

# Driving solenoid coils efficiently in switchgear applications

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## Introduction

A primary objective of all power systems is to maintain a very high level of continuity of service and, when intolerable conditions occur, to minimize their extent and the outage time. Loss of power, voltage dips, overcurrents, and overvoltages will occur because it is impossible to avoid the consequences of natural events, physical accidents, equipment failure, or misoperation owing to human error. A combination of devices used to protect electrical equipment from these events is known as *switchgear*. Solenoids and relays are integral parts of any switchgear equipment, as they connect/disconnect the mains to/from the protected equipment through coil energization and contacts. This article touches upon the characteristics of solenoid coils typically found in relays, contactors, and valves. It also covers methods of driving them and explains a trend in efficient driving. This article also shows some example switchgear application circuits.

Overcurrent-protection devices, such as circuit breakers, are used to protect conductors from excessive current flow. These protective devices are designed to keep the flow of current in a circuit at a safe level to prevent the circuit conductors from overheating. Contactors are primarily used to make (connect) or break (disconnect) contact in the conducting element. They are used in systems where the break-and-make connection is either frequent or unchanged for long time periods.

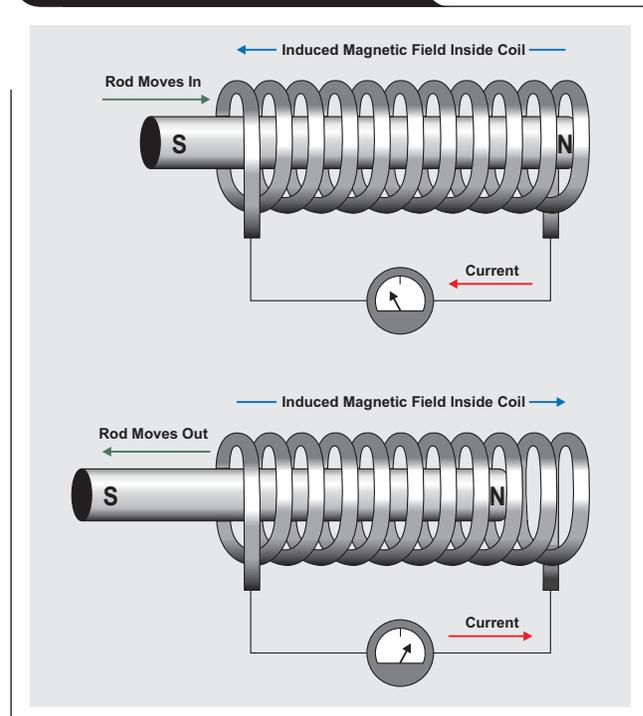
To protect a circuit against heavy currents, a protective device must determine when a fault condition develops and automatically disconnect the electrical equipment from the source. An overcurrent-protection device must be able to recognize the difference between overcurrents and short circuits and to respond in the proper way. Slight overcurrents can be allowed to continue for some period of time; but, as the current magnitude increases, the protection device must respond faster. For instance, short circuits must be interrupted instantaneously.

## Characteristics of solenoid coils

Electromechanical solenoids consist of an electromagnetically inductive coil wound around a movable steel or iron slug termed the *armature*. The coil is shaped such that the armature can be moved in and out of its center, altering the coil's inductance and thereby becoming an electromagnet (Figure 1). The armature is used to provide a mechanical force to some mechanism.

A solenoid's main electrical characteristic is that of an inductor, in that it possesses inductance, which is the characteristic that opposes any change in current. This is

Figure 1. Working of a solenoid



why current does not immediately reach a maximum level when a solenoid is energized. Instead, the current rises at a steady rate until it is limited by the DC resistance of the solenoid. An inductor (in this case a solenoid) stores energy in the form of a concentrated magnetic field. Whenever current is present in a wire or conductor, a magnetic field, however small, is created around the wire. With many turns of wire wound into a coil, such as in a solenoid, the magnetic field becomes very concentrated. This electromagnet can be used to control a mechanical valve via an electrical signal. As soon as the solenoid is energized, the current increases, causing the magnetic field to expand until it becomes strong enough to move the armature. The armature movement increases the concentration of the magnetic field as the armature's own magnetic mass moves farther into the magnetic field. Remember, a magnetic field changing in the same direction of the current creating it induces an opposing voltage into the windings. Because the magnetic field quickly expands when the armature strokes, it causes a brief reduction in the current through the solenoid windings. After the armature strokes, the current continues on its normal upward path to its maximum level. The result is

the current waveform in Figure 2. Notice the prominent dip in the rising portion of the current waveform.

### Driving the solenoid coil: Voltage or current drive?

As mentioned earlier, the armature of a solenoid is used to provide a mechanical force to some mechanism. The force applied to the armature is proportional to the coil's change in inductance with respect to the armature's change in position. The same force is also proportional to the current flowing through the coil (based on Faraday's law of induction). Equation 1 determines the force that a solenoid electromagnet will exert on a passing charge:

$$\text{Force} = Q \times V \times (\text{Magnetic constant} \times N \times I), \quad (1)$$

where  $Q$  is the charge of the passing point charge;  $V$  is the velocity of the point charge; the magnetic constant is  $4\pi \times 10^{-7}$ ;  $N$  is the number of turns in the solenoid coil; and  $I$  is the current running through the solenoid. This shows that the electromagnetic force of a solenoid is directly related to the current.

Traditionally, voltage drive is used to drive the solenoid coils; hence, a continuous power is consumed in the coil. A negative effect of this power consumption is the heating of the coil and, in turn, the entire relay. The coil temperature is a result of ambient temperature; self-heating due to the coil's power consumption of  $V \times I$ ; heating induced by the contact system; magnetization losses due to eddy currents; and other heat sources, such as components in the vicinity of the relay.

Due to coil heating, the coil resistance increases. The resistance at elevated temperature is expressed by Equation 2:

$$R_{\text{Coil}_T^\circ\text{C}} = R_{\text{Coil}_{20^\circ\text{C}}} [1 + k_{R_T}(T^\circ\text{C} - 20^\circ\text{C})], \quad (2)$$

where  $R_{\text{Coil}_{20^\circ\text{C}}}$  is the  $20^\circ\text{C}$  value for resistance, and  $k_{R_T}$  is the thermal coefficient of copper, equal to 0.0034 per degree Celsius. Based on  $R_{\text{Coil}_{20^\circ\text{C}}}$ , typically given in the datasheet of a solenoid coil, the worst-case coil resistance at high temperature can be calculated. During circuit design, care has to be taken that the calculations are made for worst-case conditions, such as the highest possible coil temperature at the operating pick-up voltage.

Another point to note is that for a given coil, the pick-up current remains the same at any condition. The pick-up current depends on the pick-up voltage and the coil resistance ( $I_{\text{Pick-up}} = V_{\text{Pick-up}}/R_{\text{Coil}}$ ). Most relay coils are made of copper wire. Due to the increase in coil temperature, the coil resistance increases as per Equation 2. Hence, the pick-up voltage for the hot coil should be higher to generate the required pick-up current. For example, if a 12-VDC relay's pick-up voltage is 9.6 VDC and the coil resistance is

Figure 2. Solenoid current

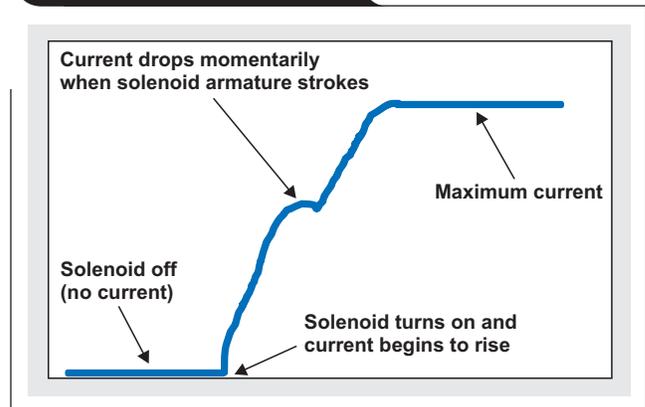
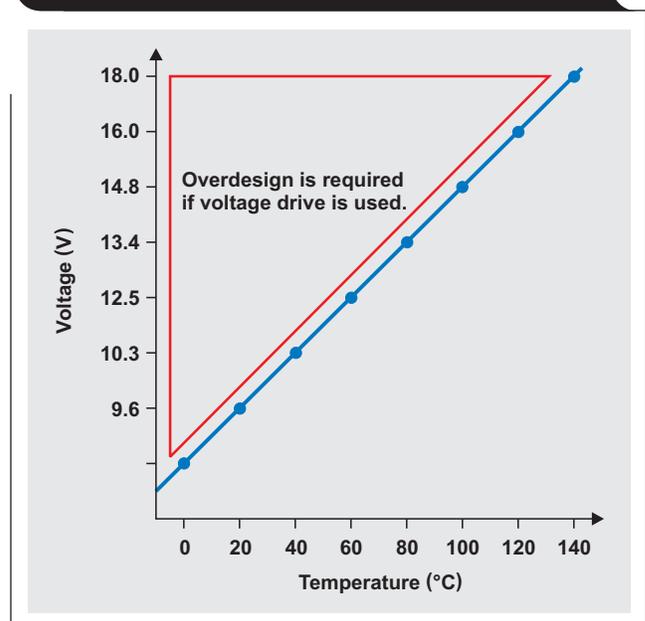


Figure 3. Overdesign for solenoid voltage drive



400  $\Omega$  at  $20^\circ\text{C}$ , then  $I_{\text{Pick-up}} = 24$  mA. When the coil temperature is increased to  $40^\circ\text{C}$ , the coil resistance increases to 432  $\Omega$ . Hence the pick-up voltage will be 10.36 VDC. (The pick-up current remains the same.) In other words, an increase in temperature by  $20^\circ\text{C}$  increases the pick-up voltage by 0.76 VDC. In relays operating with higher duty cycles, the pick-up voltage may increase slightly for each successive cycle due to the coil's temperature rise. Figure 3 shows that the user may have to overdesign the coil if voltage drive is used.

In short, voltage drive forces overdesign because current varies with variations in coil resistance, temperature, supply voltage, and the like. So using current drive is optimal for many devices with solenoids.

### Optimizing power consumption

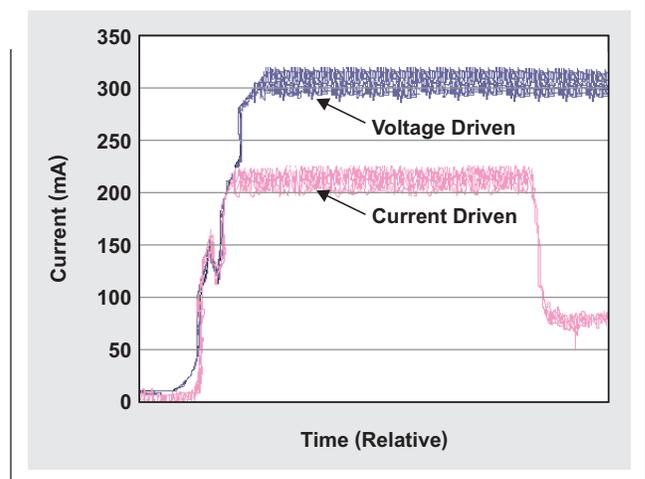
Closing a relay or valve requires a lot of energy. The instantaneous current that activates the solenoid actuator, called the *peak current* ( $I_{Peak}$ ), can be high. However, once the relay or valve is closed, the current required to keep it in that condition, called the *hold current* ( $I_{Hold}$ ), is significantly less than the peak current. Typically, the hold current is less than the peak current:  $I_{Hold} \ll I_{Peak}$ .

When voltage drive is used, the current flowing through the solenoid coil is continuous and higher than when current drive is used (Figure 4). Unlike voltage drive, current drive requires no margin for parameter changes caused by temperature or solenoid-resistance variations. The design requires separate values for peak current, which may be in the range of amperes, and steady-state hold current, which may be only 1/20 of the peak-current value.

### Current-control implementations for driving a solenoid coil

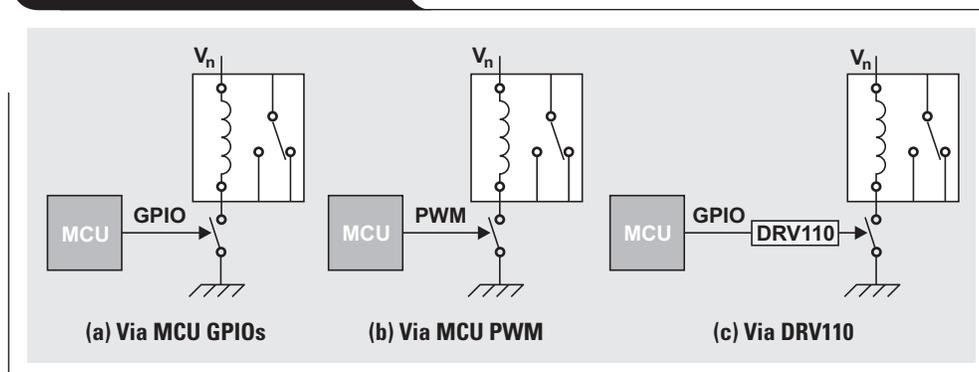
Traditionally, the solenoid coil is driven directly through the general-purpose inputs/outputs (GPIOs) of the microcontroller (MCU) (Figure 5a). The coil is activated via a switch controlled by a GPIO from the MCU. A new driving system has been developed that uses pulse-width modulation (PWM) of the waveform (Figure 5b). The coil is activated via a switch controlled by a PWM from the MCU, and the

**Figure 4. Solenoid current with voltage drive and current drive**

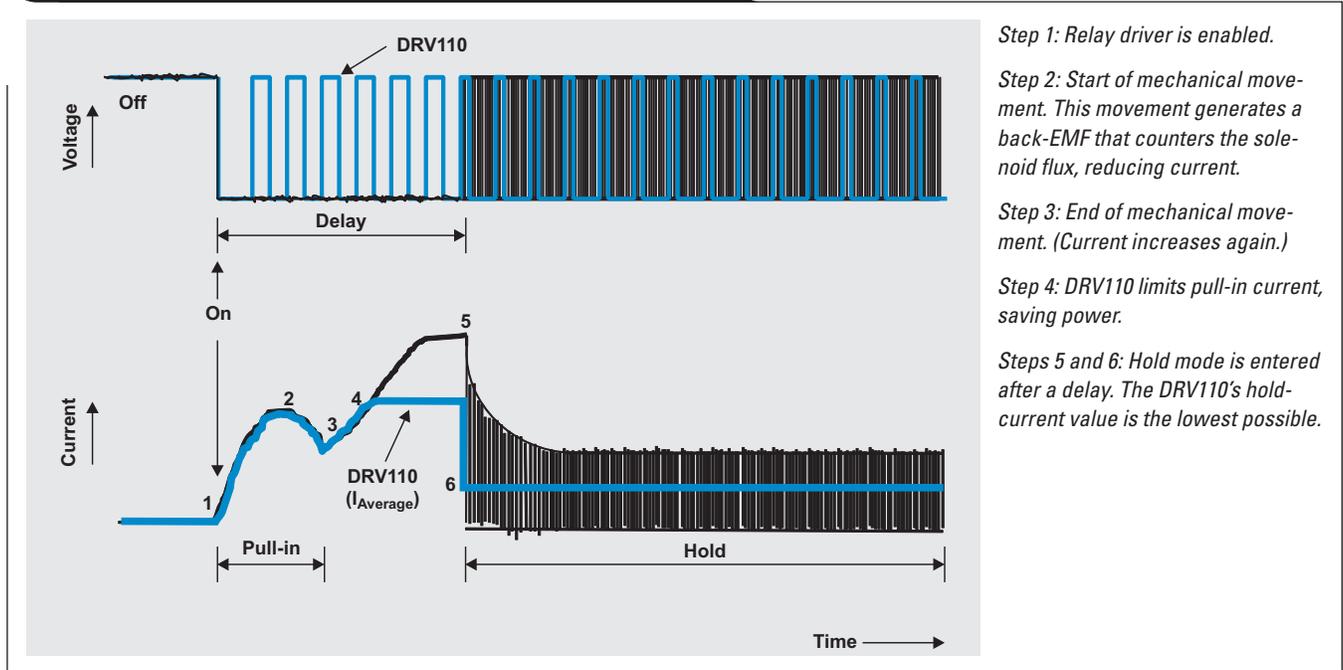


duty cycle determines the average current through the coil. For this article, the Texas Instruments DRV110, a power-saving solenoid controller with integrated supply regulation, was used (Figure 5c). This DRV110-based system was designed to regulate the current with a well-controlled waveform to reduce power dissipation. After the initial ramping, the solenoid current is kept at a peak value to ensure correct operation, after which it is reduced to a lower hold level to avoid thermal problems and reduce

**Figure 5. Coil-driving methods**



**Figure 6. Operation of conventional driver versus DRV110**



power dissipation. The graphs given in Figure 6 compare the operation of a conventional driver with that of the DRV110. Note that other methods reduce voltage but need to have an overhead to guarantee that the hold current is always maintained across temperature.

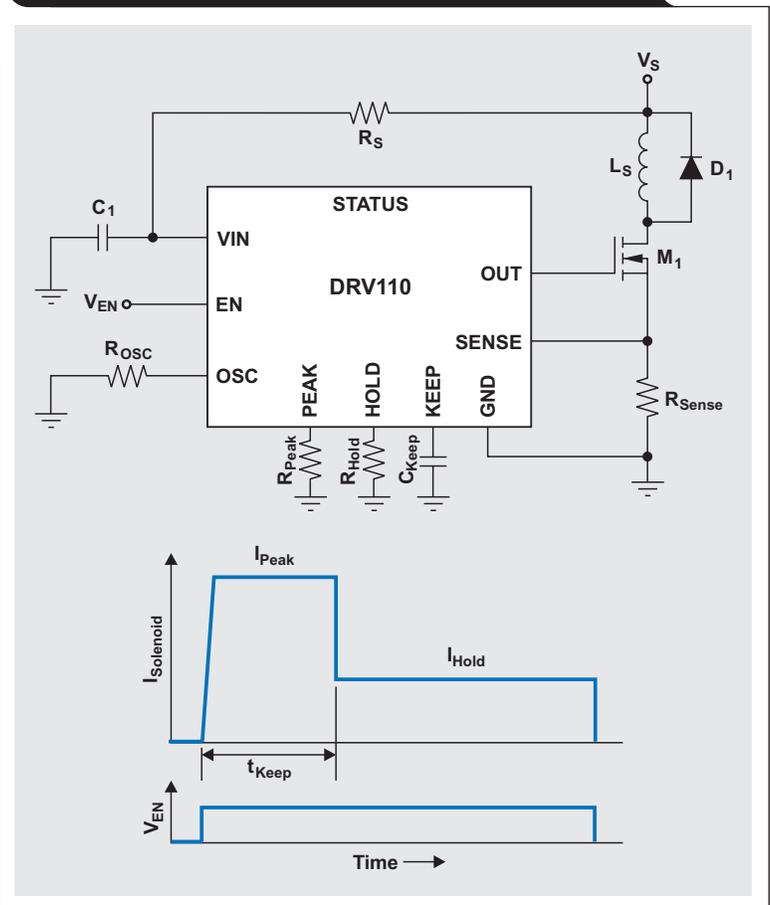
A typical application circuit based on the DRV110 is shown in Figure 7. The DRV110 controls the current through the solenoid ( $L_S$ ), also shown in Figure 7. Activation starts when the EN pin voltage is pulled high, either internally or by an external driver. In the beginning of activation, the DRV110 allows the load current to ramp up to the peak value ( $I_{Peak}$ ) and regulates it there for time  $t_{Keep}$  before reducing it to  $I_{Hold}$ . The load current is regulated at the hold value as long as the EN pin is kept high. The initial current ramp-up time depends on the inductance and resistance of the solenoid. Once the EN pin is driven to GND, the DRV110 allows the solenoid current to decay to zero.

**Determining  $I_{Peak}$  and  $I_{Hold}$  of the DRV110**

The activation (peak) current of the DRV110 is determined by the coil's ON resistance and the pick-up voltage required by the relay. This resistance value at maximum temperature ( $R_{Coil\_T(max)}$ ) and the relay nominal operating voltage ( $V_{nom}$ ) can be used to calculate the  $I_{Peak}$  value required at maximum temperature:

$$I_{Peak} = \frac{V_{nom}}{R_{Coil\_T(max)}} \quad (3)$$

**Figure 7. Typical application circuit for DRV110 and solenoid's current waveform**



The hold current of the DRV110 is determined by the ON resistance of the coil and by the voltage required to keep the relay from dropping out. To keep a relay from dropping out, manufacturers give recommended voltage values in their datasheets; however, some margin for vibration and other contingencies should be added to these. Many relay manufacturers give 35% of the nominal voltage as a safe limit. Assuming this to be enough, the  $R_{\text{Coil}_T(\text{max})}$  value and the relay nominal operating voltage ( $V_{\text{nom}}$ ) can be used to calculate the  $I_{\text{Hold}}$  value that works over the temperature:

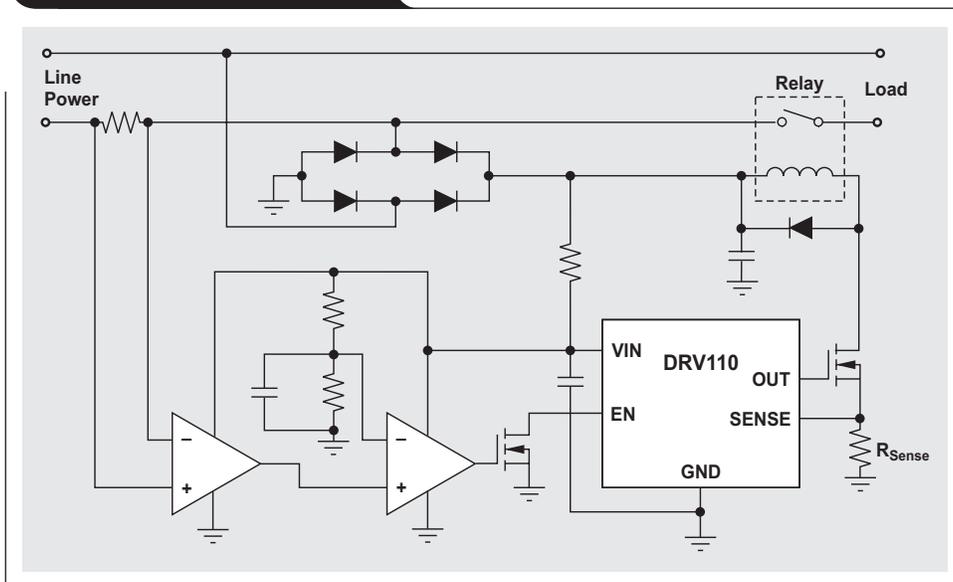
$$I_{\text{Hold}} = \frac{0.35 \times V_{\text{nom}}}{R_{\text{Coil}_T(\text{max})}} = 0.35 \times I_{\text{Peak}} \quad (4)$$

## Examples of switchgear applications

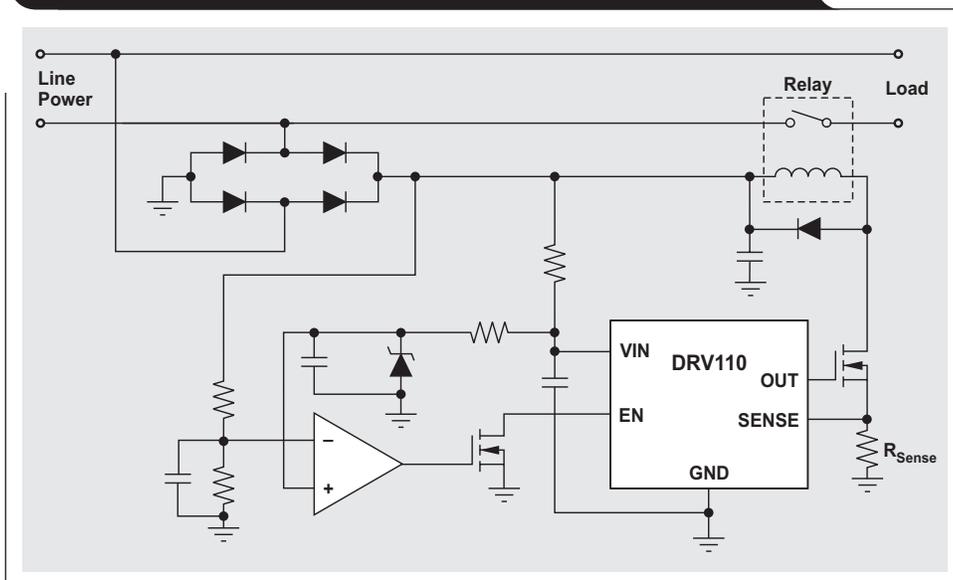
Overload protection will cause a device to break the circuit connection if the load current exceeds the rated current of the device for a specified duration. The protection circuit implemented in Figure 8 derives the enable (EN) signal by measuring current as well as voltage. (To simplify Figures 8–10, the DRV110 pin connections for OSC, PEAK, HOLD, and KEEP are not shown.)

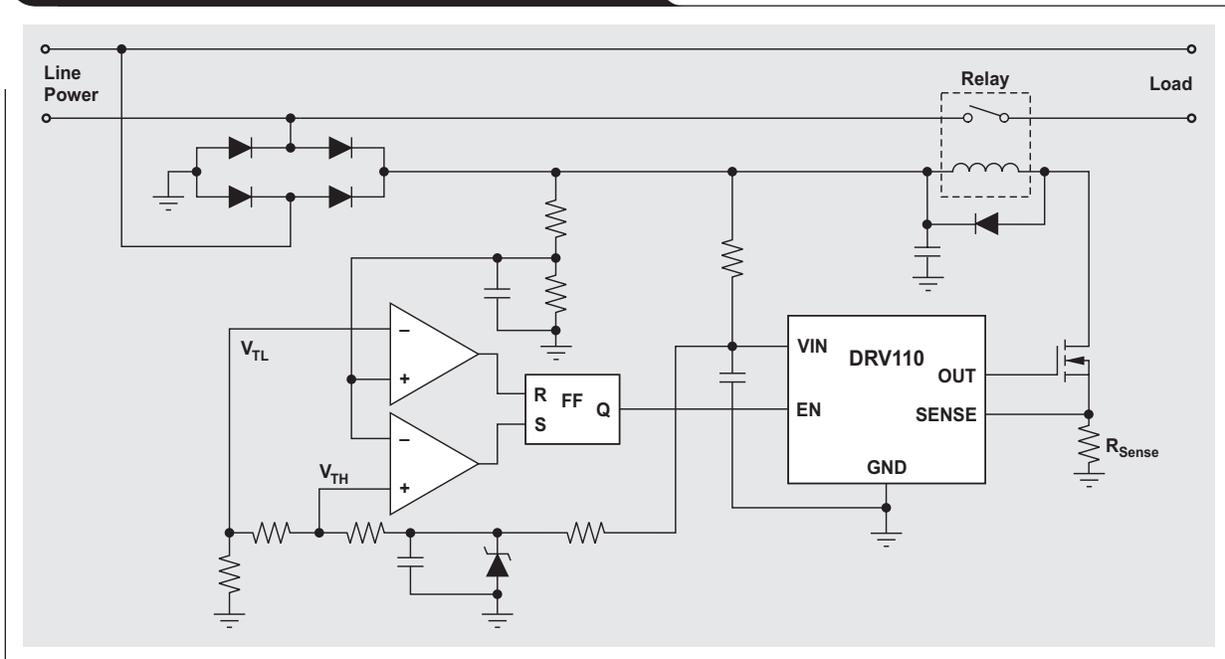
A magnetic contactor needs a current to be passed through the coil to move the contacts into a closed or open position. Figure 9 shows the implementation of an RMS-voltage-sensing circuit in a contactor system that uses the DRV110.

**Figure 8. Overload protection**



**Figure 9. Magnetic-contactor system with RMS-voltage sensing**



**Figure 10. Undervoltage and overvoltage protection**

Undervoltage and overvoltage protection also can be implemented by using the DRV110 (Figure 10). Two comparators are used to measure the high and low threshold voltages. Based on the outputs of each comparator, the SR flip-flop sends an enable (EN) signal to the DRV110.

### Conclusion

There are many benefits to using a power-saving solenoid controller with integrated supply regulation. To achieve energy savings, current regulation is the most accurate way of controlling actuator force. No margin needs to be added because the system is immune to variations in coil resistance, supply voltage, and temperature. System reliability is also improved because the solenoid action is repeatedly optimal. Finally, system cost is optimized. With energy accurately controlled, coils can be overdriven to get acceptable performance from a smaller, cheaper coil.

### Reference

1. "Power saving solenoid controller with integrated supply regulation," DRV110 Datasheet. Available: [www.ti.com/slvsba8-aaj](http://www.ti.com/slvsba8-aaj)

### Related Web sites

Amplifiers:

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