The Application Of Conductivity-Modulated Field-Effect Transistors

Application Note May 1992 AN7332.1

Summary

The development of conductivity-modulated field-effect transistors, FETs, makes available to the system designer another solid-state device that can be used to implement power switching control. This paper reviews differences between the standard and the newly developed FET. It shows the significant advantages that the conductivity-modulated FET has over the standard FET. Several applications are presented to show that this new type of device works well in practical situations. The relative immaturity of the conductivity-modulated FET may limit its initial utilization. But as the family grows and product innovation and refinement takes place, this newest member of the power semiconductor family will become a viable alternative to the other members.

General Considerations

The development of the power field-effect transistor has made available to the power-stage designer an entire new family of power semiconductors. Over the past 5 to 6 years, the breadth of product has grown to encompass the requirements of a large number of applications. A limiting factor that has slowed the utilization of power FETs in the high-current, high-voltage applications is the fact that the on-state resistance ($R_{DS(ON)}$) in a standard FET is related to its breakdown voltage (B_{VDSS}) by a nearly cubic power, i.e., $R_{DS(ON)} \approx B_{VDSS}$ 2.8. What this implies, as Figure 1 shows, is that as the breakdown voltage increases, the on-state resistance climbs even faster.

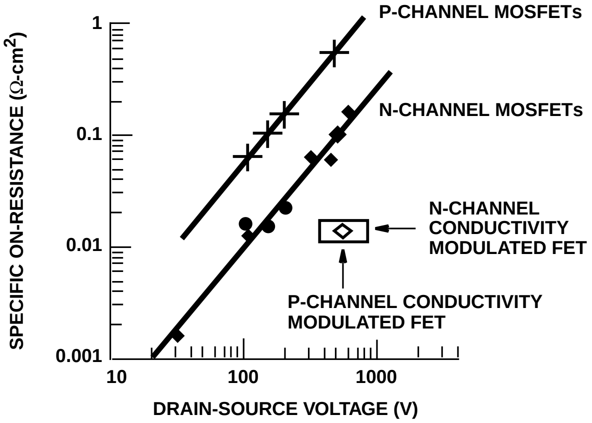

FIGURE 1. SPECIFIC ON-RESISTANCE OF P AND N-CNANNEL MOSFETS AND CONDUCTIVITY-MODULATED FETS vs FORWARD BLOCKING VOLTAGE.

The MOSFET on-state resistance is contributed to primarily by three components of the transistor: the MOS channel, the neck region, and the extended drain region. The extended drain region contributes the most to the on-state resistance in high-voltage MOSFETs. To achieve a lower on-state resistance at a given blocking voltage, the usual technique is simply to make the die larger. However, increasing the die size has its limitations from a manufacturing point of view, since MOSFETs, with their very fine horizontal geometries, are highly defect-yield sensitive. As die size increases, the likelihood of a defect resulting in a nonfunctional part increases exponentially. This tendency, combined with a smaller number of parts per wafer, limits the availability of low-on-state-resistance, high-voltage MOSFETs.

A change in the horizontal geometry of the MOSFET can lower the specific on-state resistance per unit area. By using more channel width with smaller source cells placed closer together, a reduction in on-state resistance can be achieved. A limitation on how close these cells can be placed arises from a possible localization of field concentrations that will limit the voltage breakdown of the structure to less than the theoretical rating due only to impurity concentrations. Therefore, for a given breakdown voltage, there exists a minimum spacing of the cell structure. Generally, the higher the required breakdown voltage, the further apart the cells must be placed.

As stated earlier, the extended drain region of the MOSFET generally contributes the most to the on-state resistance in high-voltage MOSFETs. As the required blocking voltage is increased, this region must be made thicker and more lightly doped to be able to support the desired voltage. It is this region's contribution to on-state resistance that the conductivity-modulated field-effect transistor drastically reduces. This reduction occurs as the result of the injection of minority carriers from the substrate and, in specific on-state resistance per unit area, is about 10 times less than in a standard MOSFET at the 400V BV_{DSS} level, as shown in Figure 1.

Further analysis has shown that the specific on-state resistance may be nearly independent of blocking-voltage level. This finding implies that at a BV_{DSS} of 1000V, the reduction in conductivity-modulated FETs over the standard MOSFETs could be perhaps 50 to 1. These reductions in on-state resistance per unit area that the conductivity-modulated FETs can achieve present the possibility that high-voltage high-current FET-type devices can become more readily available because of the smaller die sizes associated with conductivity-modulated FETs.

Comparison of Standard and Conductivity-Modulated FETs

Standard and conductivity-modulated FETs share some characteristics, but are substantially different in others. Shown in Table 1 is a listing of the major characteristics that make the conductivity-modulated FETs unique among power semiconductor families. Foremost, it is a voltage-gated device; its input characteristics are similar to standard power MOSFETs of comparable chip size. Very little drive power is required at low to moderate switching frequencies. The device remains under the control of the gate within its normal operating conditions. It exhibits the normal linear mode as well as the fully saturated on-state of conventional power MOSFETs. When the gate voltage is removed, the device turns off, unlike the thyristor family of power semiconductors, which must be either externally or naturally (internally) commutated.

TABLE 1. CONDUCTIVITY-MODULATED FET CHARACTERISTICS

Voltage Gated	Small gate power required. Similar to standard power MOSFET.
Turn Off	When gate drive is removed... Unlike an SCR!
Nonlinear On-State Voltage drop	Like that of an SCR.
Turn On Speed	Fast! Comparable to a standard power MOSFET.
Turn-Off Speed	Slow! Comparable to a bipolar transistor.
Temperature Independent On-State Voltage Drop	Unlike the typical 2x variation of a power MOSFET.

The on-state voltage drop or resistance characteristic of a conductivity-modulated FET is markedly different from that of a standard power MOSFET, and is similar to that of a thyristor family member, the SCR. There is an offset voltage component (typically 0.6V) due to the p-n junction on the drain side, and a somewhat nonlinear resistive component, both of which are in series between the drain and source terminals. This series arrangement results in a highly nonlinear equivalent resistance, unlike the linear resistive characteristic of $V_{DS(ON)}$ of a standard FET.

The structure of the conductivity-modulated FET operates during its turn on just as a standard FET does, hence its turn-on speed is very similar to that of a standard FET. With its high input impedance and its short propagation delay, the turn-on transition of the conductivity-modulated FET, as well as the standard power FET, is easily controlled by the gate driving circuit. This characteristic allows the designer the ability to control EMI and RPI generation easily. With other power semiconductors, it may be necessary to employ elaborate circuit schemes to limit rapidly rising in-rush currents.

A significant characteristic that must be considered in power switching applications is that of turn-off speed. The internal action that makes the conductivity-modulated FET such a silicon-efficient device also makes it an inherently slower device during turn-off. The injection of the minority carriers during the on-state conduction of current results in these carriers being present at the moment of turn-off. Without any way of removing these carriers by external means, they must recombine within the structure itself before the device can revert to its fully off-state condition. The quantity of these carriers and how fast they can deplete themselves determines the turn-off switching speed of the conductivity-modulated FET. This process of recombination is considerably slower than the simple discontinuance of majority carrier flow by which the standard power FET turns off. Hence, again, the conductivity-modulated FET is an inherently slower device. Its turn-off speed lies somewhere between the performance of a thyristor and that of a bipolar transistor.

The final characteristic that makes the conductivity-modulated FET different from a conventional FET is the variance of on-state voltage with temperature. The characteristic of the conductivity-modulated FET is similar to that of an SCR, varying about $-0.6\text{mV}/^{o}\text{C}$. The conventional FET has a positive temperature coefficient such that on high-voltage devices the $R_{DS(ON)}$ will double from its $+25^{o}\text{C}$ value when the junction temperature reaches $+150^{o}\text{C}$. The system designer must take this characteristic into consideration when the heat sink is being designed for the system.

It is these similarities and differences that make the conductivity-modulated FET a unique member of the family of power-semiconductor switching devices. Applications of this alternative power switching device invariably make use of one or more of its unique characteristics.

Applications

Automotive Ignition

An application that can take advantage of the low drive-power capability of the conductivity-modulated FET is the electronic automotive ignition system. In Figure 2, the control IC takes the signal from the pickup coil located in the distributor and regulates the current through the ignition coil. At the proper time, the IC removes base drive from the bipolar transistor, which all systems currently employ as their coil driver. This removal of base drive allows the transistor to shut off which, in turn, causes a rapid decrease in the ignition-coil primary current. As the primary current decreases to zero, the energy stored in the field surrounding the primary is transferred to the secondary coil. The secondary coil, consisting of many more turns than the primary, transforms this energy into a higher voltage, resulting in a spark being generated in the cylinder. The control IC determines when this spark occurs, so as to derive usable power. With the use of a bipolar transistor, it is estimated that approximately two-thirds of the power dissipation that occurs in the control IC is the result of the need to be able to drive the required base current of the ignition output transistor. The high-impedance input of the conductivity-modulated FET virtually eliminates the base-current drive dissipation of the control IC.

With improved silicon usage, the conductivity-modulated FET brings to power semiconductor switching devices the die size necessary to attain the required voltage and current-handling capabilities of the electronic ignition. This smaller-sized die makes possible smaller modules, whether they be hybrid or standard PC-based systems, than those currently implemented with bipolar-transistor technology.

Brushless DC Motors

Another emerging application that can make use of conductivity-modulated FETs is the emerging field of brushless DC motors. In this class of application, the solid-state devices are used to electronically switch the voltage to the multiplicity of windings that are employed. The motor consists of an armature that has a number of N and S poles consisting of high-strength permanent magnets. The stator is made up of the multiplicity of windings that were mentioned above; the windings are spaced incrementally about the outside frame of the housing. The voltages to these windings are all electronically switched to create a rotating magnetic field. The armature then rotates to maintain its relative position within the moving magnetic field. The switching of the voltage on the stator windings is done by means of power semiconductor devices. A basic block diagram of such a system is shown in Figure 3.

The control logic provides the proper sequence of drive signals based on the rotation direction desired, the speed desired, and the enable input. These requirements are combined with the inputs from the hall-effect sensors to determine which power devices should be activated. Since the current through the stator windings must be bidirectional, the half-bridge or totem-pole output configuration is used to steer the current. This circuit implementation is generally performed with complementary devices, although single-polarity devices can be used with increased circuit complexity.

In a typical 120V off-line system, like the one shown in Figure 3, the switching devices must have a 300V to 400V blocking capability. For larger size motors, where larger currents are necessary, the use of power FETs generally implies the use of large die to achieve a low power dissipation to meet the heat-dissipation capability of the packaging. The conductivity-modulated FET, with its temperature-independent on-state-voltage-drop characteristic, helps this situation by keeping the dissipation lower than can be achieved with a standard power FET because of the increasing $R_{DS(ON)}$ characteristic of that device. The small die size of the conductivity-modulated FET, the result of better silicon utilization, again makes them the practical choice in motor control not only because of their electrical characteristics, but also because of the lower manufacturing cost of the die.

As stated above, system complexity can be reduced with complementary devices. Although p-channel conductivity-modulated FETs are not yet commerically available, laboratory samples have been fabricated which offers better silicon utilization efficiency than their conventional p-channel counterparts. This statement is based on the fact that p-channel MOSFETs require a 2.5 times larger area than an n-channel device for the same $R_{DS(ON)}$. The easier drive requirements for the n-channel (directly driven from the control IC) and the simplified voltage-translation circuit for driving the p-channel devices, combined with the smaller die size with potentially lower device cost for comparable power handling capability, makes the conductivity-modulated FET a natural for the brushless DC motor application.

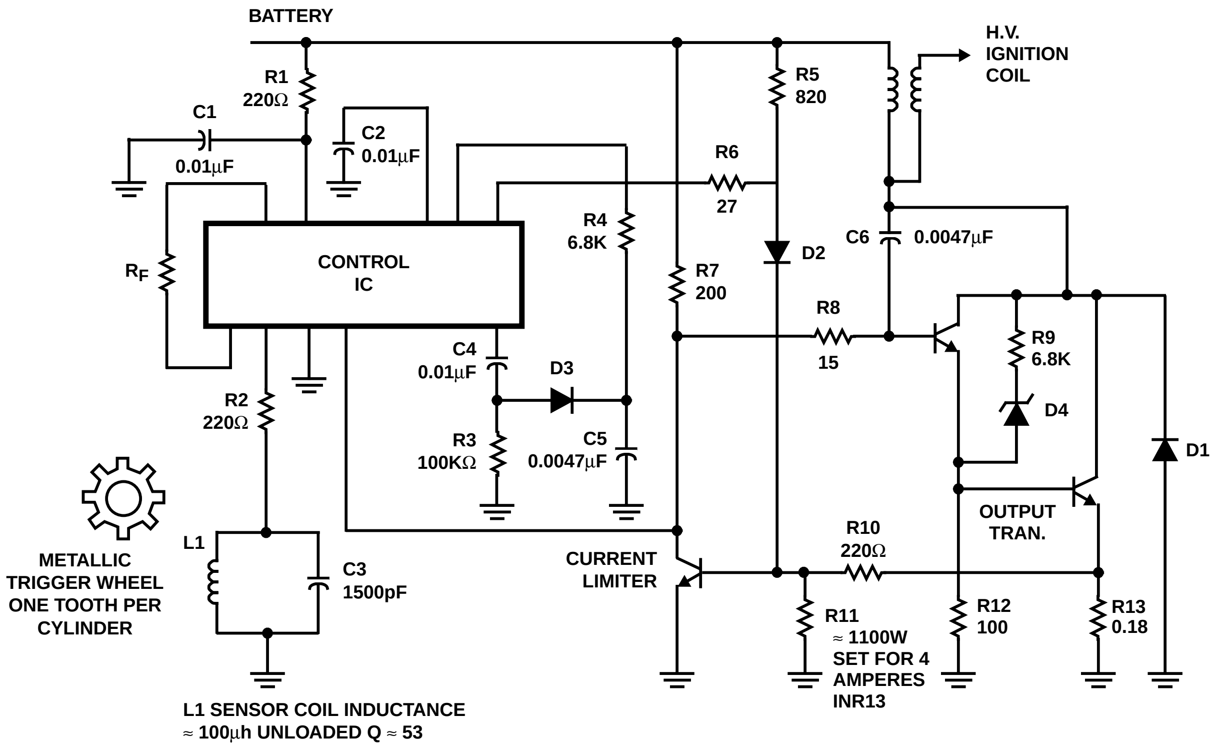

FIGURE 2. TYPICAL IGNITION SYSTEM

Switching Power Supply

One final application that has the potential for conductivity-modulated FET usage is the switching power supply. A half bridge configuration implementation is presented in Figure 4. The system shown uses a standard PWM control IC to drive the conductivity-modulated FETs through the T2 transformer. The voltage drive characteristic of these devices makes the design of transformer T2 quite simple. The control IC is more lightly loaded because it does not have to supply a continuous base drive, as would be necessary with bipolar transistors.

The operating frequency and the "dead time" are the limitations placed on this system when conductivity-modulated FETs are used. The inherent lower switching speeds of these types of devices make these limitations necessary. The system is currently limited to the 20kHz to 30kHz range, with dead times as low as 1 to 2 microseconds. This characteristic is comparable to many existing bipolar systems.

Improvements in switching speeds will occur as the conductivity-modulated FET matures. It is, however, unlikely that they will ever have the same switching speeds as standard power FETs. This limitation prohibits their use in some of the newer higher-frequency power supplies being designed now with conventional FETs. However, in higher-power supplies, where conventional FETs must be paralleled to achieve a low enough $R_{DS(ON)}$ for good efficiency, the conductivity-modulated FET may present a viable alternative with its smaller die size. Although the operating frequency of the system may have to be compromised to use them.

Conclusion

The conductivity-modulated FET represents a progression in the ever-advancing state-of-the-art development that occurs in the world of solid-state devices. The unique structure of these devices presents characteristics that make them equivalent in many ways to conventional FETs but superior in other ways. The system designer must take into account these similar and dissimilar characteristics to properly use them. The capabilities of the conductivity-modulated FETs allow them to make inroads into applications currently served by bipolar transistors, and in some cases conventional power FETs. As the devices mature through innovation and product refinement, conductivity-modulated FETs will become vital members of the family of solid-state power-semiconductor devices.

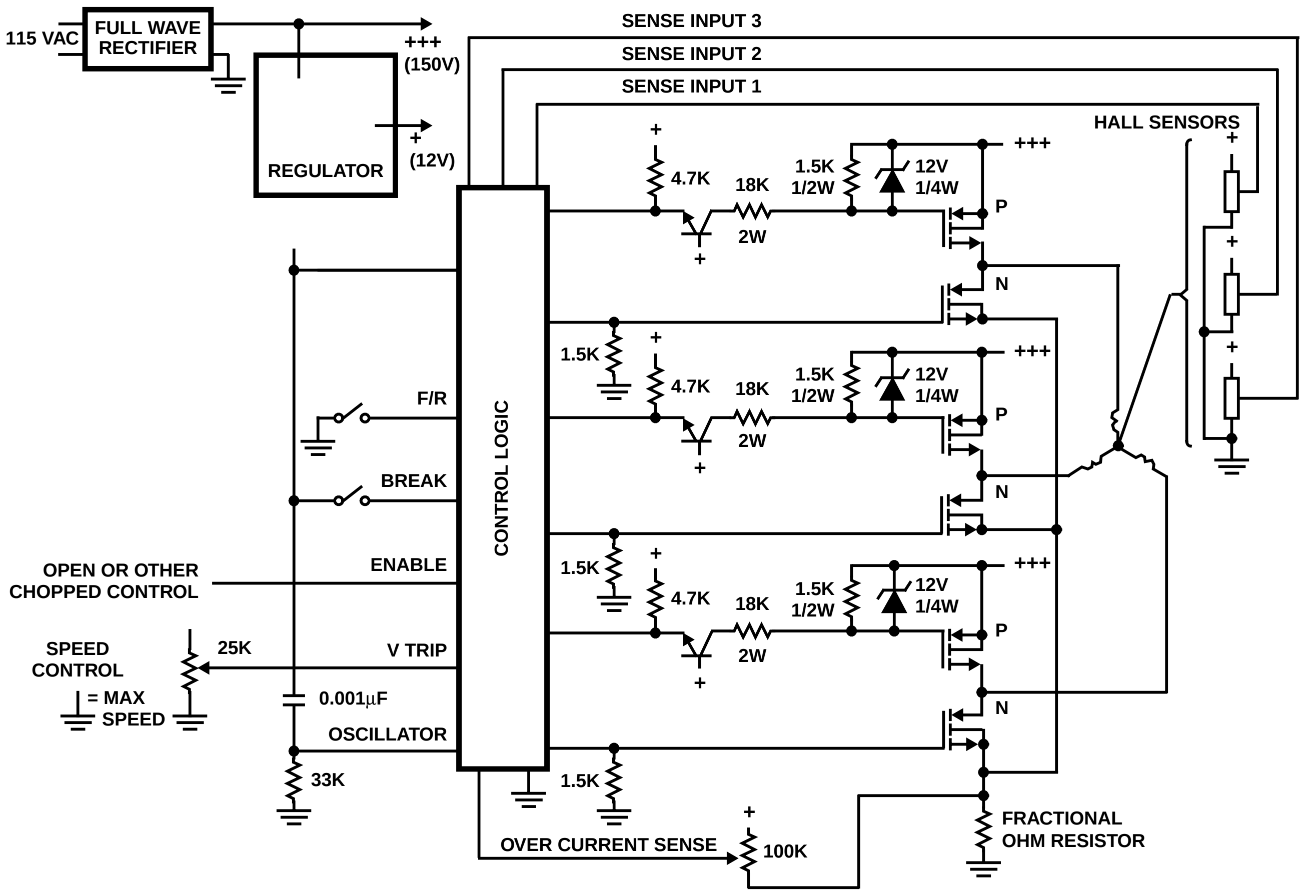

FIGURE 3. CONTROL CIRCUIT FOR THREE-PHASE BRUSHLESS DC MOTOR

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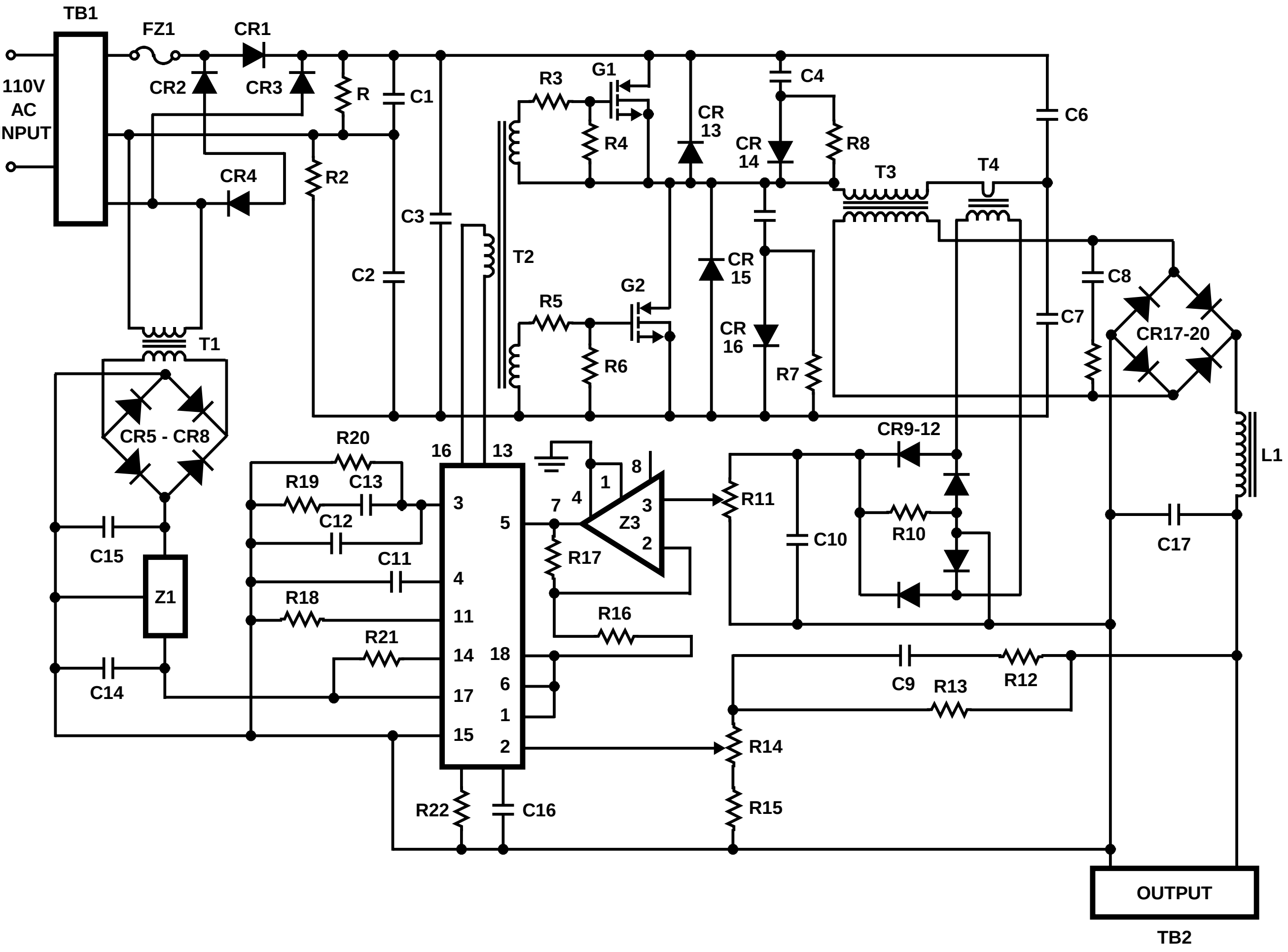

FIGURE 4. HALF-BRIDGE SWITCHING POWER SUPPLY

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