricant and seals are all affected by temperature. This is illustrated by the following:

- 1) As a general rule, ball bearing or gear lubricant life is halved for every 25°F (approximately 14°C) increase in temperature. Heat will eventually degrade most lubricants and seals, leading to leakage, increased friction and extra maintenance.
- 2) Generally, the motor insulating life is halved for each 10°C increase in total temperature.”

Long life is especially important for motors used in industrial machinery that might be operated during three working shifts a day, or 24 hours per day. Motors are generally designed for a certain number of operating hours, so a motor designed for 10,000 hours of running time would be expected to last almost five years if used eight hours per day and five days per week. But that same motor might last just over one year if used 24 hours per day and seven days per week. If that life is further cut in half because of the extra heating from an unfiltered control, then that motor might have to be replaced every six months.

BRUSH LIFE. With an unfiltered control a high peak current is necessary to maintain the necessary average current output for a given power requirement. These higher peak currents contribute to accelerated brush and commutator wear, reducing brush life to as much as 50% compared to operation with a filtered control. This is even more evident in critical high speed applications like laboratory centrifuges. In these instances,

brush life is short to begin with because of the increased linear speed between the brushes and the commutator when operating at speeds as high as 15,000 RPM. Using an unfiltered control in these situations means you might have to replace the brushes every few months depending on how often and how long the centrifuge is used.

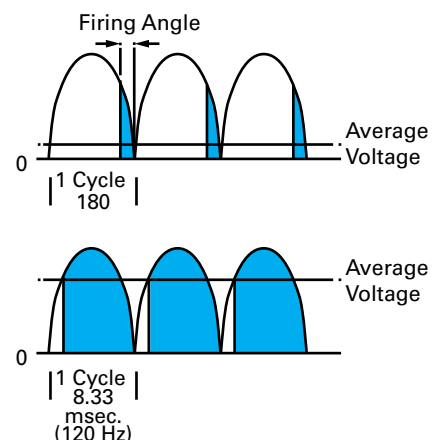
SPEED RANGE. Maximum speed can be 45 percent higher with filtered controls. The maximum output voltage of an unfiltered control powered from a 115 VAC line is 90 VDC, whereas the maximum output from a filtered control is 130 VDC. Since the speed of a DC motor is proportional to the DC voltage, the motor will run faster with a filtered control (typically 2,500 RPM) than it will with an unfiltered control (typically 1,725 RPM).

A wide speed range is important in applications that require operation at both a very low speed and a very high speed. For example, in a printing press, motors are used to drive the pumps that supply ink. During the printing process, the motors run at a low speed and maintain a constant pressure. At the end of the printing process, there is a flushing process to clean the ink out of the system. During the flushing process, the motors run at a high speed.

CONTINUOUS TORQUE. A motor might develop as much as fifty percent greater continuous torque with a filtered control. Motor torque ratings are based on thermal limits of the motor insulation system, among other things. For example, consider a certain motor with Class A insulation that is rated for a continuous load of 101 oz-in. with a 1.0 FF control in 40°C ambient conditions. The National Electrical Manufacturers Association (NEMA) standards dictate that the temperature rise of this motor under rated load not exceed 70°C. If this same motor were used with a 1.6 FF control, the load would have to be reduced to 58 oz-inches, or only 57 percent of the 1.0 FF rating, to keep the same temperature rise of 70°C.

Silicon Controlled Rectifier (SCR)

An SCR is a three-terminal device with an anode, a cathode and a gate. It functions as a diode (only conducts current in the forward direction from the anode to the cathode) but will do so only when a trigger voltage is applied to its gate. Once an SCR is fired, the gate signal can be removed without stopping conduction. Conduction ceases when the positive voltage is removed from the anode. When an SCR is used to rectify alternating current, the point during the positive half cycle of the input current at which the rectifier is turned on can be adjusted by the timing of the application of the trigger signal to the gate. At the end of the positive half cycle, the SCR automatically turns off as the applied polarity of the voltage reverses. The timing of the trigger signal determines the "firing angle" (the electrical angle from the zero crossing point when the SCR fires). When the SCR is switched on, current flows to the motor winding. The position of the firing angle determines the average voltage and, in turn, the output speed. If the SCR fires early in the cycle, current flows to the windings for a longer time and the average voltage is higher.



The effect of the firing angle on the average voltage of an unfiltered full-wave SCR control

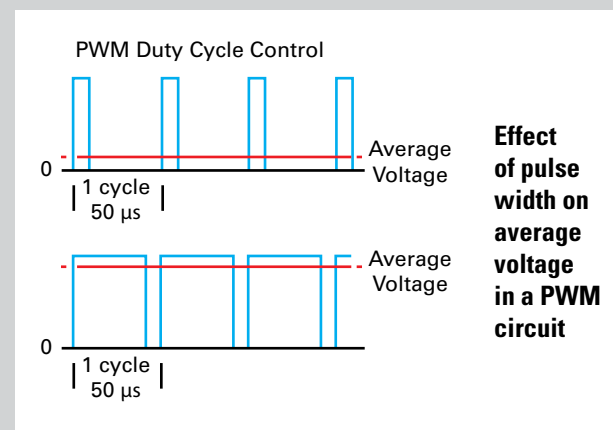
AC CURRENT DRAW. AC root-mean-square (RMS) current draw of unfiltered SCR control can be 20 percent lower. During each half cycle of the AC line voltage, a large current spike occurs in a filtered SCR control because of the charging of the filter capacitor. Depending on the control and size of the motor used, this current spike could be five times the actual DC current going to the motor. This raises the RMS AC current going into the control and puts a greater demand on the AC power supply and other components like circuit breakers, relay contacts, switches, fuses, etc. In a large factory where hundreds of machines in the same operation are powered at once, the cost of the additional AC power required to drive the filtered control might outweigh other cost considerations.

EMI. Unfiltered controls can produce less electromagnetic interference (EMI). The same current spikes described above might cause problems in applications that have other components sensitive to EMI or in applications that are required to meet a certain Electromagnetic Compatibility (EMC) or Federal Communications Commission noise limit. Even though both types of controls would require AC line filters to meet European EMC standards, the filtered control might need a more expensive one because of the higher current rating.

SUMMARY. Proper speed control selection depends on an understanding of how DC motors are affected by various grades of DC voltage. The degree to which alternating current is rectified (converted) to direct current will determine the overall efficiency of the motor and control system. We measure the departure from pure DC using the term form factor, with pure DC having a form factor of 1.0. When motors are operated from rectified power versus pure DC, the increase in motor heating for a constant output is approximately proportional to the square of the form factor. For continuous duty applications, this increased heating effect must be accommodated. If you're using a cheaper unfiltered control, you might need to purchase a larger, more costly motor to keep motor operating temperatures within design

Pulse Width Modulation (PWM)

PWM circuits use transistor switches instead of SCRs as voltage control devices. When the transistor is switched on, current flows in the motor winding. Just like the SCR control, the firing angle in a PWM circuit (the electrical angle between the start of the cycle and the point at which the transistor begins to conduct) determines the average voltage and, in turn, the output speed. A wider pulse width will result in a higher average voltage.



limits. If you select a filtered control, which lowers motor operating temperatures, you might save on overall system cost since a smaller, less expensive motor is all that's necessary. Smaller motors offer the additional benefits of lower weight and space savings.

Before selecting a DC motor speed control for your application, determine the performance criteria important to your operation and then evaluate whether a filtered or unfiltered speed control will be better for your brush type PMDC motor application.

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Filtered DC Motor Speed Controls

The WPM filtered control provides high torque and lower operating temperatures. It features pulse width modulation (PWM) circuitry for precise speed control. DIP switches allow the control to be easily calibrated for different size motors. Controls are available with either ¼" quick connect tabs or a plug-in terminal block.

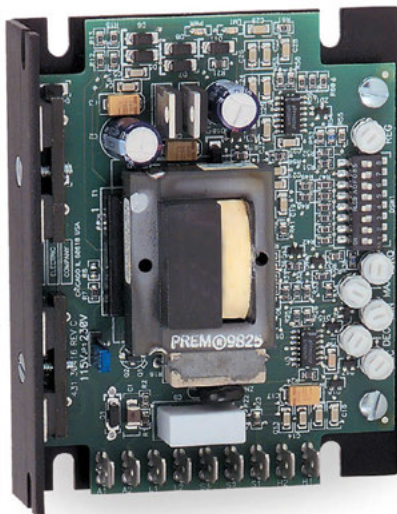
- **Input Voltage:** 115 VAC, 50/60 Hz; **Output Voltage:** 0-130 VDC
- **Form Factor:** 1.0
- **Inhibit Function:** connections for optional user-supplied inhibit switch available
- **Filtered DC Output:** for cooler motor operation, longer brush life, lower audible noise, and wider speed range
- **Back EMF Feedback:** maintains better than 2% speed regulation
- **Two Diagnostic LEDs:** indicate when power is on and when current output is at limit set by TORQ pot
- **User-Adjustable Pots:** for torque limit, minimum speed limit, maximum speed limit, acceleration time, and speed regulation
- **Speed Adjustment:** 10 kΩ single turn speed pot (supplied with chassis type controls); speed can also be adjusted via isolated 0-5 VDC remote signal (optional isolation card required)
- **Optional Model 3984 Isolation Card:** provides 4-20ma interface, a grounded circuit reference, and signal for multiple controls; sold separately



Enclosed and chassis models available

Unfiltered DC Motor Speed Controls

The UPM unfiltered control draws lower AC line current than comparable SCR filtered controls. DIP switches allow the control to be easily calibrated for different size motors. Controls are available with either ¼" quick connect tabs or a plug-in terminal block.



Enclosed and chassis models available

- **Input Voltage:** Chassis model operates from either 115 VAC or 230 VAC line, selectable with plug-in jumper; the enclosed model features a factory-installed 115 Volt AC line
- **Output Voltage:** 0-90 VDC; 0-180 VDC
- **Form Factor:** 1.6
- **Switchable Output:** for 0-90 VDC or 0-180 VDC (chassis models only)
- **Back EMF Feedback:** maintains better than 2% speed regulation
- **Two Diagnostic LEDs:** indicate when power is on and when current output is at limit set by TORQ pot (chassis models only)
- **User-Adjustable Pots:** for torque limit, minimum speed limit, maximum speed limit, acceleration time, deceleration time and speed regulation
- **Inhibit Function:** connections for optional user-supplied inhibit switch available
- **Speed Adjustment:** 10 kΩ single turn speed pot (supplied with chassis type controls); speed can also be adjusted via isolated 0-5 VDC remote signal (optional isolation card required)
- **Optional Model 3984 Isolation Card:** provides 4-20ma interface, a grounded circuit reference, and signal for multiple controls; sold separately

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