## PDHonline Course E246 (4 PDH)

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# DC Dynamic Braking

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# DC Dynamic Braking

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## Definition

Dynamic Braking is a method used to electrically stop movement of a mechanical device. This method generally precludes use of other mechanical braking devices. Electrical energy is used to halt movement and defeat inertia of the moving device after the power used to create and maintain movement is removed. The key word here is "**energy**".

Energy refers to force at a distance at a prescribed period of time. Horsepower is commonly used to express mechanical power. However, it actually is a classical term for energy. Horsepower is defined as 550 ft. lbs. sec. Thus, if we were to lift 275 pounds for 2 feet for 1 second, we would exert one horsepower (275 lbs. times 2 ft. for 1 sec. would equal 550 ft. lbs. sec.). A frequently used term for electrical power is watts. For direct current applications, watts is generally the product of voltage times amperage. However, classical terms for electrical energy is coulombs or joules. One joule is equal to one watt second. When we pay our electric bill, we are paying for energy in the form of kilowatt hours (or thousands of watts per hour). The conversion of electrical energy to mechanical energy is 746 watt sec. to one horsepower. The dimension of power and time is crucial to Dynamic Braking. Not only must we specify the task of stopping device movement, but we must also specify the time frame in which the movement must stop.

The advantages in using electrical Dynamic Braking rather than mechanical braking devices can be readily recognized. Response to braking commands can be immediate; the braking action can be easily automated; components are generally less expensive; and the braking device requires less maintenance. Perhaps the main disadvantage is that the electrical energy required to stop the device within the required time may not be conveniently available.

## Considerations for Circuit Development

We will concentrate on Dynamic Braking of devices employing direct current motors. While circuits can be devised to perform dynamic braking on Alternating Current motors, the principles of motor operation are different. Direct current motor rotation can be easily reversed by simply reversing the polarity of the voltage (or current). AC motors sometimes require changes to the internal circuit or wiring hookup. Thus, simply reversing the current flow effects braking action on a DC motor.

Our first concern in circuit development is to define the task and parameters of performance. What must be done? How reliable and accurate must performance be? How much energy can be used and how much is available? Other associated considerations are cost of product, cost and time to develop and ease of manufacture. Once the task and parameters are defined, we consider the components necessary to complete the task. This can range from high-tech devices such as custom computers to commonly available resistors, capacitors etc.

When considering the task, the application of the device must be taken into account. An application I have experienced involved a remotely controlled, long range, optical zoom lens which required instant stopping while focusing. On a larger scale, Dynamic Braking is used to supplement brakes on trains. This course will deal with a model airplane DC motor used to drive a propellor. It was chosen for an essential reason, the components were readily available.

## Defining the Task and Parameters

Our task will be to stop rotation of the propellor as quickly as possible to prevent injury to people or objects that might be near the propellor blades when it is on the ground. Also, stopping rotation quickly upon landing will assist in shortening the landing roll. An attractive feature would be to actually reverse propellor rotation upon landing to effect reverse thrust braking of the airplane and further shortening the landing run. The circuit must employ only components that are light in weight to keep aircraft weight to a minimum. The function must be controlled by a simple switch which can be operated with a remote controlled device for maneuvering the airplane. The device is limited to minimal use of the energy that is provided for the operation of the airplane motor. Any additional energy sources must be minimal in weight.

The power source to be used for motor operation is a 6 volt battery capable of delivering 30 amperes for about 15 minutes. Upon bench testing, the motor with the propellor installed used approximately 29 amperes upon initial application of power with amperage decreasing to steady state condition at approximately 22 amperes within about ½ second. Upon removal of power, the propellor stopped rotating in 3 to 4 seconds, indicating that friction was minimal. These tests were done with little or no external air movement.

It is stressed that this data is approximate. More precise measurements would require high quality instrumentation. The accuracy for collecting data was accommodated with a digital multimeter and timer. Keeping this in mind, the data is adequate for calculation of parameters. In order to stop the propellor, it will be necessary to apply at least the same amount of energy in opposition to the movement that was used to accelerate the propellor to steady state velocity. The energy, therefore, to accelerate the device to steady state rate of revolution (revolutions per minute or RPM) can be approximately determined by calculating the watt-secs. or joules expended at startup (6 volts from 29 to 22 amperes for ½ second). Because overcoming inertia from a stopped position was necessary, the amperage naturally varied before achieving steady state condition. Although the rate of amperage change may not have been linear, we will assume it was for the accuracy we require. Thus, we can use average amperage, given voltage and estimated time to determine the watt-secs. (or joules) required to accelerate the motor and propellor.

The following calculations depict the initial amperage as $i_o$ and the steady state amperage as $i_{ss}$. The average amperage is shown as $i_{av}$.

$$i_o \approx 29a$$

$$i_{ss} \approx 22a$$

$$i_{av} \equiv (i_o + i_{ss}) \div 2 \equiv (29 + 22) \div 2 \approx 25.5a$$

$$joules \equiv volts \times amperes @ 1\sec$$

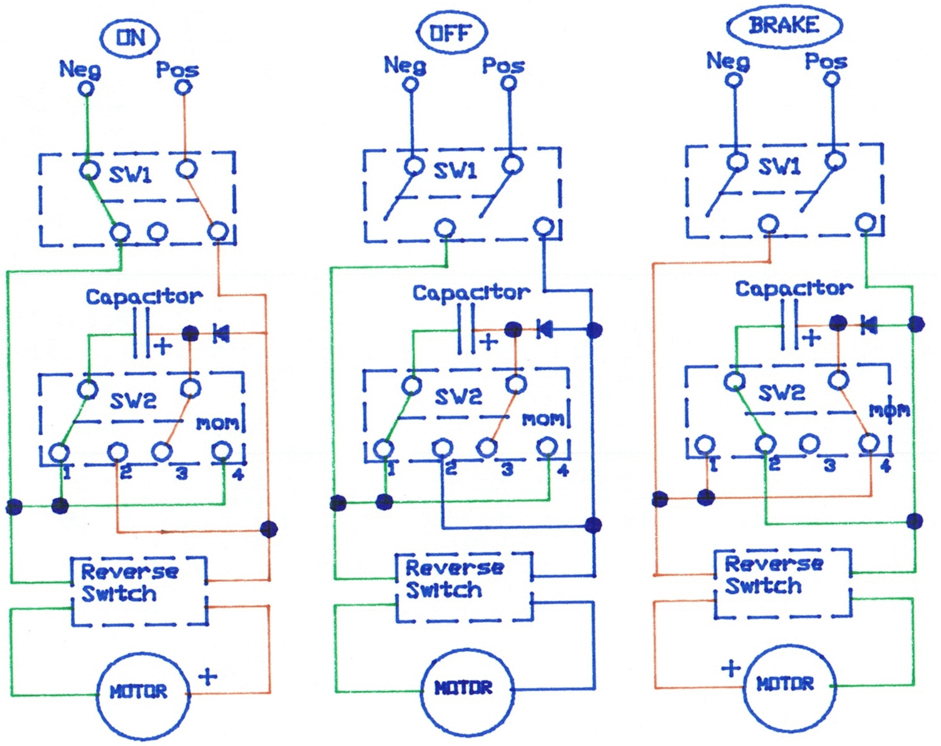
$$joules \approx 6 \times 25.5 @ 0.5\sec \approx 76.5 watt - \sec.$$

The minimum energy required to instantly stop rotation of the propellor is 76.5 joules. More energy will not only stop the device but, if the energy remains in opposition to the movement, it will actually reverse the rotation. Another consideration is the time required to deliver the proper amount of energy.

In order to calculate the time required to deliver the energy, we must consider the effective resistance of the motor. When operating a DC motor, the apparent resistance varies between the startup of the motor to the time it reaches constant speed. The original apparent resistance determines what is known as "locked rotor" resistance. This can be determined by preventing the motor from rotating, applying a known voltage and measuring the amperage through the motor. We have determined this value from our amperage data upon startup of the motor and have termed it as $i_o$ or i at time zero. As the motor achieves rotational velocity, it creates an opposing electromotive force (back EMF) which limits the amperage to that necessary to maintain energy to drive the load, in this case the propellor. We have termed this amperage as $i_{ss}$, or i at steady state. However, when power is removed from the motor, the back EMF no longer is present. Thus, in order to determine effective resistance, we can apply "locked rotor" amperage to the commonly known equation for DC resistance.

$$R \equiv {}^{v}\!/_{i} \equiv {}^{6}\!/_{29} \approx 0.21 ohms$$

We are now ready to explore options for circuitry. The conditions stated that any additional energy or power sources be minimal or, preferably, not used. While some famous scientist stated that energy can neither be created nor destroyed, we do know that energy can be stored. A common electrical energy storage device is the capacitor. Application of capacitors to AC circuits is different in some respects to DC circuits. This is illustrated in PDH course E219- "Single to Three Phase Conversion Circuit". Applying capacitors to DC circuits concentrates on their capability to store energy. As we know, capacitors consist of two plates of conductive material placed in very close proximity to each other with a thin layer of electrical insulation between them. When one plate is connected to receive a positive charge and the other connected to the negative, the plates will hold that charge until the plates are then electrically connected to dissipate the charge. The time required to dissipate the charge is related to the resistance in the connection that dissipates the charge. We can charge the capacitor with the power source used to run the motor. At the proper time, power can be removed and a calculated charge can be applied to the motor in opposite polarity to provide stopping. A greater amount of our calculated energy can be applied if reversal of the motor is desired. "Circuit 1" shows a basic circuit to accomplish this.



## Circuit 1

Circuit 1 depicts an electrical schematic designed to apply power to a motor. This is done using a switch (SW1). The switch is a double pole, single throw switch (DPST) with an "on" and an "off" position. The schematics show three circuit conditions, "ON"; "OFF"; and "BRAKE". The red lines indicate the part of the circuit that is connected to a positive side of the power and the green lines indicate the negative side. SW1 connects to a second switch (SW2) which is connected to a capacitor. This switch is a double pole, double throw switch with a momentary position for one position. A third switch (labeled "Reverse Switch") is shown, but is an option. It is not used on this application, but can be used to reverse direction for a positioning device (such as a zoom lens). This will be considered to remain in the position shown for our discussion.

When the circuit is in the "ON" position (left diagram) SW1 connects the power source directly to the motor. The motor positive connection is shown with a plus sign. While the motor is being normally powered, SW2 is in a normal position and has connected the power negative side to the capacitor through pin 1. The positive side of the power is connected through a diode to the other capacitor connection. The diode is shown as an arrow figure. This is an electrical "check valve" and will only allow current flow in the direction of the arrow. Thus, while the motor is running, the capacitor is charged to the system voltage. Note that the lines in red show positive charge and in green show negative charge when a circuit is completed.

When the circuit is in the "OFF" position (middle diagram), SW1 is turned to the "off" position and SW2 is left in the normal position. Power is now disconnected to the motor and the capacitor terminals are not connected. Although the negative terminal of the capacitor is still connected to the motor, current cannot flow to the motor from the positive side because the diode prevents current flow in that direction. Note that there is no complete circuit, and part of the wiring contains neither red nor green lines. Also note that no connection exists between the positive and negative terminals of the capacitor, thus the capacitor remains charged. In this case, the motor will coast to a stop.

When the circuit is in the "BRAKE" position, Dynamic Braking is actuated. To effect braking, SW2 is switched to the momentary position. This can only remain while the switch is held in this position. When the switch is released, it is spring loaded to return to the normal position. In the momentary or "BRAKE" position, the negative terminal of the capacitor is connected through pin 2 of SW2 to the side of the motor that was previously connected to the positive power source. The positive side of the capacitor is connected through pin 4 of SW2 to the side of the motor that was connected to the negative power source. Note that the positive (red line) is directed to the opposite side of the motor as shown in the "ON" diagram. The stored energy in the capacitor will continue delivering power in the opposite direction, providing dynamic braking until its energy is depleted or until the switch is released. The device is now prepared to be run again upon turning power on through SW1. In the application for a model airplane, both switches can be operated remotely with remote control devices, or SW2 can be replaced with a relay operated automatically from SW1. For immediate braking action, SW2 must be switched immediately after SW1 switches off the power. If immediate braking is not switched on, the propellor will be allowed to deplete its kinetic energy in coasting to a stop or slowing rotation. Thus, if dynamic braking is applied later, the energy in the capacitor will be greater than required to stop and the excess energy in the capacitor will tend to reverse motor rotation.

The next task is to determine the specifications for the components. The switch SW1 must be able to switch and carry at least 30 amperes steady state. The switch SW2 (or relay if used) must be able to carry a 30 amperes surge for a very short time. The diode must be able to sustain a surge amperage caused by a 6 volt potential for a fraction of a second, probably not more than 30 amperes. The energy required was previously determined to be 76.5 watt-secs. to stop the propellor. The equation for determining the value of a capacitor to store energy is $W=(½)\ Ce^2$. W represents joules in watt-secs., C represents the value for capacitance in farads and E represents the value of voltage used to charge the capacitor. However, the equation represents energy available provided the capacitor charge is completely dissipated. Thus, we will be concerned with a capacitance value larger than that indicated in order to effect stoppage within a reasonable time span.

$$W \equiv {}^{1}\!/_{2}\, Ce^{2}$$

$$C \equiv \frac{2W}{e^{2}} \equiv \frac{2\,x\,76.5}{36} \equiv 4.25\, farads$$

To effect stopping in reasonable time, we shall increase this value by 50% and calculate the time to stop movement. Thus, 150% of 4.25 farads is **6.38 farads**. The time and rate of power dissipation can be determined by voltage and amperage decrease in discharging a capacitor.

Voltage increase and decrease in charging and discharging a capacitor is exponential in nature. It is related to the mathematical "natural" number "e" (2.713~~~). Because we will be using "e"

for that number, we will depart from use of that letter in the next few calculations to signify voltage and will use lower case “v” instead.
$v_o$= voltage at time zero or charged voltage
$i_o$ = amperage at time zero or initial amperage
$v_t$ = voltage at specified time
$i_t$ = amperage at specified time

$$v_t \equiv v_o e^{\frac{-t}{RC}}$$

$$i_t \equiv i_o e^{\frac{-t}{RC}}$$

$$Joules_t \equiv v_t i_t \equiv v_o i_o e^{\frac{-2t}{RC}} \equiv v_o \frac{v_o}{R} e^{\frac{-2t}{RC}} \equiv \frac{v_o{}^2}{R} e^{\frac{-2t}{RC}}$$

To calculate the amount of energy imparted within a given time, we integrate the equation.

$$Joules \equiv \frac{V^2}{R} \int_0^t e^{\frac{-2t}{RC}}$$

$$\int e^{ax} dx \equiv \frac{1}{a} e^{ax}$$

$$\textit{Simplified:}$$

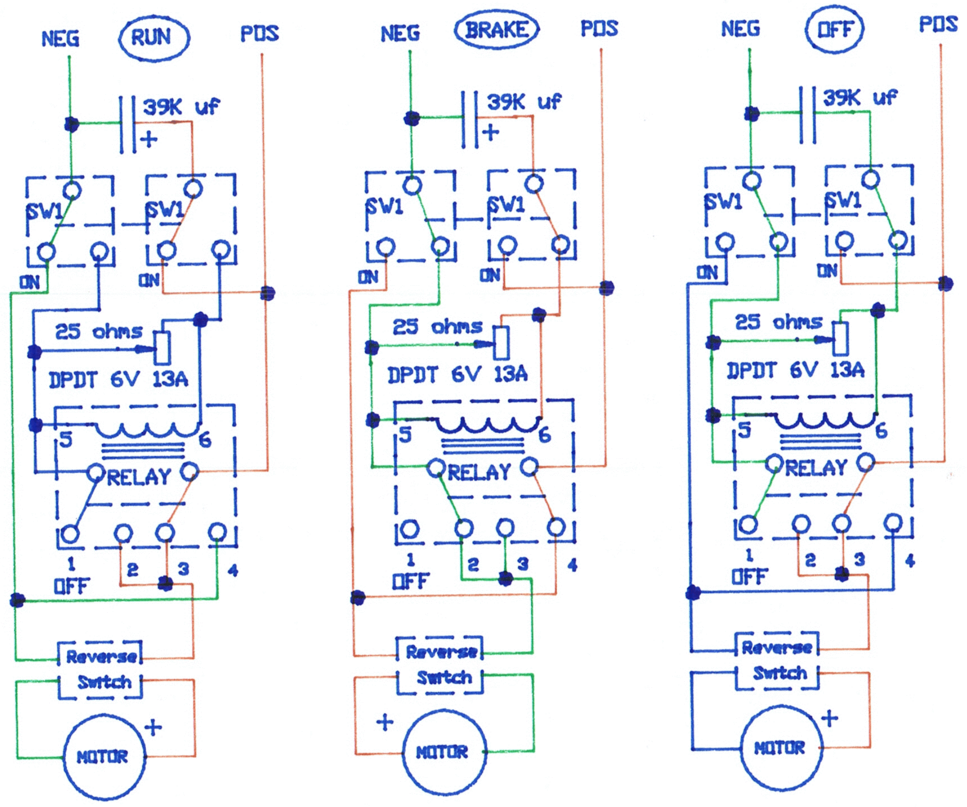
$$Joules \equiv \frac{Vo^2 C}{2} {}_0^t \left[1 - e^{\frac{-2t}{RC}}\right]$$

Using the appropriate values for the elements in this equation::
$V_o$ = 6 Volts; C = 6.38 Farads; R = 0.21 ohms; and Joules = 76.5 watt-secs
We will solve for t. **t = 0.736 seconds**.
Checking our calculations, we use t = 0.736 secs. and solve for the Joules in the equation.
We arrive at a solution. **Joules = 76.6 watt-secs**– close enough!

Now we shall evaluate the solution.

We have discovered that the solution will halt movement within about 3/4 second from removing power to the motor. However, we have specified a capacitor which stores 150% of the required energy in order to enable stoppage within a reasonable time. This means that about 38 watt-secs of energy will continue to be applied to the motor. The motor will be reversed for a short period of time unless the energy is disconnected from the motor. This requires further circuitry. Also, we stated that the components must be light in weight. A capacitor of over 6 farads will be too heavy for installation in a model airplane. While this solution can function in some applications, it is not feasible for this application.

Instead of an energy storage device, perhaps we can use the existing motor power source to provide the braking energy. We will require reversing the polarity of the motor power for only a few tenths of a second. Remote switching can be easily done with a relay. These devices are light in weight, actuated by low currents and can switch high currents. In order to control time duration, we can use the voltage decrease feature of a charged capacitor to operate only the relay. The energy required to do this is far less than needed to stop the motor and can be done with a much smaller and lighter capacitor. “Circuit 2" shows such a circuit.



**Circuit 2**

Again, the red lines indicate positive polarity and green represents negative polarity. The “Reverse Switch” shown is also an option and will be considered to remain in this position for our discussion. It can be used in alternate applications. Note that only one switch is used in this circuit (SW1). It is a double pole, double throw (DPDT) switch. It contains two common terminals. Each switches two poles in two positions. The commons are mechanically joined. The circuit also employs a relay with the same switch configuration (DPDT). The schematics show three circuit conditions, “RUN”, “BRAKE” and “OFF”. The relay is actuated by a coil which is powered by a capacitor while in the BRAKE position. Connected across the coil of the relay is a variable resistor (potentiometer) which is adjustable from 0 to 25 ohms.

The RUN circuit condition shows SW1 in the “on” position. Power is delivered to the motor through the switch and the relay. The relay is not actuated and connects the power to the positive side of the motor through terminal 3, and the switch SW1 connects the negative to the opposite side of the motor. The motor now turns in the intended direction. The capacitor is connected to the negative polarity of the power source and is connected to the positive polarity through the “on” position of the second pole of SW1. When the switch is in this position the capacitor is charged to the power source voltage.

The BRAKE circuit condition shows SW1 moved to turn power off to the motor. SW1 now diverts the negative polarity of the motor power source to one coil terminal (5) of the relay. The positive side of charged capacitor is connected through the second pole of SW1 to the opposite coil terminal (6). The relay now actuates while the capacitor is discharging and assumes the condition shown in the BRAKE circuit. It is important to note that the potentiometer is connected in parallel to the coil. When the relay actuates, negative power from the motor power source is applied to the side of the motor that was formerly connected to the positive through terminal 2, and positive power from the motor power source is applied to the side that was negative through terminal 4. The power polarity has been effectively reversed and reverse power is afforded to the motor and propellor until the capacitor is discharged. If the capacitor discharges too quickly, full braking will not occur. If the capacitor is still discharging after stopping the motor, reversal of direction will occur. As earlier indicated, resistance and capacitance have a relationship to time of discharge, thus the potentiometer is designed to adjust this. This feature will be discussed later.

The OFF circuit condition simply shows the circuitry that exists once the capacitor is discharged and the relay returns to the normal “off” position. Note that SW1 is in the same position as in the BRAKE condition. The relay switches are in the same position as in the RUN circuit. Although a part of the circuit is still connected to negative power, nothing is connected to positive power, and no current is flowing. The capacitor is discharged and ready to receive the RUN circuit when SW1 is turned on.

Selection of components for this circuit used the same parameter requirements for current and voltage for SW1 and the relay switches, namely 30 amperes at 6 volts DC. The task was now to select the value of the capacitor. When determining the time to discharge a capacitor, electrical engineers have a favorite tool. It is the “RC” time tool. When the capacitance value is multiplied by the resistance value in a simple circuit, it represents the time (in seconds) the capacitor discharges to approximately 37% of the original voltage.

$$\frac{V_t}{V_o} = e^{\frac{-t}{RC}} = e^{-1} = \frac{1}{2.713} \approx 0.37$$
$$when RC = t$$

The manufacturer of the relay specifies the resistance of the coil as 40 ohms requiring a minimum of 6 volts DC to actuate. We cannot place an adjustable resistor in series with the coil to adjust rate of discharge because we require a full 6 volts to be applied to actuate the coil. However, we can place the adjustable resistance in parallel with the coil and adjust the effective resistance without reducing the initial voltage on the relay. Now it becomes necessary to know the voltage at which the relay will de-actuate. Unfortunately, the manufacturers are rather reticent at specifying this data because variations occur with each relay. Also, we will want the option to adjust the duration just to provide braking or to provide braking plus reversal of rotation. When we design adjustment, we consider adjustments that are minimally sensitive to positioning. Thus, we use a potentiometer that gives us variations of resistance within the confines we anticipate and with reasonable movement. A potentiometer was chosen with a total value of 25 ohms. The adjustment knob is rotated approximately 270 degrees for resistances of zero to 25 ohms. The most critical adjustment is the time for braking. We shall set this time at 0.3 seconds; however we will allow sufficient adjustment to increase or decrease this resistance. Thus, we shall assign a value on the potentiometer of less than half the adjustment range, 10 ohms, which will allow more adjustment for longer duration. Normally, a relay will de-actuate at about 40 to 50% of the actuating voltage, so we can begin with our trusty "RC" tool to determine a capacitance value for 37%, knowing we have adjustment available.

The potentiometer will be placed in parallel with the coil. We will use 40 ohms for the coil and 12.5 ohms for the adjusted potentiometer. Time for de-actuation will be 0.3 seconds.

$$R_c = coil = 40 ohms$$

$$R_p = potentiome\ ter = 10 ohms$$

$$R_t = total$$

$$\frac{1}{R_c} + \frac{1}{R_p} = \frac{1}{R_t} = \frac{1}{40} + \frac{1}{10} = \frac{5}{40} = \frac{1}{R_t}$$

$$R_t = 8 ohms$$

$$RC = t$$

$$C = \frac{t}{R} = \frac{0.3}{8} = 0.038\ farads$$

This value is also termed "38k uf", or 38 thousand microfarads. The capacitor in Circuit 1 is 168 times larger. This capacitor weighs only a few ounces and is suitable for use in the model airplane. The capacitor used is the closest value available, 39k uf. Now, the longest time duration for voltage to achieve 37% can be calculated by using the maximum resistance adjusted on the potentiometer (25 ohms). When $R_p$ is inserted into the equation above, the $R_t$ becomes 15.4 ohms and the time becomes 15.4 X 0.039 = 0.6 seconds. This indicates that any reverse thrust action will be minimal after braking. If more time is desired, the potentiometer can be replaced with one of 50 ohms or greater to provide greater "RC". However, this will make adjustment for braking more difficult.

It must be recognized that all components come with value tolerances, particularly capacitors. This device is one that will satisfy the task and parameters defined. Thus, prior to redesigning a circuit once a workable circuit is completed, it must be assembled and tested. Using components described in Circuit 2, the circuit was assembled and tested. The device functioned well. Adjustment of the potentiometer produced stoppage of the propellor almost immediately after normal power was removed. The adjustment was turned to zero ohms, and inadequate braking was afforded, which indicated adjustment could be afforded to compensate for component tolerance variations. The adjustment was then set to maximum resistance (25 ohms). The motor stopped and was placed into reverse for about 1½ seconds. Upon further testing, it was determined that the relay de-actuated at about 25% of voltage. This variation is to be expected and supports the decision not to change the value of the potentiometer.

This concept can be used with other electrical propulsion devices, such as linear motors. Relay switching can also be applied to AC motors. The point is: define the task; define parameters of performance; determine components available; confirm feasibility of design and components; and explore other circuit options.