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Gate Driver ICs Enable Higher Efficiency In Air-Conditioning Systems

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Most electricity used in residential, industrial and commercial buildings is consumed by heating, ventilation and air-conditioning (HVAC) systems—or more precisely, the air conditioner. According to the U.S. Department of Energy, motors account for more than 50% of the total electricity consumed by these systems. Modern semiconductor power devices can help achieve as much as 30% higher efficiency—leading to increased energy savings, which are in high demand by government agencies and consumers.

One key subsystem receiving a lot of attention in the HVAC space is air conditioning. There are two key trends in the design of air conditioners that are intended to improve their energy efficiency. One is the increasing use of variable frequency drives (VFDs) in compressors and condenser fans.[1] The other is the inclusion of active power factor correction (PFC) in air-conditioning power supplies. Both of these trends represent the adoption of switched-mode power conversion in systems that previously relied on less-efficient, line-frequency electronics to power the compressors and fans.[2]

The advent of VFD and PFC circuits in air conditioning systems creates specific requirements for power controllers, gate drivers and power switches. Gate drivers in particular play an important role in achieving superior performance and efficiency in these applications. In addition to supporting design for high efficiency, gate drivers must be sufficiently robust to handle the harsh environments and noisiness in air conditioning systems.

In this article, I'll discuss the types of gate driver ICs that are available for use in modern-day air conditioners. The application focus here will be on the split air conditioners used in residential and commercial applications, specifically on the PFC and VFD power stages found in the outdoor units within these air conditioners. After some brief discussion of air conditioning functions and the typical power topologies used to power compressors and fans, I'll discuss gate-driver requirements for these topologies and some IC options that address these needs.

The gate driver ICs discussed here are for silicon IGBTs and MOSFETs. However, the concepts will also apply to the types of SiC and GaN power switches that may find their way into air conditioning applications in the future.

While many of the descriptions in this article of gate-driver operation will be familiar to experienced power designers, the details about specific driver ICs and features available for use in air conditioning applications may be informative even to those well versed in the technology. In addition, these discussions will be especially helpful for appliance designers who are just beginning to apply power electronics in their applications.

Air-Conditioning Systems

Most common air conditioners are called split air conditioners. This is because there are two units: the indoor unit (comprising the evaporator and fan) and outdoor unit (comprising the condenser, fan and compressor). Most residential homes and office spaces use the more-efficient split systems, while smaller homes such as mobile homes use packaged systems, which combine the elements of indoor and outdoor units into one. This paper focuses on the split system.

Between the two units in a split system, the outdoor unit has more power electronics and different stages that are suitable for a discussion of active PFC and VFD. Therefore, I'll restrict the discussion to the power topology and associated gate drivers pertinent to the outdoor unit. But before getting into the details of the power topology of the modern air-conditioning system, it is important to understand the value of VFD and PFC.

Traditional air conditioners were based on an on- or off-type compressor, which meant that they worked at maximum capacity or not at all. VFDs have a motor in the compressor unit, whose speed can vary by modulating the voltage, current and frequency of the power delivered to the compressor. As a result, the system does not have to run at full speed. This dramatically cuts down on energy costs and is by far the largest benefit of VFDs. Also, VFDs allow you to match the speed of motor-driven equipment to the load requirement, which could just be cooling a living room, for example, rather than the whole house.

Since air conditioners operate at relatively high power levels, typically on the order of a few kilowatts, implementing active PFC improves power quality and reduces harmonic distortion. This reduces the amount of reactive power that ends up going back to the grid as wasted or unutilized power.

Power Topologies In Air-Conditioning Systems

Power topologies in modern air-conditioning systems typically employ Si-based IGBTs as the power switch. Pulse width modulation (PWM) controls the power transfer in this topology.

Figs. 1 and 2 show block diagrams of the outdoor unit without and with the fan drives, respectively.

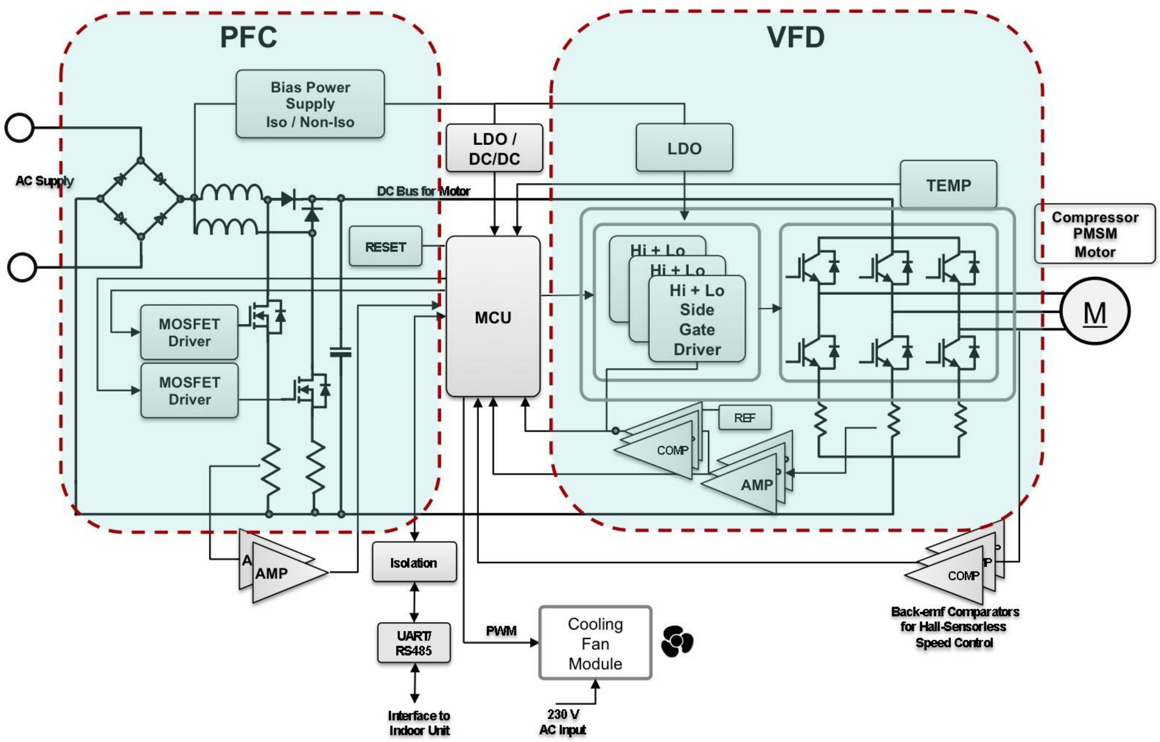

Fig. 1. Air-conditioner outdoor unit—compressor drive with PFC.

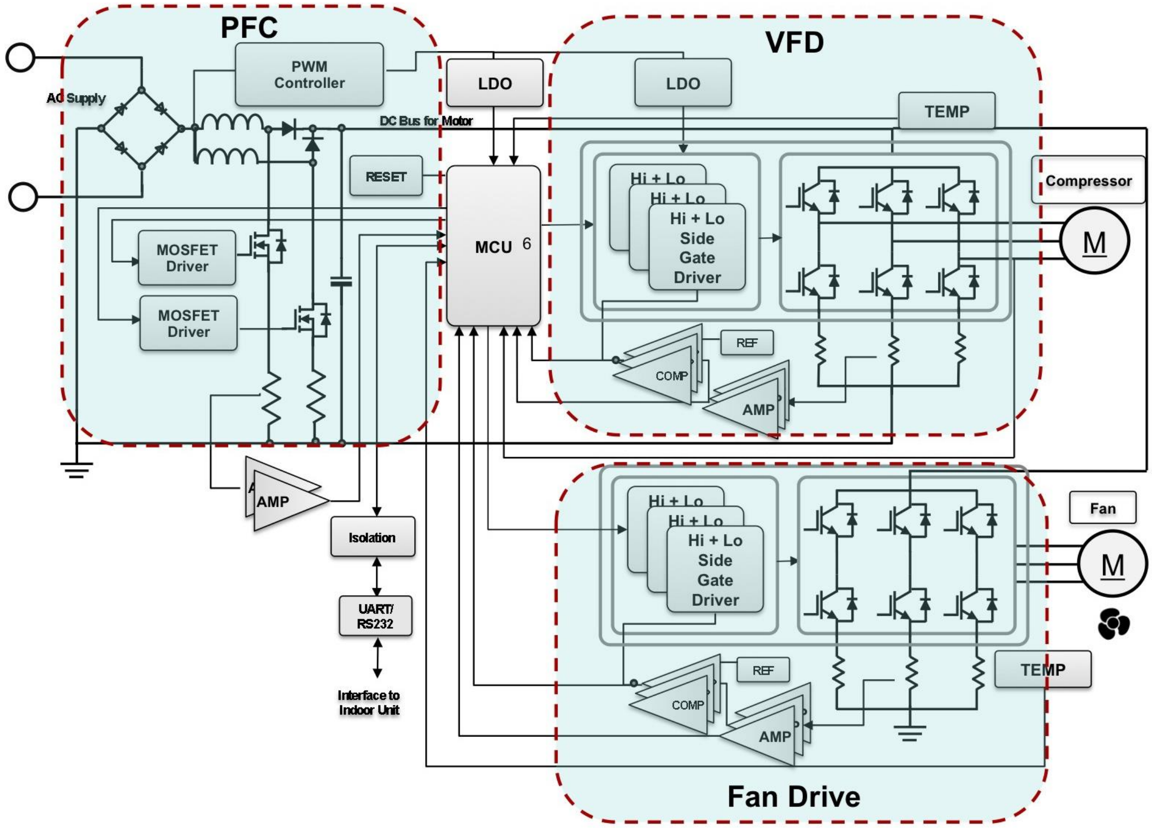

Fig. 2. Air-conditioner outdoor unit—compressor and fan drives with PFC.

The switching frequency employed in the VFD and fan drive inverters is typically up to 20 kHz. Caution is necessary when designing inverters to switch between 10 kHz and 16 kHz, as this range is audible to humans and the noise becomes annoying for consumers. As a result, the compressor generally operates below 8 kHz and the fans operate above 18 kHz.

Front-End PFC And Gate Drivers

As Figs. 1 and 2 illustrate, the first stage of the power-conditioning unit is the ac-dc converter, also known as the rectifier. This converter converts the incoming power supply from ac to dc using four diodes connected in a bridge. Inductors and capacitors are connected before the converter to reduce the electrical noise introduced into the power supply by transistor switching. The active PFC circuit can either be a single-phase boost PFC for lower power levels or an interleaved boost PFC for high-power applications.

The PFC topology uses either a single- or dual-channel low-side gate driver. Before getting into the details of the driver, it is important to understand the boost topology.

Fig. 3 shows the boost converter circuit, one of the simplest dc-dc converter topologies. In a boost topology, the input voltage (V_{IN}) is raised to a higher value (V_{OUT}) based on a conversion equation that holds well under steady-state conditions. This conversion is dependent on the duty cycle, D. Here, D is the ratio of time that switch Q1 stays on to the total time period (on-time plus off-time).

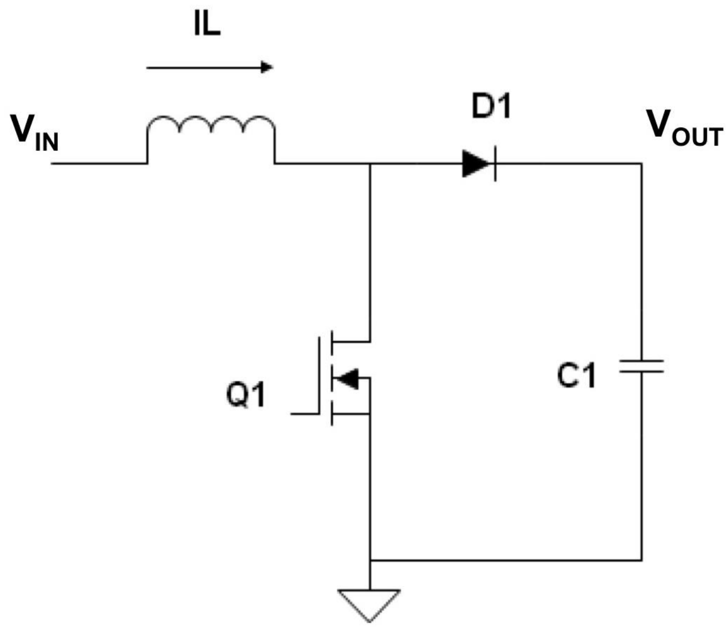

Fig. 3. Example of a simple boost-topology circuit.

A controller that regulates the duty cycle by sensing the output voltage and/or output current determines the time at which the power switch, Q1, will remain on and off. Since the controller's output levels are signal levels, a circuit is required to boost this signal to switch Q1. This is the *gate driver*.

A basic gate driver level-shifts the voltage to higher voltages, especially if the controller is a microcontroller or microprocessor with an output signal of 5 V, 3.3 V or below. It also provides sufficient drive current (for fast charging and discharging of the power switches, which are capacitive by nature—MOSFETs and IGBTs). Fast charge/discharge turns the power switch on and off quickly, which reduces power loss.

Fig. 4 shows an example of a low-side, single-channel gate-driver integrated circuit (IC) driving Q1 using a digital microcontroller unit (MCU).

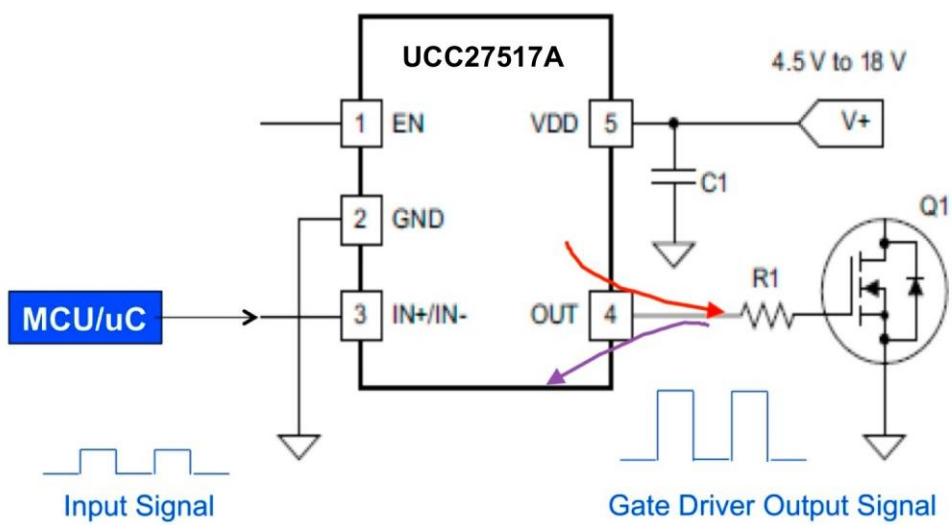

Fig. 4. Low-side, single-channel gate-driver IC driving Q1 using a digital controller.

Note that the input signal to the gate-driver IC (along with the MCU's output signal) is amplified in the driver's output signal to charge and discharge the power switch's capacitors. The driver ground (GND) reference is the same as the source terminal of the power switch. Such a driver is called a *low-side driver*.

This single-channel low-side driver is a good fit for the single-phase boost PFC topology (based on Fig. 3.)

One low-side gate driver driving two switches is called a *dual-channel low side* (Fig. 5.) Interleaved PFC topologies (commonly used in air conditioners because they are popular in high-wattage systems) require such drivers. Figs. 1 and 2 show the PFC topology to be interleaved.

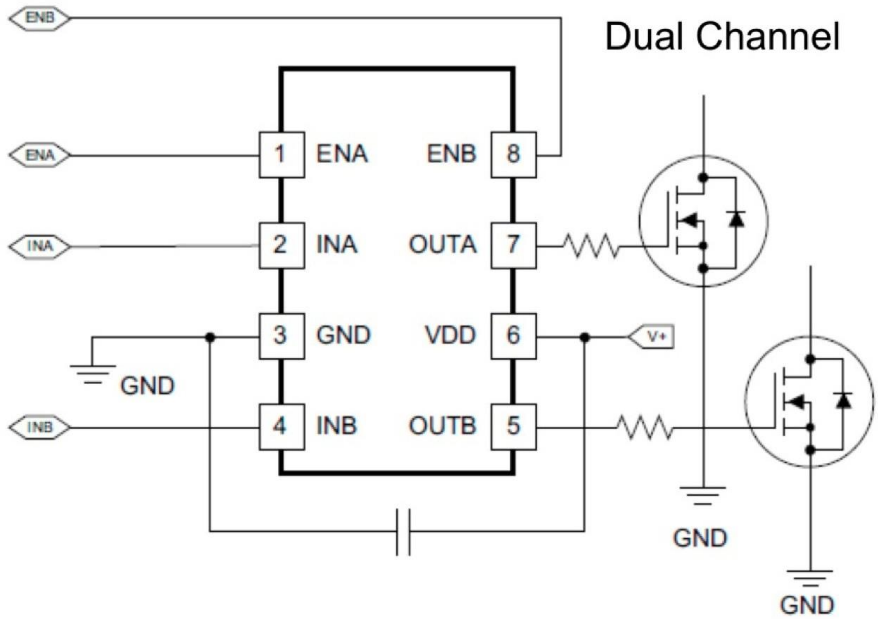

Fig. 5. Dual-channel driver configuration.

It is also possible to have two separate single-channel drivers for an interleaved topology. This could in turn help cut down wiring losses due to parasitic inductances between the driver and IGBTs because each single-channel driver can be placed in close proximity to the switch, whereas a dual-channel driver needs an optimal position between the two switches in the system board layout.

Since IGBTs are used in front-end PFCs as well, the operating voltage to switch the IGBTs for the gate driver needs to be at least 15 V. This means that the driver needs to have enough margin to handle 15 V, and therefore the maximum supply-voltage requirement will be higher: on the order of 25 V to 30 V. The Texas Instruments (TI) UCC27531D[3] is a single-channel driver suitable for such applications.

In a low-side gate driver:

- The driver IC GND is the same as the power-switch source terminal.
- The reference level for LOW output is GND.
- The single-channel variety has one input and one output; the dual-channel variety has two inputs and two outputs.

Back-End Inverter For VFDs And Gate Drivers

The inverter is the second stage of the power-conditioning unit, as shown in Figs. 1 and 2. An inverter topology, as shown in Fig. 6, simply generates a three-phase voltage to power the compressor motor, which could be a brushless dc (BLDC) motor or an ac induction machine. The inverter switches are six discrete IGBT transistors.

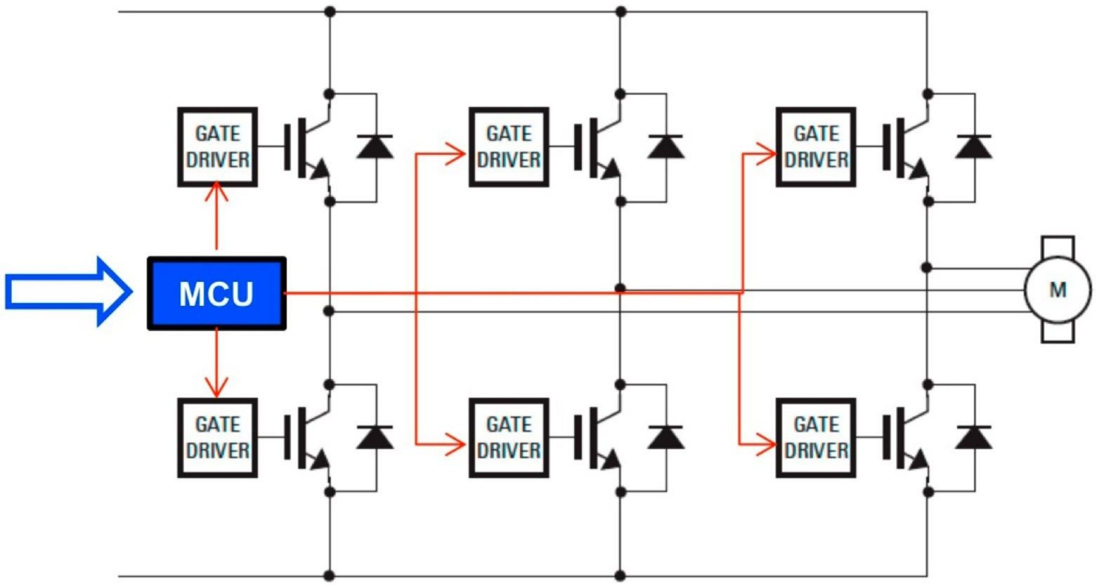

Fig. 6. High-power, three-phase inverter for compressor (VFD).

This inverter topology has a high- and low-side switch. A high-side switch is similar to a low-side switch, except that it has a floating reference point. This means that the driver required to drive the high-side switch needs to be floating as well. There are gate drivers designed to drive both the high- and low-side switches in one IC, and such a device is described as a high-/low-side driver.

Note that the typical voltage rating required on the high side is about 600 V. This voltage range ensures enough margin in the power switch and driver handling, and that voltage is around 1.5 to 2 times that of the actual operating voltage, about 200 to 400 V dc. One example of a typical 600-V driver is TI's recently released UCC27714[4] as shown in Fig. 7.

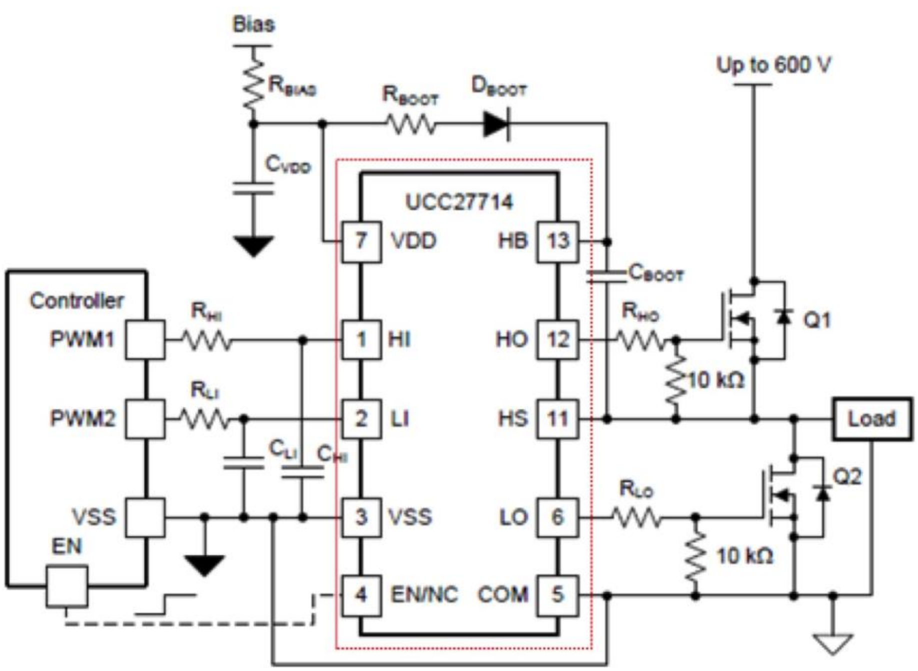

Fig. 7. High-/low-side driver configuration.

A driver like the UCC27714 controls two switches, H and L, arranged in a bridge configuration with two inputs, HI and LI, and two outputs, HO and LO. The LO drives the L switch with a source for the lower switch, L, which is the same as GND. The reference level for LO output is GND.

Alternatively, HO drives the H switch with the source of the upper switch, U, referenced to HS (not referenced to GND). The reference for HO output is HS (HO level-shifted to the HS pin). HS, HO and HB are high-voltage pins in high-/low-side drivers.

A half-bridge driver is a special version of a high-/low-side driver. An internal circuit ensures that HO and LO can never be on simultaneously. This prevents cross-conduction between H and L (also called *shoot-through*). Sometimes just one IN pin controls both the HO and LO states.

In this case:

- IN high = HO high, LO low.
- IN low = HO low, LO high.

These drivers also carry added capabilities such as dead-time control and adaptive delays—all to prevent cross-conduction between the high- and low-side switches. Motor-drive applications use these drivers quite frequently.

Intelligent power modules (IPMs) offer another option for switching the inverter IGBTs. A single housing integrates all six IGBTs (for the three-phase power-supply case, as shown in Figs. 1 and 2), gate-driver circuit and protection schemes.

Another option is to employ three high-/low-side gate drivers, one for each leg. Or, if you are using IGBTs as the power switches for higher power, with rail voltages greater than 600 V, using single-channel drivers is common because these drivers have integrated protection features such as desaturation and short-circuit detection. These drivers also have some level of galvanic isolation: capacitive, magnetic or optical. Drivers integrated with this isolation feature are called isolated gate drivers.

Many driver configurations, especially isolated gate drivers, have a drive current capability below 5-A peak. To boost the drive current, many applications use discrete npn-pnp totem-pole circuits. Several recently developed gate-driver ICs are replacing these discrete solutions.

Such a configuration effectively reduces the bill of materials (BOM) component count and printed circuit board (PCB) space and increases system reliability. There are also applications where protection features are not required to be part of the gate-driver solution. An air-conditioning manufacturer might simply want to implement a proprietary solution. In such cases, implementing a single-channel gate driver with just an isolator could be an option (Fig. 8).

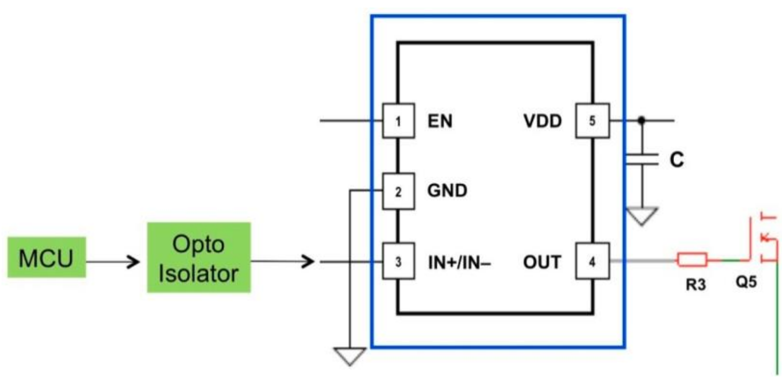

Fig. 8. Single-channel driver IC solution replacing a totem-pole npn-pnp for boost driver stage.

The fan drive unit is very similar to the inverter/compressor stage.

Summary

Air-conditioning systems are becoming increasingly efficient; advances in power electronic switches such as MOSFETs and IGBTs have made this possible. In this article, I discussed a key enabling device that improves efficiency and reliability—the gate driver IC—and reviewed the requirements of the overall system.

I discussed functionalities and the various types and features of gate drivers, along with system requirements at various stages of power conditioning. I chose an outdoor air-conditioning unit to illustrate the value of these gate drivers. The choice of gate drivers depends on the power device it needs to switch, the component count (single-channel versus bridge drivers), and requirements such as dead-time control to avoid shoot-through between high- and low-side switches and isolation.

References

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3. UCC27531D FET and IGBT single gate driver.
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