

MOS Controlled Thyristors (MCTs)

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8.1 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 [1],

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) [2]. Harris Semiconductors (Intersil) originally made the MCTs, but the MCT division was sold to Silicon Power Corporation (SPCO), which has continued the development of MCTs.

8.2 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

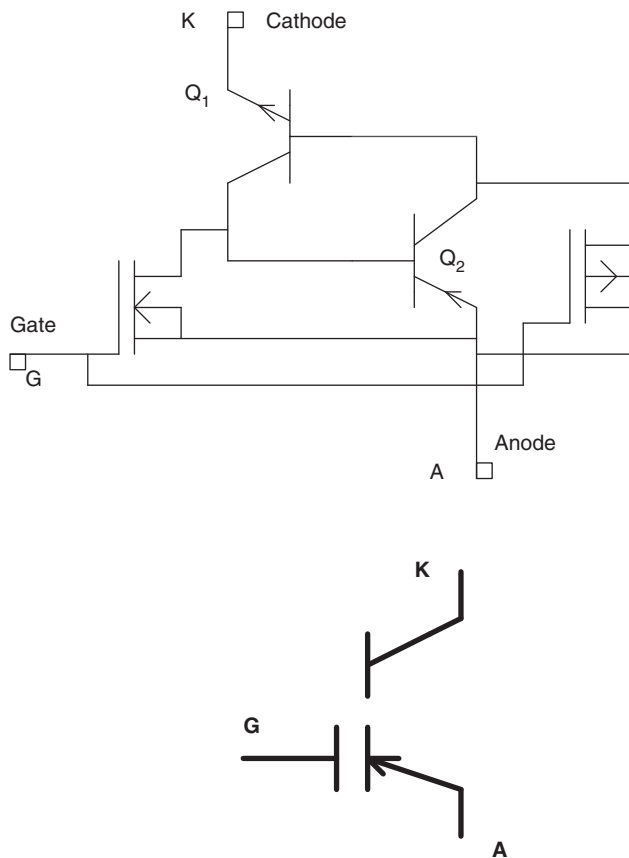


FIGURE 8.1 Equivalent circuit and symbol of an MCT.

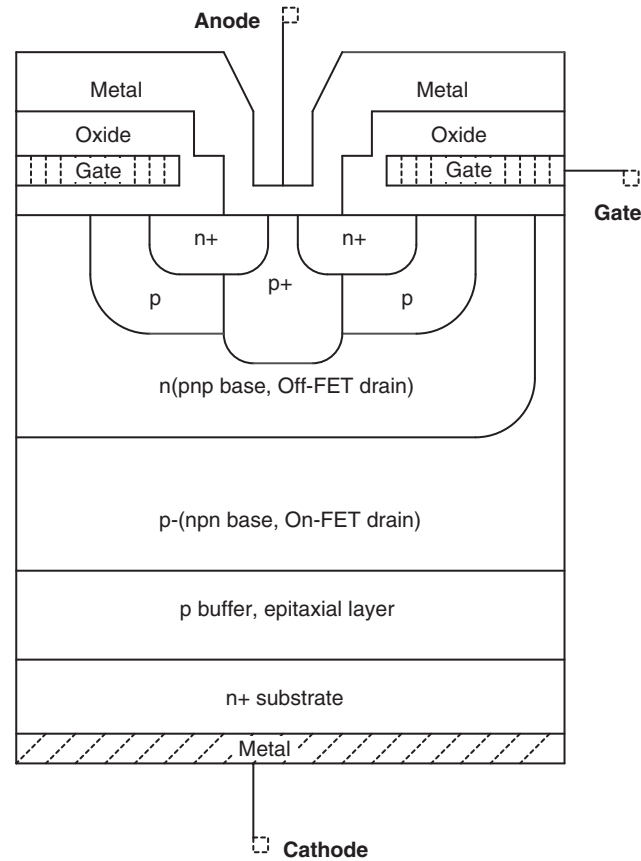


FIGURE 8.2 Cross section of an MCT unit cell.

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) Q_1 and Q_2 , 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 Q_2 helps to turn the SCR on, and the NMOS located across the base-emitter junction of Q_2 turns it off. In the actual fabrication, each MCT is made up of a large number ($\sim 100,000$) cells, each of which contains a wide-base $nnpn$ 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 ($\sim 4\%$) 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.

8.2.1 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 Q_1 (*nnp*) thereby turning it on. The regenerative action within $Q_1 - Q_2$ 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 without 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 Q_2 (*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. However, for larger currents, the gate pulse has to be wider and more often has to occupy the entire off-period of the switch.

8.3 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 $\approx 70\%$ higher than that of an IGBT having the same total current [2]. 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

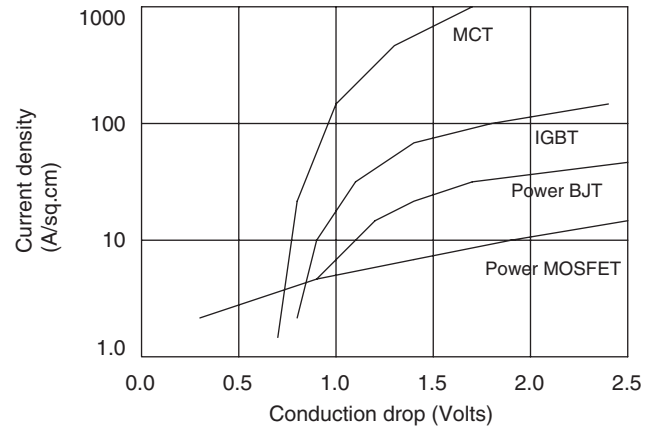


FIGURE 8.3 Comparison of forward drop for different devices.

lower currents with the temperature coefficient turning positive at larger current [2]. 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 $r_{DS}(ON)$ 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 [3].

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 are 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 [4]. 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 [2]. Power MOSFETs become 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.

8.4 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 [3]. 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 V for turn-off and greater than 10 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 [3].

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 [5–7]. 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 [8]. An intermediate section, with a BJT that is either cut off or saturated, provides -10 and $+15$ V through potential division.

8.5 Protection of MCTs

8.5.1 Paralleling of MCTs

Similar to power MOSFETs, MCTs can be operated in parallel. Several MCTs can be paralleled to form larger modules with only slight derating of the individual devices provided the devices are matched for proper current sharing. In particular, the forward voltage drops of individual devices have to be matched closely.

8.5.2 Overcurrent Protection

The anode-to-cathode voltage in an MCT increases with its anode current and this property can be used to develop a protection scheme against overcurrent [5, 6]. The gate pulses to the MCT are blocked when the anode current and hence the anode-to-cathode voltage exceeds a preset value. A Schmitt trigger comparator is used to allow gate pulses to the MCT when it is in the process of turning on, during which time the anode voltage is relatively large and decreasing.

8.5.2.1 Snubbers

As with any other power device, the MCT is to be protected against switching-induced transient voltage and current spikes by using suitable snubbers. The snubbers modify the voltage and current transients during switching such that the switching trajectory is confined within the safe operating area (SOA). When the MCT is operated at high frequencies, the snubber increases the switching loss due to the delayed voltage and current responses. The power circuit of an MCT chopper including an improved snubber circuit is shown in Fig. 8.4 [5, 7]. The turn-on snubber consists of L_s and D_{LS} and the turn-off snubber consists of R_s , C_s , and D_{CS} . The series-connected turn-on snubber reduces the rate of change of the anode current dI_A/dt . The MCT does not support V_s until the current through the freewheeling diode reaches zero at turn-on. The turn-off snubber helps to reduce the peak power and the total power dissipated by the MCT by reducing the voltage across the MCT when the anode current decays to zero. The analysis and design of the snubber and the effect of the snubber on switching loss and electromagnetic interference are given in References [5] and [7]. An alternative snubber configuration for the two MCTs in an ac-ac converter has also been reported [8]. This snubber uses only one capacitor and one inductor for both the MCT switches (PMCT and NMCT) in a power-converter leg.

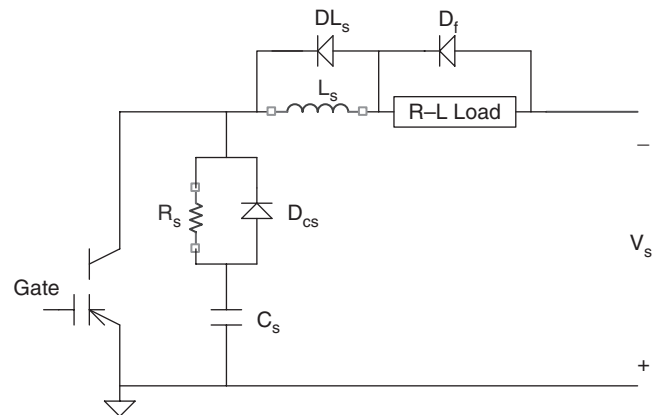


FIGURE 8.4 An MCT chopper with turn-on and turn-off snubbers.

8.6 Simulation Model of an MCT

The operation of power converters can be analyzed using PSPICE and other simulation software. As it is a new device, models of MCTs are not provided as part of the simulation libraries. However, an appropriate model for the MCT would be helpful in predicting the performance of novel converter topologies and in designing the control and protection circuits. Such a model must be simple enough to keep the simulation time and effort at a minimum, and must represent most of the device properties that affect the circuit operation. The PSPICE models for Harris PMCTs are provided by the manufacturer and can be downloaded from the internet. However, a simple model presenting most of the characteristics of an MCT is available [9, 10]. It is derived from the transistor-level equivalent circuit of the MCT by expanding the SCR model already reported in the literature. The improved model [10] is capable of simulating the breakover and breakdown characteristics of an MCT and can be used for the simulation of high-frequency converters.

8.7 Generation-1 and Generation-2 MCTs

The Generation-1 MCTs were commercially introduced by Harris Semiconductors in 1992. However, the development of Generation-2 MCTs is continuing. In Gen-2 MCTs, each cell has its own turn-on field-effect transistor (FET). Preliminary test results on Generation-2 devices and a comparison of their performance with those of Generation-1 devices and high-speed IGBTs are available [11, 12]. The Generation-2 MCTs have a lower forward drop compared to the Generation-1 MCTs. They also have a higher di/dt rating for a given value of capacitor used for discharge. During hard switching, the fall time and the switching losses are lower for the Gen-2 MCTs. The Gen-2 MCTs have the same conduction loss characteristics as Gen-1 with drastic reductions in turn-off switching times and losses [13].

Under zero-current switching conditions, Gen-2 MCTs have negligible switching losses [13]. Under zero-voltage switching, the turn-off losses in a Gen-2 device are one-half to one-fourth (depending on temperature and current level) the turn-off losses in Gen-1 devices. In all soft-switching applications, the predominant loss, namely, the conduction loss, reduces drastically allowing the use of fewer switches in a module.

8.8 N-channel MCT

The PMCT discussed in this chapter uses an NMOSFET for turn-off and this results in a higher turn-off current capability.

The PMCT can only replace a P-channel IGBT and inherits all the limitations of a P-channel IGBT. The results of a 2D simulation show that the NMCT can have a higher controllable current [13]. It is reported that NMCT versions of almost all Harris PMCTs have been fabricated for analyzing the potential for a commercial product [3]. The NMCTs are also being evaluated for use in zero-current soft-switching applications. However, the initial results are not quite encouraging in that the peak turn-off current of an NMCT is one-half to one-third of the value achievable in a PMCT. It is hoped that the NMCTs will eventually have a lower switching loss and a larger SOA as compared to PMCTs and IGBTs.

8.9 Base Resistance-controlled Thyristor [14]

The base resistance-controlled thyristor (BRT) is another gate-controlled device that is similar to the MCT but with a different structure. The Off-FET is not integrated within the p -base region but is formed within the n -base region. The diverter region is a shallow p -type junction formed adjacent to the p -base region of the thyristor. The fabrication process is simpler for this type of structure. The transistor level equivalent circuit of a BRT is shown in Fig. 8.5.

The BRT will be in the forward blocking state with a positive voltage applied to the anode and with a zero gate bias. The forward blocking voltage will be equal to the breakdown voltage of the open-base pnp transistor. A positive gate bias turns on the BRT. At low current levels, the device behaves similarly to an IGBT. When the anode current increases, the operation changes to thyristor mode resulting

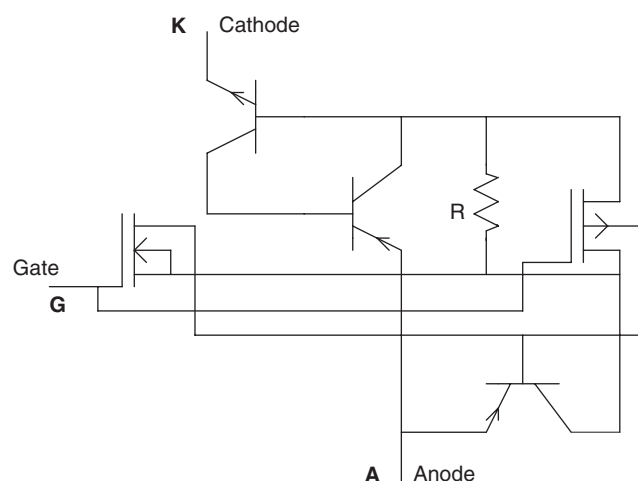


FIGURE 8.5 Equivalent circuit of base resistance-controlled thyristor (BRT).

in a low forward drop. Applying a negative voltage to its gate turns off the BRT. During the turn-off process, the anode current is diverted from the N^+ emitter to the diverter. The BRT has a current tail during turn-off that is similar to an MCT or an IGBT.

8.10 MOS Turn-off Thyristor [15]

The MOS turn-off (MTO) thyristor or the MTOT is a replacement for the GTO and it requires a much smaller gate drive. It is more efficient than a GTO, it can have a maximum blocking voltage of about 9 kV, and it will be used to build power converters in the 1–20 MVA range. Silicon Power Corporation (SPCO) manufactures the device.

The transistor-level equivalent circuit of the MTOT (hybrid design) and the circuit symbol are shown in Fig. 8.6. Applying a current pulse at the turn-on gate (G1), as with a conventional GTO, turns on the MTOT. The turn-on action, including

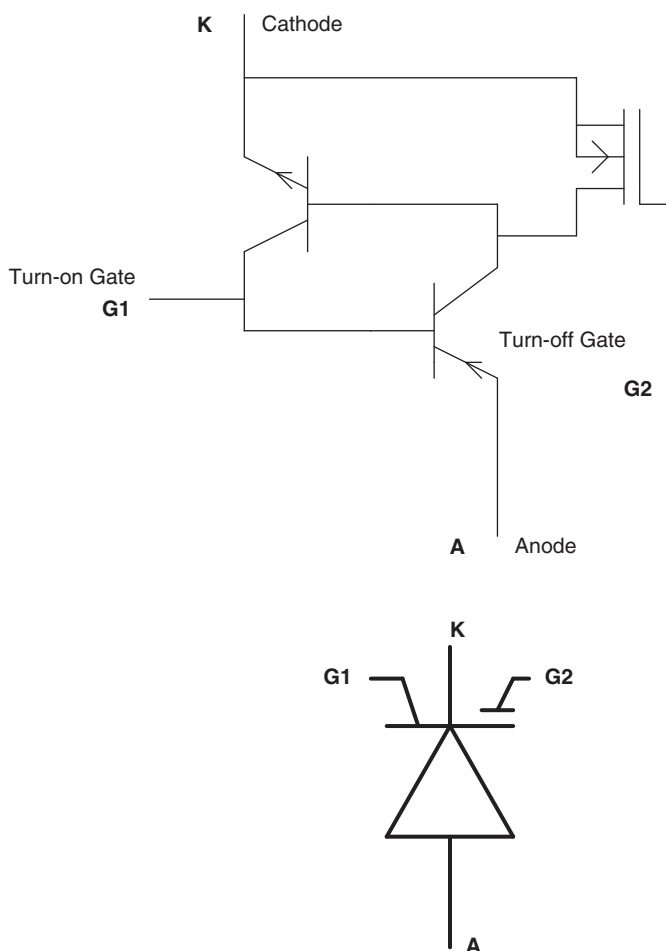


FIGURE 8.6 Equivalent circuit and symbol of a MOS turn-off (MTO) thyristor.

regeneration, is similar to a conventional SCR. Applying a positive voltage pulse to the turn-off gate (G2), as with an MCT, turns off the MTOT. The voltage pulse turns on the FET, thereby shorting the emitter and base of the $nnpn$ transistor and breaking the regenerative action. The MTOT is a faster switch than a GTO in that it is turned off with a reduced storage time compared to a GTO. The disk-type construction allows double-side cooling.

8.11 Applications of PMCT

The MCTs have been used in various applications, some of which are in the area of ac-dc and ac-ac conversion where the input is 60 Hz ac. Variable power factor operation was achieved using the MCTs as a force-commutated power switch [5]. The power circuit of an ac voltage controller capable of operating at a leading, lagging, and unity power factor is shown in Fig. 8.7. Because the switching frequency is low, the switching losses are negligible. Because the forward drop is low, the conduction losses are also small. The MCTs are also used in circuit breakers.

8.11.1 Soft-switching

The MCT is intended for high-frequency switching applications where it is supposed to replace a MOSFET or an IGBT. Similar to a Power MOSFET or an IGBT, the switching losses will be high at high switching frequencies. The typical characteristics of an MCT during turn-on and turn-off under hard switching (without snubber) are shown in Fig. 8.8. During turn-on and turn off, the device current and voltage take a finite time to reach their steady-state values. Each time the device changes state, there is a short period during which the voltage and current variations overlap. This results in a transient power loss that contributes to the average power loss.

Soft-switching converters are being designed primarily to enable operation at higher switching frequencies. In these

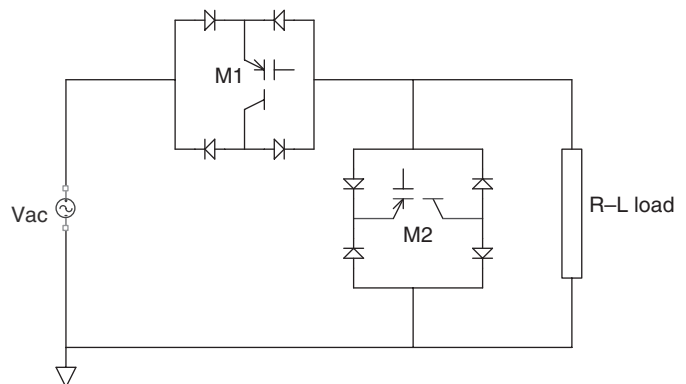


FIGURE 8.7 Power circuit of MCT ac voltage controller.

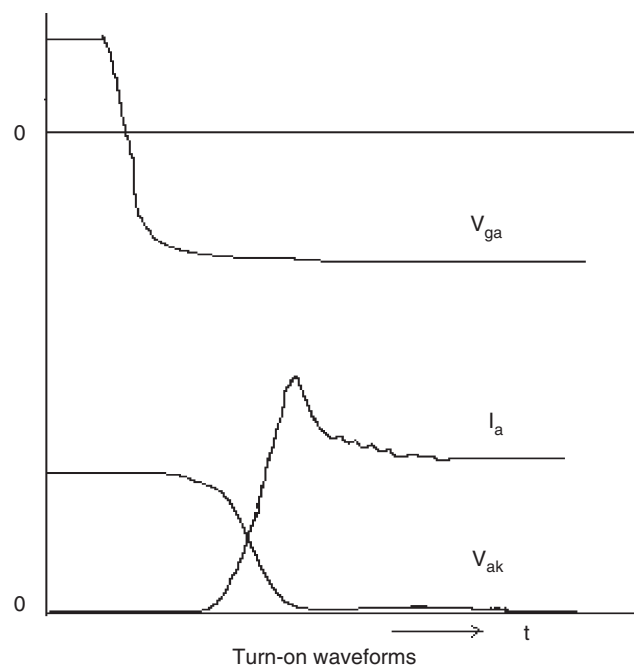
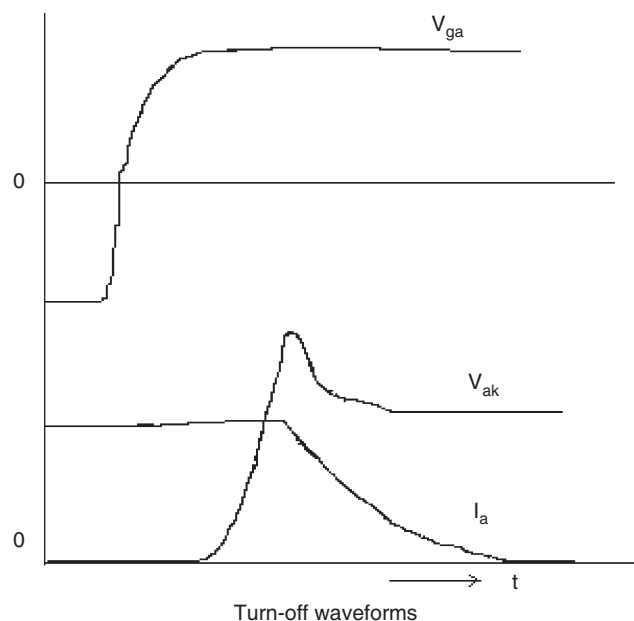


FIGURE 8.8 The MCT turn-off and turn-on waveforms under hard switching.

converters, the power devices switch at zero voltage or zero current, thereby eliminating the need for a large safe operating area (SOA) and at the same time eliminating the switching losses entirely. The MCT converters will outperform IGBT and power MOSFET converters in such applications by giving the highest possible efficiency. In soft-switching applications, the MCT will have only conduction loss, which is

low and is close to that in a power diode with similar power ratings [12]. The Generation-1 MCTs did not turn on rapidly in the vicinity of zero anode-cathode voltage and this posed a problem in softswitching applications of an MCT. However, Generation-2 MCTs have enhanced dynamic characteristics under zero voltage soft switching [16]. In an MCT, the PMOS On-FET together with the *pnp* transistor constitute a *p*-IGBT. An increase in the number of turn-on cells (decrease in the on-resistance of the *p*-IGBT) and an enhancement of their distribution across the MCT active area enable the MCT to turn on at a very low transient voltage allowing zero voltage switching (ZVS). During zero voltage turn-on, a bipolar device such as the MCT takes more time to establish conductivity modulation. Before the device begins to conduct fully, a voltage spike appears, thus causing a modest switching loss [12]. Reducing the tail-current amplitude and duration by proper circuit design can minimize the turn-off losses in softswitching cases.

8.11.2 Resonant Converters

Resonant and quasi-resonant converters are known for their reduced switching loss [17]. Resonant converters with zero current switching are built using MCTs and the circuit of one such, a buck-converter, is shown in Fig. 8.9. The resonant commutating network consisting of L_r , C_r , auxiliary switch T_r , and diode D_r enables the MCT to turn off under zero current. The MCT must be turned off during the conduction period of D_z . Commutating switch T_r must be turned off when the resonant current reaches zero.

A resonant dc link circuit with twelve parallel MCTs has been reported [18]. In this circuit, the MCTs switch at zero-voltage instants. The elimination of the switching loss allows operation at higher switching frequencies, which in turn increases the power density and offers better control of the spectral content. The use of MCTs with the same forward drop provides good current sharing.

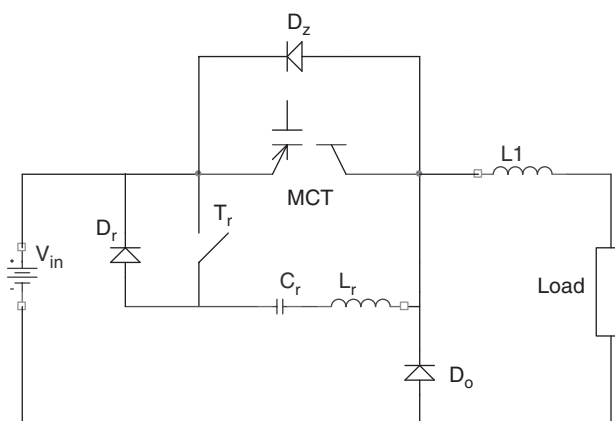


FIGURE 8.9 Power circuit of MCT resonant buck converter.

The MCTs are also used in ac-resonant-link converters with pulse density modulation (PDM) [19]. The advantages of the PDM converter, such as zero-voltage switching, combined with those of the MCT make the PDM converter a suitable candidate for many ac-ac converter applications. In an ac-ac PDM converter, a low-frequency ac voltage is obtained by switching the high-frequency ac link at zero-crossing voltages. Two MCTs with reverse-connected diodes form a bidirectional switch that is used in the circuit. A single capacitor was used as a simple snubber for both MCTs in the bidirectional switch.

8.12 Conclusions

The MCT is a power switch with a MOS gate for turn-on and turn-off. It is derived from a thyristor by adding the features of a MOSFET. It has several advantages compared to modern devices like the power MOSFET and the IGBT. In particular, the MCT has a low forward drop and a higher current density which are required for high-power applications. The characteristics of Generation-2 MCTs are better than those of Generation-1 MCTs. The switching performance of Generation-2 MCTs is comparable to the IGBTs. At one time, SPCO was developing both PMCTs and NMCTs. The only product that is currently under the product list of SPCO is the voltage/current controlled Solidtron, which is a discharge switch utilizing an n -type MCT. The device features a high current and high dI/dt capability and is used in capacitor discharge applications. The data on Solidtron can be obtained at: http://www.siliconpower.com/Solidtron/Solid_home.htm.

Acknowledgment

The author is grateful to Ms. Jing He and Mr. Rahul Patil for their assistance in collecting the reference material for this chapter.

8.13 Appendix

The following is a summary of the specifications on a 600 V/150 A PMCT made by SPC:

| | |
|---|------------------|
| Peak Off-state Voltage, V_{DRM} | −600 V |
| Peak Reverse Voltage, V_{RRM} | +40V |
| Continuous Cathode Current, ($T = +90^{\circ}\text{C}$), I_{K90} | 150 A |
| Non-repetitive Peak Cathode Current, I_{KSM} | 5000 A |
| Peak Controllable Current, I_{KC} | 300 A |
| Gate to Anode Voltage (Continuous), V_{GA} | $\pm 15\text{V}$ |

| | |
|---|----------------------|
| Gate to Anode Voltage (Peak), V_{GAM} | $\pm 20\text{ V}$ |
| Rate of Change of Voltage ($V_{GA} = 15\text{ V}$), dV/dt | 10 kV/ μs |
| Rate of Change of Current, di/dt | 80 kA/ μ |
| Peak Off-state Blocking Current (I_{DRM}) ($V_{KA} = -600\text{ V}$, $V_{GA} = +15\text{ V}$, $T_c = +25^{\circ}\text{C}$) | 200 μA |
| On-state Voltage (V_{TM}) ($I_K = 100\text{ A}$, $V_{GA} = -10\text{V}$, $T_c = +25^{\circ}\text{C}$) | 1.3 V |

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