Switching Characteristics of MCT in Resonant DC Link Soft-Switching Power Converters

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Abstract - **The MOS controlled thyristor (MCT) is a power device that shows promise of having very high power densities with simple control circuitry. Because of the capability of achieving low loss and high switching frequencies with resonant dc link converters, it is important to characterize the behavior of the MCT in these circuits. Simulations and experiments are performed using an MCT in both zero voltage switching and zero current switching resonant converters. A comparison of the results of these tests is given.**

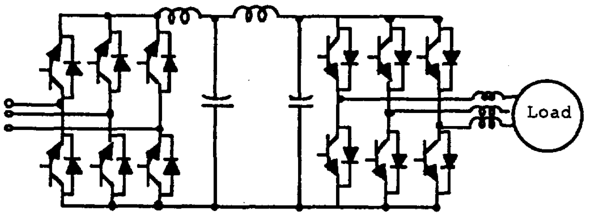
I. INTRODUCTION

Tremendous progress has been made in recent years in the development of both new power devices and new circuit topologies to improve performance in high power ratings. For example, the MCT has been developed as an attractive power device that includes the features of both an SCR and a MOSFET. Likewise, in circuit development, resonant dc link (RDCL) circuits have gained much attention for achieving high frequency, low loss switching operation.

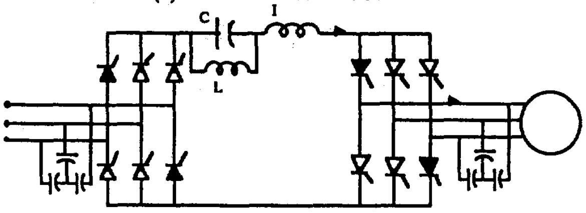
The MOS gated MCT device is ideally able to handle high voltages and carry large currents that can be switched up to tens of kHz. In particular, the MCT is intended to replace the currently used power devices (SCRs and GTOs) for power levels greater than those achievable with BJTs and similar devices. Although the device is currently not available commercially, studies of the device have already shown some of its advantages including faster switching times than standard bipolar devices and less conduction losses than IGBTs [11,12].

Two types of resonant DC link (RDCL) soft-switching converters have been proposed and investigated for high frequency switching power converters [1,2]. The first type, named the resonant DC link voltage source inverter, is shown in fig. 1 (a) and the other, named the resonant DC link current source inverter, is shown in fig. 1 (b). In effect the current source inverter is essentially the dual of the voltage source inverter. While in the voltage source inverter the DC link voltage oscillates between zero and a crest value, which is made possible by an LC resonant tank, the DC link current oscillates between zero and a crest value in the current source inverter. It can be seen that the power devices parallel to the resonant DC link voltage achieve "zero-voltage-switching" (ZVS) and the power devices in series with the resonant DC link current achieve "zero-current switching" (ZCS) if they are turned on or off at the zero-crossing (voltage or current) instants. Because the RDCL techniques have reduced the switching losses of the power device in the converter to virtually a zero level, the switching frequency of the power devices are increased by several orders of magnitude over what is normally achievable in hard-switching converters.

The switching characteristics of a power device used in a RDCL voltage source converter might be substantially different when used in a current source inverter. Studies of the GTO in the RDCL voltage source converter revealed that because of anode current peaking at device turn-off (which is not present in hard switching converters) and because of power losses due to tail current, the gating current plays an important role. In fact, the tail power losses in the RDCL ZVS converters have been found approximately the same as those in the hard-switching converters [8]. However, the GTO displays a quite different behavior when it is used in a



(a) Parallel resonant dc link



(b) Series resonant dc link

Fig. 1. Resonant link circuit topologies

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RDCL current source converter. The most remarkable result found with current source converters is the switching loss improvement over voltage source converters. At a current amplitude of 300A, and an equivalent switching frequency of 20 kHz, the turn-off losses are as low as 5 mJ. The explanation for these very good results has been attributed to the short duration of the peak current, the smooth decrease of anode current, and the soft rise time of anode voltage [9].

The importance of the characterization of the power devices for the RDCL converters has been made apparent in many recent publications [7,8,9]. In general, under the RDCL soft-switching operation, the power device switching characteristics are more important than the device thermal endurance. The storage time, along with forward and reverse recovery times are very critical parameters in determining the attainable switching frequency and power rating. In addition, it has been shown that improved switching characteristics are achievable with the proper matching between power device and circuit topology [9].

As a new device, the MCT has displayed its potential, and as a new circuit topology, the voltage and current source RDCL circuits have also displayed their potential. However, the combined characteristics of the MCT device in the two different RDCL have not been studied at present. To ensure a further understanding and full utilization of MCT potentials in the RDCL converters, studies of the MCT switching characteristics in the two different RDCL power converters are necessary. In this paper, the switching characteristics of the MCT in resonant dc link soft-switching voltage and current source converters are investigated. In particular, a computer model is used to simulate the turn-on and turn-off dynamics of the MCT device in the resonant dc link voltage and current source converters and the performance is compared. A laboratory experiment is designed and constructed to test the switching behavior of the MCT in two different RDCL topologies. The experimental results are presented and compared to those from the simulation. The difference between the MCT behavior in the two RDCL converter circuits is highlighted and suggestions are made for the practical application of the MCT in RDCL converters.

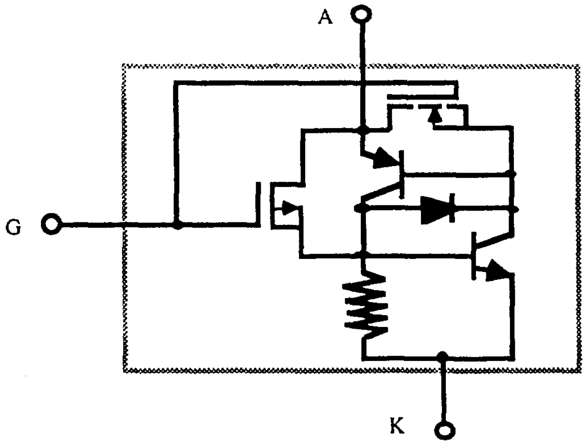

Fig. 2. The MCT model

II. THE MCT IN RESONANT LINK CONVERTERS

Like the GTO the MCT is a four layer device, but unlike the GTO a pair of MOSFETs have been integrated into the device to simplify gate drive requirements. Because of their similarity to GTOs, it is expected that MCTs would behave similar to GTOs in RDCL circuits. Tail currents, similar to what is found with the GTO, have also been noted in zero voltage switching resonant converters [13]. Improvements in MCT switching, like improvements seen with the GTO, would therefore be expected when switched under the zero current conditions found in series RDCL converters.

Because of the input MOSFETs integrated into the MCT, it does have some qualities that make it behave differently than a GTO. It was found that during turn-on the MCT requires a positive anode voltage to initialize the triggering [12]. This is because it takes a relatively high turn-on voltage to cause enough current to flow through the on FET to latch the PNPN thyrisor. Although these delays have been minimized in newer devices [13], small discontinuities are still apparent during turn-on in zero voltage circuits like the parallel RDCL converter. Series RDCL converters do not have this problem suggesting another advantage for their use with MCTs.

III. SIMULATIONS

A. *The MCT model*

In order to perform simulations of the desired circuits, a model of the MCT was developed for use in PSPICE. The model is based on a two-transistor SCR model with two additional MOSFETs used to simulate the MOS inputs at the gate of the MCT. The circuit configuration of this model is shown in fig. 2. Equations were developed to systematically generate the parameters required for the devices in the model based on data sheet information. These equations were based on semiconductor physic relationships, but some empirical adjustments were made to better model the behavior of the device [10]. A listing of the PSPICE model used in these simulations is given in fig. 3.

B. *Simulation Results*

The MCT model was used to do PSPICE simulations for both of the circuits of fig. 4. Results were analyzed to compare switching characteristics and losses in the two circuit configurations.

Observing the switching characteristic of the ZVS resonant circuit a small discontinuity is seen in the current as the current is transferred from the antiparallel diode to the MCT (fig. 5). This is expected because of the delays found when the MCT is turned on with zero voltage across it. This appears not to be a problem because of its short duration, only about 0.5μs out of a 50μs cycle. During turn off a current tail was expected to be seen. From fig. 5, however, no such tail is observed. If the scale is expanded it is possible to see a small tail. The duration of this tail is so

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;******************************
;* mct two transistor model *
;* NODE 11 ANODE
;* NODE 10 CATHODE
;* NODE 14 GATE
;.SUBCKT MCT 11 10 14
;Q1 12 13 11 QMOD1
;Q2 13 12 10 QMOD2
;DFOR 12 13 DMOD1
;MOSP 12 14 11 11 MMODP
;MOSN 13 14 11 11 MMODN
;RGK 12 10 9.375
;.MODEL DMOD1 D(BV=600)
;.MODEL QMOD1 PNP(BF=0.25,BR=0.25,IS=1.0E-8.73
;+                        ,RE=0.0,TF=1.25US,TR=2.4US)
;.MODEL QMOD2 NPN(BF=9,IS=1.0E-8.73,CJC=103PF)
;.MODEL MMODP PMOS(W=8m L=2U RB=10E12)
;.MODEL MMODN NMOS(W=1 L=2U RB=10E12)
;.ENDS
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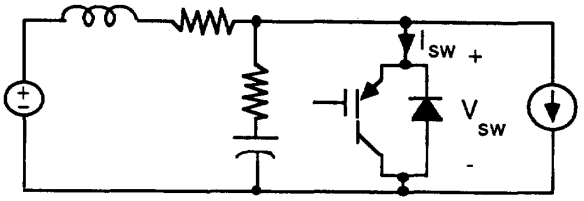
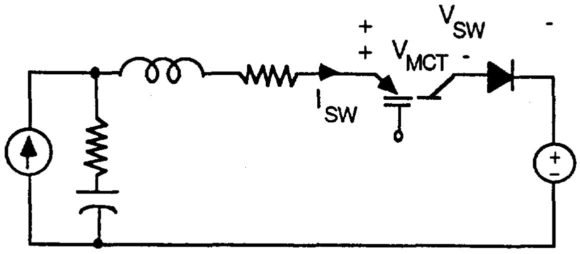
Fig. 3. Listing of PSPICE MCT model.



(a) 1-phase parallel resonant dc link



(b) 1-phase series resonant dc link

Fig. 4. Schematics of resonant circuits used.

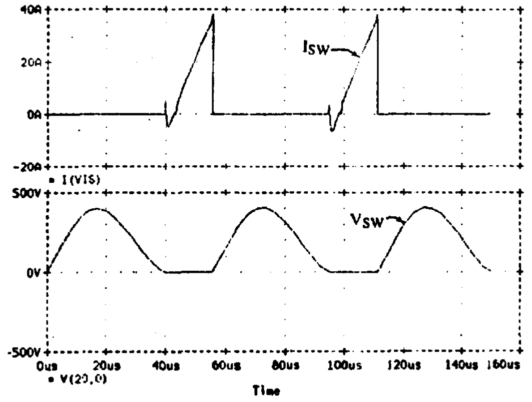
small, approximately 0.4 ns, that it is not considered of any significants.

The switching characteristics of the ZCS resonant circuit showed no noticeable transient during turn-on. During turn-off a fairly large voltage spike occurs across the diode and MCT combination (V_{SW} in fig. 6). This is caused by the di/dt that occurs during the reverse recover time of the diode. This result is not seen across the MCT alone (V_{MCT}) and is therefore not a major concern for the MCT. Because available MCTs do not have reverse blocking capabilities, the diode is required for practical resonant circuits. The voltage spike caused by the diode recovery time should, therefore, be considered when developing the circuit.

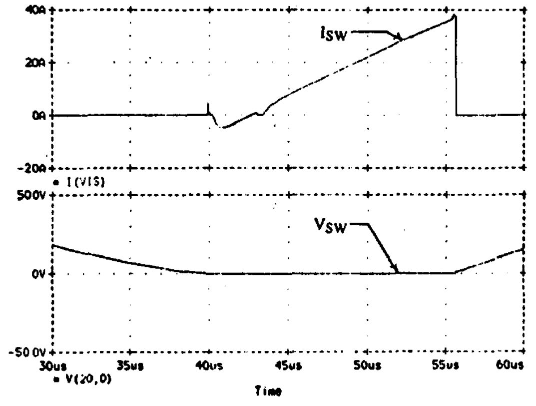
Of major importance in evaluating the MCT in RDCL converters is a consideration of the device losses. Fig. 7 shows simulation results for MCT and antiparallel diode losses in the ZVS topology while fig. 8 shows the MCT and series diode losses from the ZCS topology. Comparing the two it is immediate apparent that the conduction losses in the simple ZCS topology are much higher than the ZVS. This is because the resonant current plus the load current will flow in the ZCS topology while only the resonant current will flow in the ZVS topology. In more practical circuits, such as three phase converters where the same device is used to switch the load phases and build up current in the inductor, the switch in a ZVS converter would also carry a load current making the distinction smaller.

Observing the switching losses in the ZVS condition (Fig.7) it is seen that the power peak at turn-on is relatively small, much smaller than the turn-off peak power and the conduction losses. Therefore, turn-on losses can practically be neglected for this circuit topology. The ZCS of fig. 8 shows, however, a peak power of nearly 30 watts during turn-on that must be considered.

During turn-off the peak power appears much greater in the ZCS circuit than the ZVS circuit. Almost all of this power appears in the series diode, not in the MCT. Observing Fig. 9, which shows the power in just the MCT, this peak does not occur. Also, although the peak power in the ZCS appears



a) Currents and voltages over several cycles



b) Detail of switching transitions

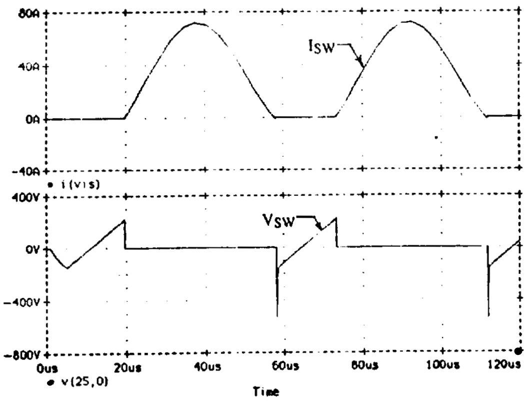
Fig. 5. Simulated currents and voltages for ZVS resonant circuit.

larger than the ZVS circuit, the net energy dissipated during switching is actually less in the ZCS because of oscillations during turn-off.

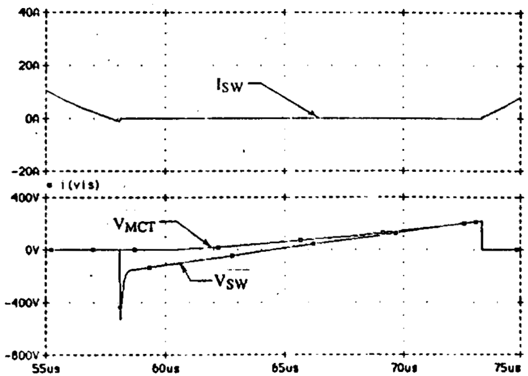
IV. EXPERIMENTAL RESULTS

To experimentally verify the findings in these simulations, each of the resonant switching circuits was constructed and voltages and currents were measured. Schematics of the actual test circuits are given in fig. 10. The devices being tested were rated at 75A and 600V.

For the ZVS resonant converter the switching voltages and currents are shown in fig. 11. Observing the time when the MCT turns on there is essentially no transient seen. During turn-off, a small current tail is noticeable. The current tail has a duration of about 1μs, longer than predicted with the simulation but small enough not to be a limiting factor in many applications.



a) Currents and voltages over several cycles



b) Detail of switching transitions

Fig. 6. Simulated currents and voltages for ZCS resonant circuit.

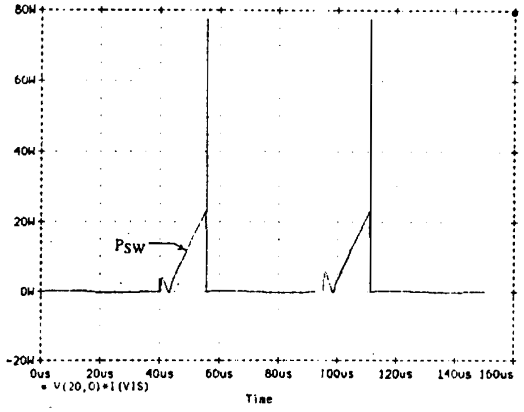


Fig. 7. Simulated switching losses for ZVS resonant circuit.

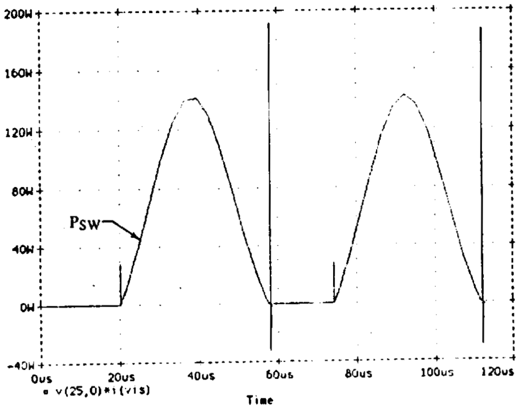


Fig. 8. Simulated switching losses for ZCS resonant circuit.

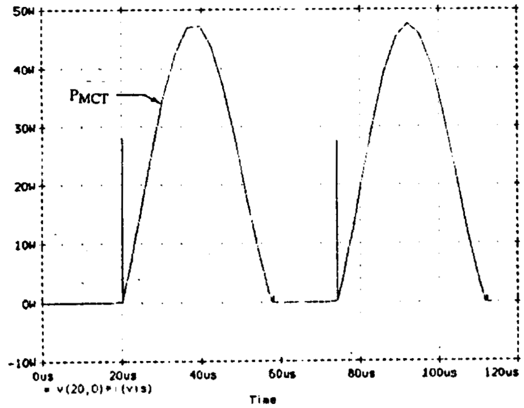
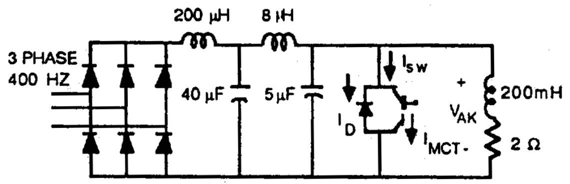
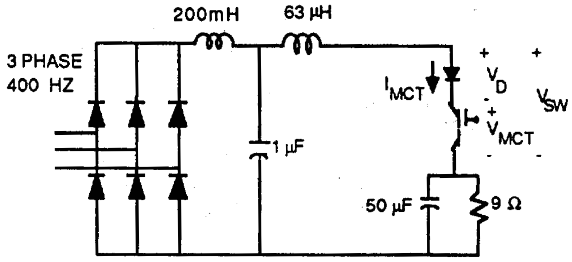


Fig. 9. Simulated switching losses in MCT for ZCS resonant circuit.



a) parallel resonant



b) series resonant.

Fig. 10. Schematics of test circuits

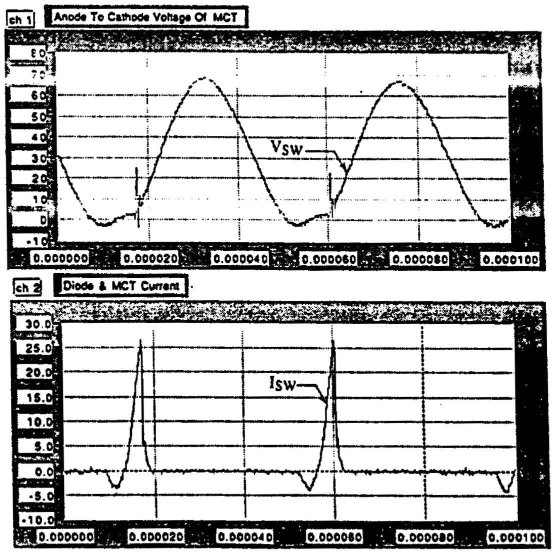


Fig. 11. Switch voltages and currents in the parallel resonant circuit.

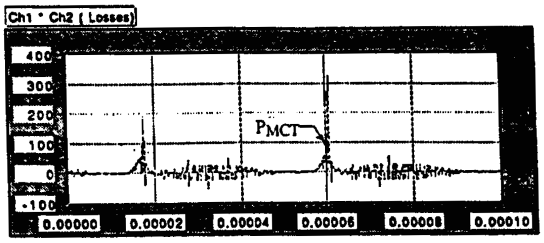


Fig. 12. Instantaneous power dissipated in the MCT of the parallel resonant circuit.

The instantaneous power dissipated in the MCT for the circuit operating under the conditions of fig. 11 is shown in fig. 12. The average power dissipated by the device was only about 4W. Peak power dissipation occurred when the tail current was present and reached values of up to 500W when switching currents of about 25A. Although the instantaneous power is high the total energy dissipated is still relatively small because of the short switching duration. (The total energy dissipated during the tail was found to be approximately 725 μJ)

For the ZCS resonant converter the switching voltages and currents are shown in fig. 13. The current shows essentially no transients at turn-on or turn-off. The voltage, however, shows transients at both switching transitions. At turn-off some ringing is observed possibly causeed by device capacitance. At turn-on there is an unexpected tail observed in the voltage suggesting that the device takes a considerable amount of time (~ 10 μs) before it completely turns on. The exact cause of this delay is still being investigated.

The instantaneous power loss for the MCT and diode switch for the conditions of fig. 13 is shown in fig. 14. The average power dissipated in this circuit was about 3.4W. A

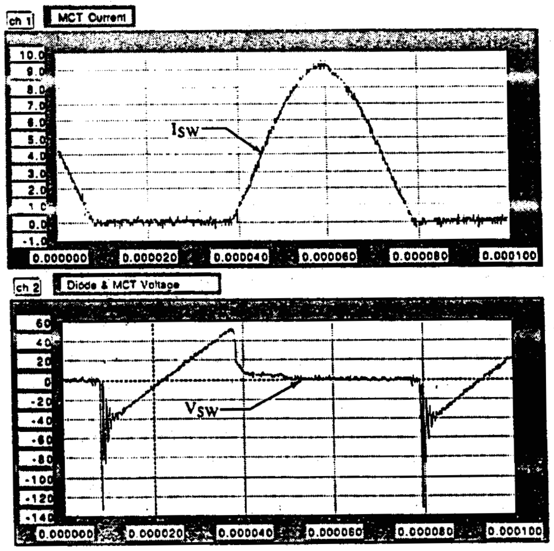


Fig. 13. Switch voltages and currents in the series resonant circuit.

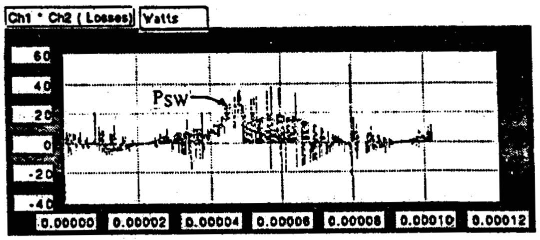


Fig. 14. Instantaneous power dissipated in the switch of the series resonant circuit.

peak power dissipation of about 60W occurred when the diode was in the reverse recovery. The total energy dissipated at this time is very small because of the short duration of the pulse. Most of the average power dissipated comes from conduction losses in the devices. In particular a large portion of the energy dissipation occurs during the voltage tail at the device turn-on.

Comparing the ZCS and ZVS results, both were found to have extremely fast switching times. The switching time of most concern is the turn-on time under ZCS. As was mentioned before, the tail found was not expected and is being investigated further. For the ZVS converter the percentage of power lost compared to the load is almost half of what was found for the ZCS condition. This is mainly due to increased conduction losses in the ZCS converter. These losses are expected to be nearly the same in more practical circuits.

V. CONCLUSIONS

A comparison of the switching behaviors of an MCT in ZCS and ZVS converters showed that such a device would perform well in either type of circuit. For the simple circuits tested, both simulations and experiments showed higher losses in the zero current switching. For more practical circuits it is believed that these losses would be more equal.

ACKNOWLEDGMENT

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