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Using Direct-Current Relays at Lower Coil Voltages

Here's how and why relays can be operated significantly below their nominal rated voltage.

Relays are common electronic components found in many devices. Solid-state switches and circuits have supplanted these devices in many ways, but they remain viable as a simple and cost-effective way to switch power and signals, RF in particular, with a relatively low-power control signal. However, a common problem for the hobbyist or experimenter is that one might locate the perfect relay for an application, only to find that the relay coil voltage is something like 24 V dc or 28 V dc with only 12 V dc power available. While others have explored the use of these higher voltage dc coils, the news of their successful application often falls on deaf ears. I was once one of the "deaf ears".

The Lowly Coil

The central element of a traditional relay is the coil. It is simply an electromagnet, and its sole purpose is to create a magnetic field of sufficient strength to attract a mechanical lever. This lever, in turn, moves electrical contacts causing a change to the electrical connections. One must be aware of the effect of the collapsing magnetic field when the relay is de-activated. However, for dc relays, this is typically addressed by a reverse-biased diode to limit the voltage-spike that can result when the source of coil current is removed. For much of my career, I simply did not give relays much more attention than that.

My cursory treatment omits many of the important subtleties of coils and relays in general, but for most applications, this level of design scrutiny is sufficient. The shape and construction of the coil is the same as with any inductor intended for ac circuits. These coils have inductance, resistance, and capacitance, just as with any other inductor. The resistance tends to dominate the behavior of the device, so inductance and capacitance can usually be ignored by the designer.

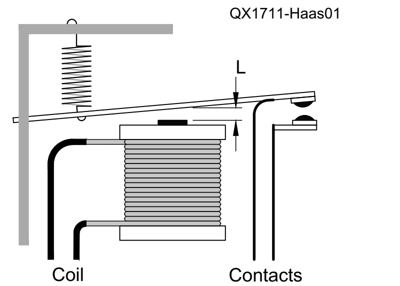

Figure 1 — A simplified relay system.

It is very easy to forget that relay coils are current-mode devices since most relays have a specified operating voltage for the coil. The operating voltage divided by the coil resistance is the current responsible for the operation of the relay. Specifying the coil voltage is tantamount to specifying its current. Still, forgetting that the current is the real star can cause one to miss some of the core concepts at work here.

Anatomy of a Relay

Figure 1 shows drawing of a simple relay. The coil current produces a magnetic field along the coil axis. If strong enough, this field will attract the nearby ferromagnetic lever, which will move towards the coil. As the lever moves closer to the coil armature (the metal core of the coil), the force on the lever increases. This force is roughly an exponential function of the air gap, *L*, which is the distance between the coil armature and the nearest point of the lever. Once the lever contacts the armature, the force required to dislodge the lever is typically orders of magnitude greater than the force that initially started moving the lever from its rest position. This concept is key to the method employed in this article.

Some Definitions

Pull-in voltage (or current) V_{pi} or I_{pi} is the minimum voltage or current that will cause the relay to engage from its rest position. When presented in a datasheet, this value generally includes allowances for variances in the relay construction and environment.

Switching delay t_d is the time that it takes for the electrical contacts to close in the engaged position once the relay coil is activated. Note that this is not the time it takes for the lever to reach the full extent of its movement.

Pull-in delay, t_{pi} is the time that it takes for the relay lever to contact the coil armature.

Pull-out delay t_{po} is the time that it takes for the relay lever to reach the open position after the relay supply is removed. This is greatly impacted by the method(s) applied to the coil to address the back-EMF that results when the supply voltage is removed.

Contact bounce time t_b is the time duration that the contacts bounce against each other one or more times for each activation event.

Holding voltage (or current) V_h (or I_h) is the minimum voltage (or current) that will hold the relay engaged once it has been pulled in and settled.

The pull-out delay t_{po} can be of concern for systems that require a fast transition between states. There isn't much that can be done to decrease the pull-in delay t_{pi} since this is a function of applied current, coil inductance, and the mass of the lever assembly, among other effects. However, t_{po} can be controlled to some extent. In general, anything that increases the coil voltage during the field collapse duration will reduce the time it takes for the field to fully collapse. The diode that is commonly used to control the coil voltage during field collapse will result in the longest possible t_{po}. Reducing t_{po} can be accomplished by using a Zener diode in series with a switching diode, oriented so that the Zener diode is reverse-biased when the switching diode is forward biased. The main concern is limiting the reverse coil voltage to below the point of failure for the coil-drive electronics.

While coil current is the ultimate quantity of interest, we generally reach this current via an applied voltage. Voltage control is easier than current control. Thus, the calculations discussed herein will deal in voltages and coil resistance. However, the resistance of the relay coil varies with temperature, so the *voltage – resistance* relationship is valid only at temperatures where the resistance value is known. Since copper resistance increases with temperature, coil current decreases with temperature, which may need to be considered if a datasheet is not available, or if operating outside of the specified temperature range

Dynamic Relay Current

It may be a surprise that a typical relay holding current is rarely more than half the minimum pull-in current. In fact, it is often less than half the minimum pull-in value. This is the effect we will exploit. By varying the relay current such that at least the minimum operating current is applied for enough time to engage the relay, followed by a reduction of this current to something greater than the holding current, the relay can be reliably operated with less than full rated current (or voltage). Here's how it works.

One popular way to accomplish a dynamic current drive is to carefully switch an appropriately sized capacitor in series with the relay coil.[1] By pre-charging this capacitor before switching, we can induce a voltage across the relay coil that is greater than the pull-in voltage. If the capacitor can hold sufficient charge — determined by the value of its capacitance, the voltage of the pre-charge, and the load current — the relay will engage. Once the capacitor is discharged, we switch in the available dc voltage supply, which must be greater than the hold-in voltage, to keep the relay engaged.

This can be accomplished with just four components in addition to the relay and its associated clamping diode. We need a DPDT switch, a capacitor, a diode, and a resistor as seen in Figure 2. In the OFF state, the supply voltage is presented to the capacitor through the current limiting resistor *R*. The value for *R* should be large enough to prevent the current rating of the switch contacts from being exceeded, but small enough that the capacitor charges quickly. I generally set *R* to 100 Ω as a starting point.

Once the switch is moved to the ON position, the charged capacitor appears in series with the relay coil such that its voltage adds to the supply voltage to provide nearly double the supply voltage across the relay coil. The capacitor then begins to discharge, and will provide current to the relay coil until its voltage dips below the forward voltage drop of diode *D*1. This diode does not clamp the coil transients, a separate diode across the relay coil is needed. From this point on, the voltage presented to the relay coil is the supply voltage minus the forward voltage drop of *D*1.

The Capacitor Value

The capacitor value must be large enough so that most of its charge is still retained after discharging for the duration of pull-in-delay. This can be calculated effectively using the equation for the discharge of a capacitor, the coil resistance, and the holding voltage of the relay. Figure 3 shows a plot of capacitor voltage versus time for a capacitor discharging through a resistance *R*. The time constant *RC* is represented by τ.

You can estimate *RC* from Figure 3. Subtract the supply voltage V_{dd} from the value of V_{pi}, then divide by V_{dd}. This ratio sets the location of interest on the *y*-axis. Read the *x*-axis value where the exponential curve intersects this value to determine the number of time-constants that are involved. Set this equal to t_{pi} and solving for *C*.

Consider a relay with a V_{pi} of 18 V, a coil resistance of 3 kΩ, a t_{pi} of 15 ms, and an available minimum V_{dd} of 10 V, then

$$\frac{V_{pi} - V_{dd}}{V_{dd}} = 0.8$$

The *x*-axis value extracted from the chart is about 0.24 *RC*. Setting this equal to t_{pi} and solving for *C*, we get 0.24 $RC = t_{pi}$, so

$$C = \frac{0.015}{0.24 \cdot 3000} = 21\ \mu\text{F}.$$

As can be seen in Figure 3, the capacitor is essentially discharged after 5 time constants. The formula is,

$$V_c(t) = V_{dd} e^{t/RC}\ ;\ t \geq 0.$$

As long as $[V_c(t) + V_{dd}] > V_{pi}$ for a duration of at least t_{pi}, the capacitor is of sufficient value to pull in the relay. $V_c(t)$ is the capacitor voltage with respect to time, and V_{dd} is the available supply voltage. Solving for *C* gives,

$$C = \frac{-t_{pi}}{R \ln\left(V_c(t)/V_{dd}\right)} \quad \text{F}$$

where $V_c(t)$ is set to $V_{pi} - V_{dd}(min)$ to find a minimum value for *C*. For example,

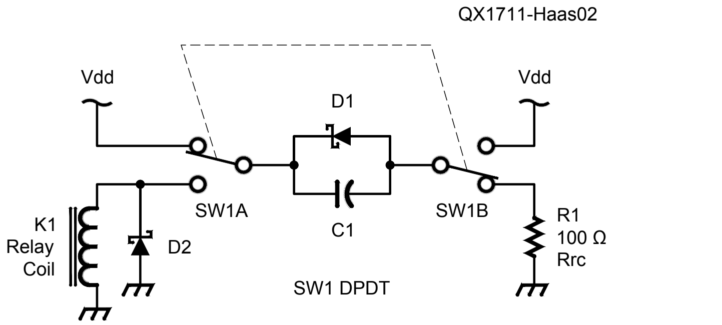

Figure 2 — A simple step-up relay drive circuit. The switch is shown in the "off" position.

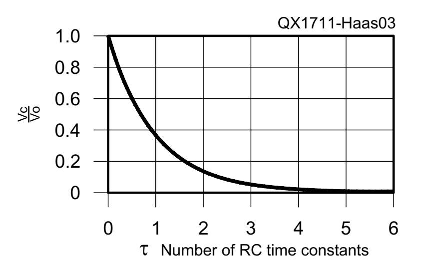

Figure 3 — This voltage versus time-constant plot for a capacitor may be used to graphically determine a value for *C*.

considering a relay with a V_{pi} = 18 V, a coil resistance R = 3 kΩ, t_{pi} = 15 ms, and $V_{dd}(min)$ = 10 V, the minimum capacitance needed is,

$$C = \frac{-0.015}{3{,}000\ln\left((18-10)/10\right)} = 22.4\ \mu\text{F}$$

which agrees well with the graphical estimate.

The relay coil exhibits inductance and parasitic capacitance. The parasitic shunt capacitance is often negligible — in the hundreds of pF at most. The inductance is usually significant — as much as several millihenry. The effect of this inductance is to resist the change in coil-current flow. When activating the relay, this will delay the buildup of the magnetic field and is reflected in the pull-in time t_{pi}. Thus, if the t_{pi} is specified or measured, the inductance need not be considered as this effect is already taken into account.

More capacitance is certainly better, at least that seems to be the popular belief. However, one must consider the charge time of the capacitor for the application at hand. In the previous example, A 20,000 µF capacitor would certainly be large enough, but its size and charge time — about 10 s — might make a noticeable impact to its application. Doubling or tripling the calculated value might be appropriate, but going beyond that is only warranted if one can tolerate or mitigate the charge-time implications.

Lacking a Data Sheet

What if there is no data sheet available for a given relay? This can be a common problem since many desirable relays can be found in surplus equipment. Manufacturer's data may be scarce or difficult to find. Fortunately, it is relatively easy to measure the required parameters.

The coil resistance can be measured with a DMM. If a clamping diode is attached connect the DMM such that the diode is reverse biased by the meter. If several of the same model relays are available, an average can be calculated. This is good practice to make sure that the relay-under-test isn't defective.

Copper resistance varies by temperature, and can be calculated for a given temperature T in °C,

$$R(T) = R(T_0)\left(1+\alpha\Delta T\right)$$

where T_0 is the reference temperature (usually 25 °C), $\Delta T = (T - T_0)$ and α is the temperature coefficient (per °C). For copper α= 0.004 per °C near 25 °C.

If the maximum operating temperature is known, this can be used to calculate the worst-case coil resistance. Most coils are wound with copper wire. A moderate temperature of 50 °C is realistic for open air mobile operation. For resistance measurements made at 25 °C, this results in a 20% increase of coil resistance at 75 °C. Calculate ΔT for the maximum expected temperature rise and this result will be used to scale readings to reach a safe over-temperature-range result. This will decrease the coil current for a given applied voltage and needs to be considered to ensure proper operation at the worst-case temperature.

Pull-in delay t_{pi} is more difficult to measure directly, but it can be estimated by measuring t_d, the time to contact closure. Doubling t_d should be a reasonable estimate for most relay geometries. This assumes that the actuation lever moves about half of its travel before activating the relay contacts. In truth, the relay lever continuously accelerates as it moves toward the armature, so this approach features a built-in "fudge-factor". If the relay mechanism is visible, this can be easily verified. For mechanisms that are not visible, a 3x value for t_d should provide more than enough margin to cover the uncertainty of the measurement.

A function generator that can achieve sub-hertz frequencies is a useful tool for this measurement. An NPN or MOSFET driver, 2-channel oscilloscope, and a variable power supply are also needed, see Figure 4. The variable supply needs to support the normal coil voltage, or must achieve at least half the rated coil voltage and allow for another offset supply to be added to achieve the desired coil voltage. Connect the transistor base — a 1 kΩ series resistor is needed for an NPN transistor — or gate to the function generator, the transistor emitter or source to ground, and the collector or drain to one side of the coil. A reverse biased diode across the coil is also needed to protect the drive circuits. Connect the other coil terminal to the power supply and set the voltage to the nominal coil voltage. The common terminal of the relay contacts is connected to ground. Connect one channel of the oscilloscope to the function generator output, and the other to the normally open terminal of the relay contacts. The normally open connection also needs a pull up resistor, 10 kΩ is a reasonable value, to either the coil supply voltage, or some other convenient power source that shares the same ground as the relay common terminal.

Operate the function generator at about 1 Hz, with a square-wave output that varies from ground to a positive voltage level sufficient to saturate the switching transistor. Observe the two waveforms on the oscilloscope and adjust the timing and triggering to produce several horizontal divisions of separation between the rising edge of the function generator, and the falling edge of the relay contact signal. Measure the time delay between these edges. Observe this time delay over multiple edges and select the largest value. Some relays will exhibit a noticeable difference in the timing

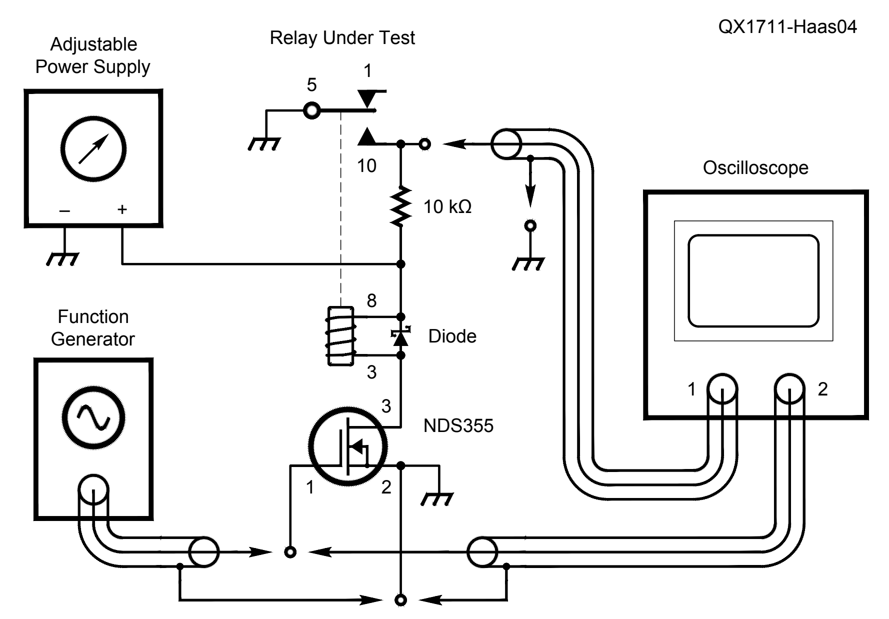

Figure 4 — Test setup for measuring critical relay parameters.

of these edges. This value is the nominal t_d of the relay. If bounce is observed, use the first edge to establish the timing value. The bounce delay t_b may be of interest to the end-use application, so make a note of it for later reference.

The same setup used above is also used to measure V_{pi}. Reduce the coil supply voltage slowly until the relay no longer engages. Increase the voltage until the relay begins to operate normally and record this as V_{pi1}. Then, repeat the t_d measurement. Note the values for voltage and timing. This value for t_d will generally be larger than the one determined at nominal voltage and it is this value that should be used in calculations. The pull-in voltage is,

$$V_{pi} = V_{pi1}\left(1+\alpha\Delta T\right)$$

The undisturbed V_h (no mechanical or thermal changes) can be measured by forcing the relay to engage at nominal voltage and slowly lowering the coil voltage until the relay contacts release. This measurement does not use the function generator switch; simply ground the relay coil connection that was connected to the function generator driver. This value is generally not of much use except to get an idea of the ideal lower limit for V_h. A practical value for V_h requires the relay to be subjected to vibration and temperature extremes that represent real exposure conditions. Unfortunately, the equipment to produce these stimuli are generally out of reach of most experimenters. Controlled shocks can be induced to try to release the relay lever, but these may easily miss a real-world target without careful planning and execution.

Generally, if the undisturbed V_h value is less than 75% of the rated coil voltage value, the relay should reliably hold in the engaged position using the techniques described here. Shock mounting the relay can also be a risk mitigation to further ensure that the relay not disengage improperly.

Adding Digital Control

A simple way to implement this control methodology is to use a DPDT switch to execute a dynamic relay current control circuit, but this simplicity comes at a cost. First, the circuit is not directly transferrable to digital control unless a second relay with a coil voltage that is compatible with the available V_{dd} is used. Second, the switch version must be physically cycled to cause relay activation. If power is applied with the switch in the ON position, the relay will not activate since the capacitor will be discharged, with no way to charge it until the switch is manually returned to the

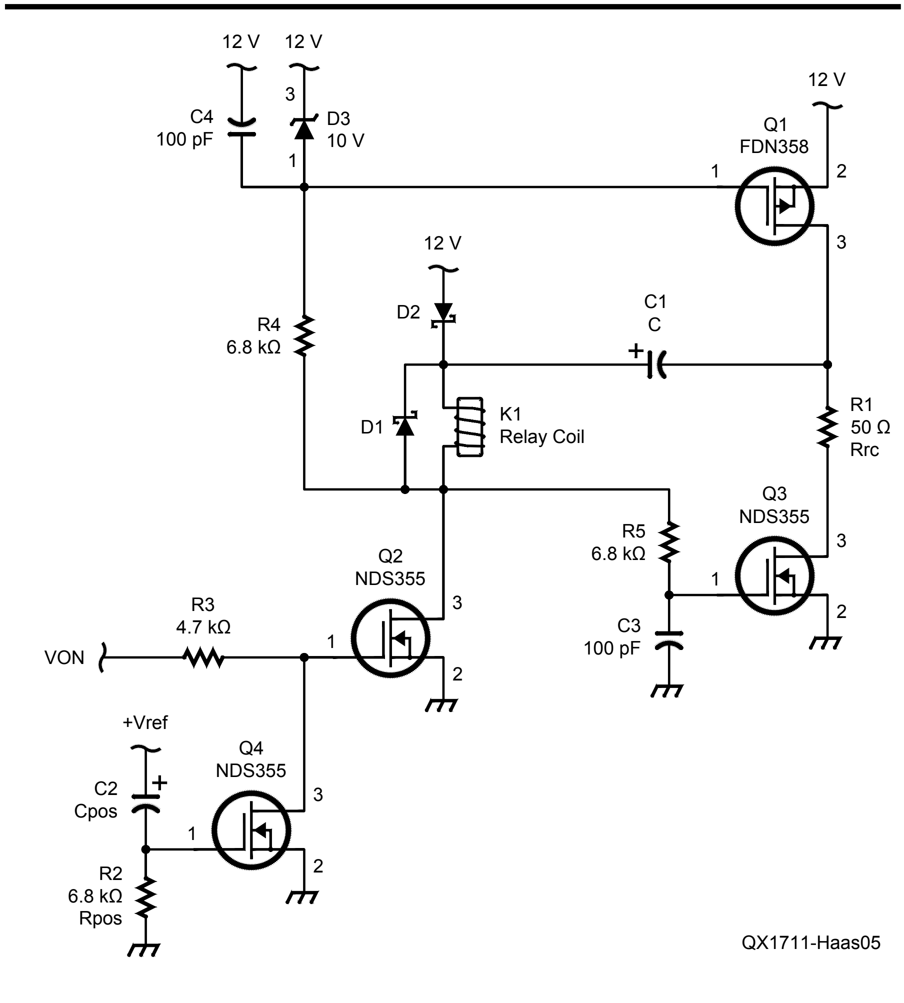

Figure 5 — Digitally controlled relay drive circuit. The +V_{ref} is a regulated voltage reference. An unregulated reference may be used, but the highest likely V_{ref} voltage must be used to calculate the value of C_{pos}.

de-activated position long enough to charge the capacitor.

Another relay can be used in place of the DPDT switch, but it just seems wrong to use a relay to activate another relay. However, a solid-state switching circuit can also accomplish the required task with just a few added components. This is implemented in Figure 5.

This circuit has several features. Some of these features can be eliminated for some applications, while others are central to the basic function. The transistors $Q1$ and $Q2$ form the core of the relay switch. When $Q1$ and $Q2$ are off (V_{ON} < 0.5 V) no current flows in the coil. $D2$ is forward biased which allows $V_{dd} - V_{D2}$ to appear at the bottom of the relay coil which turns $Q3$ on. MOSFETs are preferred since they conduct only a small leakage current which greatly minimizes the off current that flows through the relay coil. This allows C to charge via R_{rc}. A minimum charge time of $5R_{rc}C$ is sufficient to bring C reasonably close to full charge.

V_{ON} drives $Q2$ and when this voltage is above about 3 V, $Q2$ is guaranteed to turn on. This grounds the coil, turns off $Q3$ and turns on $Q1$. With $Q1$ on, the voltage at the top of the relay coil becomes the sum of V_{dd} and the voltage across the capacitor, which is essentially V_{dd} - $V_{D2}(fwd)$. Current then flows through the coil and C begins to discharge. As C discharges, V_c drops as does the voltage across the coil. When V_c drops to about $V_{D2}(fwd)$, $D2$ begins to conduct and the voltage across the coil settles to $V_{dd} - V_{D2}(fwd)$. When V_{ON} is reduced below 0.5V, the coil turns off, and the process repeats.

$Q4$ represents a power-on-set circuit. When power is first applied, C_{pos} begins charging which briefly turns on $Q4$. This forces the circuit to keep the relay in the OFF mode while C charges. For most small FETs satisfying the inequality,

$$5R_{rc}C \le R_{pos}C_{pos}\ln\left(1-\frac{V_{gs}(th)}{V_{ref}}\right)$$

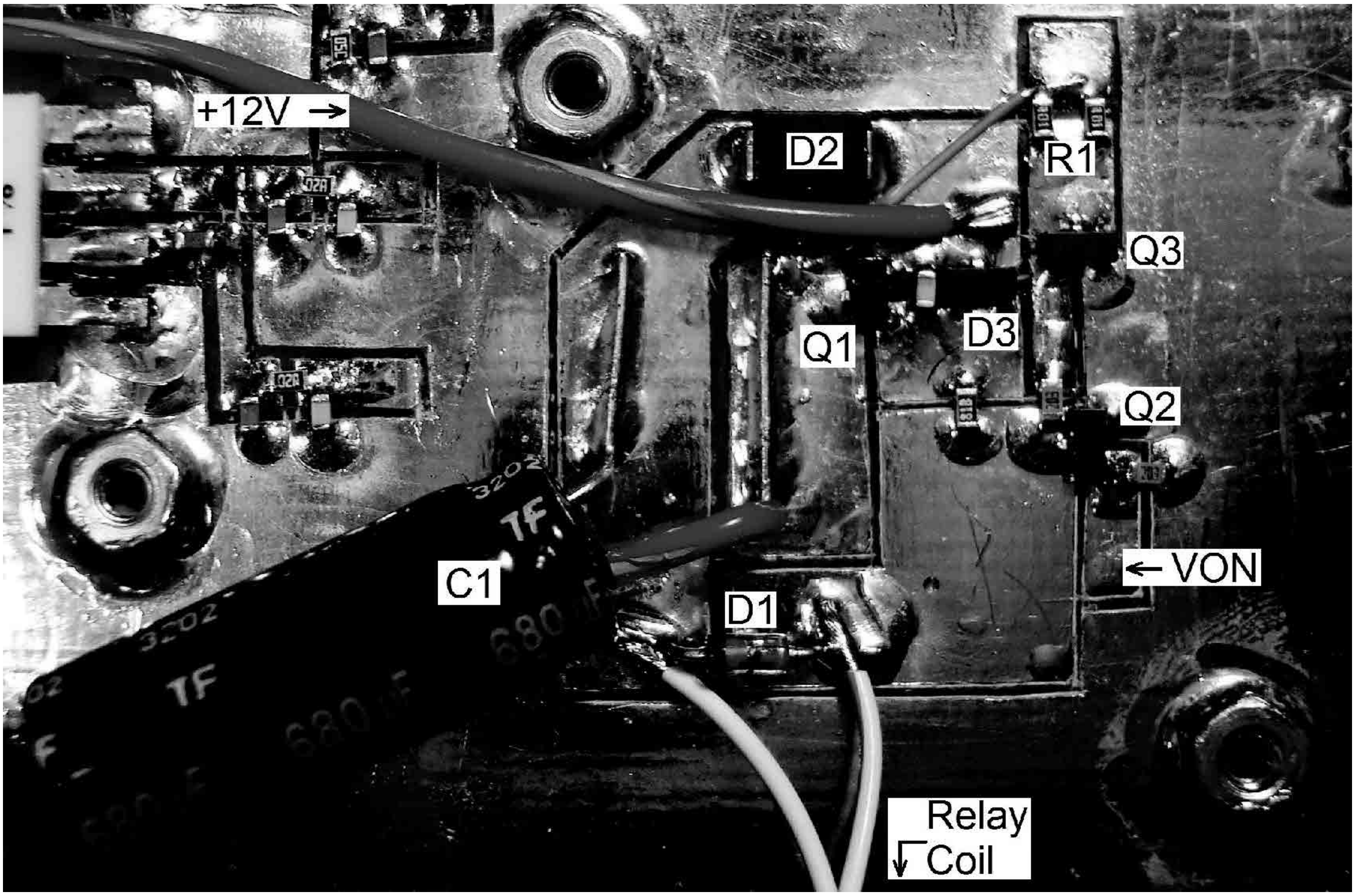

Figure 6 — Photo of an implementation of the circuit of Figure 5. The power-on set circuit was not use in this implementation. The area surrounding the circuit is ground.

will ensure that the circuit will reliably activate the relay if V_{ON} is activated before (or at the same time as) V_{dd} is applied and C has a chance to charge. $V_{gs}(th)$ is the threshold voltage of the MOSFET. Of course, this feature can be eliminated if V_{ON} will never be activated before power is applied to the relay circuit.

Figure 6 shows an implementation of this circuit using predominantly SMD components. It was implemented to drive a DowKey RF relay that requires 24 V dc, where V_{pi} = 18 V, T_{pi} = 0.025 s, R_{coil} = 250 Ω; Applying Equation (1), C = 448 µF rounded up to 680 µF. The core of the circuit is relatively compact, even with generous routing rules. The capacitor $C1$ takes up much of the circuit volume.

Conclusion

This treatise illustrates that operating a relay at lower than specified coil voltage has a sound basis in physics, and is suitable for some applications. This method reduces the power consumed by the relay coil by roughly a factor of 4 when V_{dd} is roughly half the rated coil voltage, it can have a noticeable impact when operating from battery power with high ON duty cycles. I've used this technique on several occasions, and I'm glad to have finally taken the time to examine the lowly relay in greater detail.

Joseph M. Haas, KEØFF, holds an Amateur Extra class license, and is an electrical engineer with a BSEE from the University of Missouri, Rolla, now the Missouri school of Science and Technology. He works in the MIL-AERO industry. He has worked in avionics design for 15 years, oil-field instrumentation design for 3 years, and semiconductor process equipment design for 7 years. Joseph started tinkering with electronics at the age of 6, and was first licensed as KAØGPZ just over 40 years ago. Most of his designs, both professional and hobby, are mixed-signal in nature and revolve around a microcontroller performing as a control system and/or data converter involving signals from dc up to a few megahertz. He has also designed a few RF circuits in the 2.5 GHz range and has experimented at 10 GHz. Joseph maintains a projects page at ***www.rollanet.org/~joeh/projects/****.*

Notes

[1]Didier A. Juges, KO4BB, "How to Operate 24 V relays on 12 V", **www.ko4bb.com/ham_radio/Projects/24V_Relays/**, (accessed Sep 11, 2017).