The MOS Controlled Thyristor (MCT)
Part 1

Introduction

The efficiency, capacity, and ease of control of power converters depend mainly on the power devices employed. Power devices, in general, belong to either bipolar-junction type or field-effect type and each one has its advantages and disadvantages. The silicon controlled rectifier (SCR), also known as a thyristor, is a popular power device that has been used over the past several years. It has a high current density and a low forward voltage drop, both of which make it suitable for use in large power applications. The inability to turn-off through the gate and the low switching speed are the main limitations of an SCR. The gate turn-off (GTO) thyristor was proposed as an alternative to SCR. However, the need for a higher gate turn-off current limited its application.

The power MOSFET has several advantages such as high input impedance, ease of control, and higher switching speeds. Lower current density and higher forward drop limited the device to low-voltage and low-power applications. An effort to combine the advantages of bipolar junction and field-effect structures has resulted in hybrid devices such as the insulated gate bipolar transistor (IGBT) and the MOS controlled thyristor (MCT). While an IGBT is an improvement over a bipolar junction transistor (BJT) using a MOSFET to turn-on and turn-off current, an MCT is an improvement over a thyristor with a pair of MOSFETs to turn-on and turn-off current. The MCT overcomes several of the limitations of the existing power devices and promises to be a better switch for the future. While there are several devices in the MCT family with distinct combinations of channel and gate structures, one type, called the P-channel MCT, has been widely reported and is discussed here. Because the gate of the device is referred to with respect to the anode rather than the cathode, it is sometimes referred to as a complementary MCT (C-MCT). Harris Semiconductors (Intersil) originally made the MCTs, but the MCT division was sold to Silicon Power Corporation (SPCO), which has continued the development of MCTs.

Equivalent Circuit and Switching Characteristics

The SCR is a 4-layer pnpn device with a control gate, and applying a positive gate pulse turns it on when it is forward-biased. The regenerative action in the device helps to speed up the turn-on process and to keep it in the “ON” state even after the gate pulse is removed. The MCT uses an auxiliary MOS device (PMOSFET) to turn-on and this simplifies the gate control. The turn-on has all the characteristics of a power MOSFET. The turn-off is accomplished using another MOSFET (NMOSFET), which essentially diverts the base current of one of the BJTs and breaks the regeneration.

The transistor-level equivalent circuit of a P-channel MCT and the circuit symbol are shown in Fig. 8.1. The cross section of a unit cell is shown in Fig. 8.2. The MCT is modeled as an SCR merged with a pair of MOSFETs. The SCR consists of the bipolar junction transistors (BJTs) Q1 and Q2, which are interconnected to provide regenerative feedback such that the transistors drive each other into saturation. Of the two MOSFETs, the PMOS located between the collector and emitter of Q2 helps to turn the SCR on, and the NMOS located across the base-emitter junction of Q2 turns it off. In the actual fabrication, each MCT is made up of a large number (~100,000) of cells, each of which contains a wide-base npn transistor and a narrow-base pnp transistor. While each pnp transistor in a cell is provided with an N-channel MOSFET across its emitter and base, only a small percentage (~4%) of pnp transistors are provided with P-channel MOSFETs across their emitters and collectors. The small percentage of PMOS cells in an MCT provides just enough current for turn-on and the large number of NMOS cells provide plenty of current for turn-off.
Turn-on and Turn-off

When the MCT is in the forward blocking state, it can be turned on by applying a negative pulse to its gate with respect to the anode. The negative pulse turns on the PMOSFET (On-FET) whose drain current flows through the base-emitter junction of Q1 (nnp) thereby turning it on. The regenerative action within Q1 – Q2 turns the MCT on into full conduction within a very short time and maintains it even after the gate pulse is removed. The MCT turns on with a plasma-spreading phase giving a high dI/dt capability and ease of overcurrent protection. The on-state resistance of an MCT is slightly higher than that of an equivalent thyristor because of the degradation of the injection efficiency of the N + emitter/p-base junction. Also, the peak current rating of an MCT is much higher than its average or rms current rating. An MCT will remain in the “ON” state until the device current is reversed or a turn-off pulse is applied to its gate. Applying a positive pulse to its gate turns off a conducting MCT. The positive pulse turns on the NMOSFET (Off-FET), thereby diverting the base current of Q2 (pnp) away to the anode of the MCT and breaking the latching action of the SCR. This stops the regenerative feedback within the SCR and turns the MCT off. All the cells within the device are to be turned off at the same time to avoid a sudden increase in current density. When the Off-FETs are turned on, the SCR section is heavily shorted and this results in a high dV/dt rating for the MCT. The highest current that can be turned off with the application of a gate bias is called the “maximum controllable current.” The MCT can be gate controlled if the device current is less than the maximum controllable current. For smaller device currents, the width of the turn-off pulse is not critical. How-ever, for larger currents, the gate pulse has to be wider and more often has to occupy the entire off-period of the switch.
Comparison of MCT and Other Power Devices

An MCT can be compared to a power MOSFET, a power BJT, and an IGBT of similar voltage and current ratings. The operation of the devices is compared under on-state, off-state, and transient conditions. The comparison is simple and very comprehensive. The current density of an MCT is ≈70% higher than that of an IGBT having the same total current. During its on-state, an MCT has a lower conduction drop compared to other devices. This is attributed to the reduced cell size and the absence of emitter shorts present in the SCR within the MCT. The MCT also has a modest negative temperature coefficient at lower currents with the temperature coefficient turning positive at larger current. Figure 8.3 shows the conduction drop as a function of current density.

The forward drop of a 50-A MCT at 25 °C is around 1.1 V, while that for a comparable IGBT is over 2.5 V. The equivalent voltage drop calculated from the value of $f_{DS(on)}$ for a power MOSFET will be much higher. However, the power MOSFET has a much lower delay time (30 ns) compared to that of an MCT (300 ns). The turn-on of a power MOSFET can be so much faster than an MCT or an IGBT therefore, the switching losses would be negligible compared to the conduction losses. The turn-on of an IGBT is intentionally slowed down to control the reverse recovery of the freewheeling diode used in inductive switching circuits.

The MCT can be manufactured for a wide range of blocking voltages. Turn-off speeds of MCTs are supposed to be higher as initially predicted. The turn-on performance of Generation-2 MCTs is reported to be better compared to Generation-1 devices. Even though the Generation-1 MCTs have higher turn-off times compared to IGBTs, the newer ones with higher radiation (hardening) dosage have comparable turn-off times. At present, extensive development activity in IGBTs has resulted in high speed switched mode power supply (SMPS) IGBTs that can operate at switching speeds ≈150 kHz. The turn-off delay time and the fall time for an MCT are much higher compared to a power MOSFET, and they are found to increase with temperature. Power MOSFETs becomes attractive at switching frequencies above 200 kHz, and they have the lowest turn-off losses among the three devices.

The turn-off safe operating area (SOA) is better in the case of an IGBT than an MCT. For an MCT, the full switching current is sustainable at ≈50 to 60% of the breakdown voltage rating, while for an IGBT it is about 80%. The use of capacitive snubbers becomes necessary to shape the turn-off locus of an MCT. The addition of even a small capacitor improves the SOA considerably.
Gate Drive for MCTs

The MCT has a MOS gate similar to a power MOSFET or an IGBT and hence it is easy to control. In a PMCT, the gate voltage must be applied with respect to its anode. A negative voltage below the threshold of the On-FET must be applied to turn on the MCT. The gate voltage should fall within the specified steady-state limits in order to give a reasonably low delay time and to avoid any gate damage due to overvoltage. Similar to a GTO, the gate voltage rise-time has to be limited to avoid hot spots (current crowding) in the MCT cells. A gate voltage less than $-5 \, \text{V}$ for turn-off and greater than $10 \, \text{V}$ for turn-on ensures proper operation of the MCT. The latching of the MCT requires that the gate voltage be held at a positive level in order to keep the MCT turned off.

Because the peak-to-peak voltage levels required for driving the MCT exceeds those of other gate-controlled devices, the use of commercial drivers is limited. The MCT can be turned on and off using a push–pull pair with discrete NMOS–PMOS devices, which, in turn, are driven by commercial integrated circuits (ICs). However, some drivers developed by MCT manufacturers are not commercially available.

A Baker’s clamp push–pull can also be used to generate gate pulses of negative and positive polarity of adjustable width for driving the MCT. The Baker’s clamp ensures that the push–pull transistors will be in the quasi-saturated state prior to turn-off and this results in a fast switching action. Also, the negative feedback built into the circuit ensures satisfactory operation against variations in load and temperature. A similar circuit with a push–pull transistor pair in parallel with a pair of power BJTs is available. An intermediate section, with a BJT that is either cut off or saturated, provides $-10$ and $+15 \, \text{V}$ through potential division.