

Verification of model of bi-directional switch in context of evaluation of its losses

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ABSTRACT: In the given paper the power losses of bi-directional semiconductor switches are evaluated in the context of elaboration of an integrated matrix AC drive where such switches are used. Safe operation of the switches of a converter is extremely important factor of its successful operation of in whole. This, amongst other, assumes successful thermal design of the converter. The thermal design of matrix converters, especially integrated, is complicated due to the variety of their configurations, harder cooling conditions etc. For this reason the initial simulation of the losses through simulation seems helpful. This, however, requires an adequate model of the switches. In this paper the calculated, simulated and experimentally measured losses of the switches are compared and conclusions regarding the utilized model are made.

1 Introduction

Matrix converters have been considered as an alternative to conventional PWM converters for frequency control in AC drives. Classical matrix converter (MC) consists of nine bi-directional switches that are arranged in such a way that any input phase can be connected to any output phase (Fig. 1). This topology was proposed by Gjguyi and Pelly [1], more research was done by Venturini [2], [3].

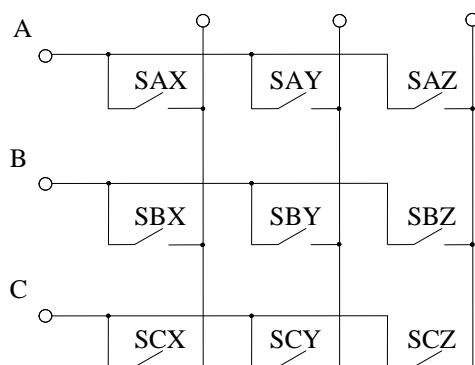


Fig. 1 - Classical 3x3 Matrix Converter

Semiconductor devices become smaller and with greater performance. This allows integration for power converter inside an electrical machine. Higher integration level of electrical drives can be considered in application

where motor and inverter separate installation is obstructive. It has been proposed to integrate MC in AC machine since MC does not contain bulk reactive components [4].

2 Power Losses of Bi-directional switch

The key feature of a bi-directional switch is its capability of conducting current and blocking voltage in both directions. At the given time there are no bi-directional semiconductor elements available on the market. However, these bi-directional switches can be composed of discrete elements. There are several widely spread configurations of such switches.

Fig. 2 represents the bridge based bi-directional switch. It includes only one switching device and a diode bridge. The collector of the IGBT is connected to the anodes of the bridge, and the emitter is connected to the cathodes. Thus the switch is placed on the DC side of the bridge. Only one active switching element makes this solution a very attractive one from point of view of costs and complexity of gate drive circuits. However, there are two considerable disadvantages related to this circuit. It is impossible to provide the separate control of the current for each polarity and there are relatively high conduction losses due the series connection of three power semiconductor devices in each conduction path.

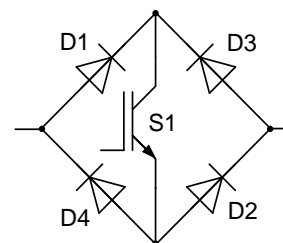


Fig. 2 - Bi-directional switch based on a diode bridge

Few other bi-directional switch arrangements are based on the counter-parallel connection of two IGBTs. Due to the weak reverse blocking capabilities of common IGBTs such configurations include also diodes connected in series in the same direction as the enforced IGBT. One modification of such arrangement, known as common

emitter switch, implements two IGBTs whose emitters are connected together (Fig. 3). Therefore, the diodes of such configuration have common anodes. This configuration has lower conduction losses due to the smaller number of semiconductor elements in the conduction path compared to diode bridge configuration. Second, it is possible to independently control current direction that allows safe commutation of load current and reduce commutation losses [5]. For more efficient space usage IGBTs with built in anti parallel diodes can be used.

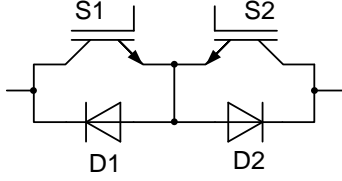


Fig. 3 - Common emitter bi-directional switch

3 Power losses in Matrix Converter

Power losses of any switch mode converter, including MC, consist of conduction losses and commutation losses. Conduction losses are proportional to forward voltage drop of across the semiconductor device and the current flowing through the device. The forward voltage drop is dependent on the current flowing through the device and its junction temperature. These relationships require an iterative calculation since the device losses and the junction temperatures are interdependent [5]. Conduction losses per switch are calculated as the sum of conduction loss in IGBT and in corresponding diode. That is why conduction losses in MC are higher compared to conventional voltage source inverters.

Commutation losses in IGBT occur due to finite switching time during which device changes its state. Commutation losses are proportional to commutation frequency at which device operates. These losses also are junction temperature dependent that makes iterative loop between losses and junction temperature more complex.

It is assumed that commutation time of IGBT compared to conduction time is negligible. In this case losses for one output phase of MC can be calculated as conduction losses in each phase (1).

$$P_{loss\ ph\ con} = \sum_{n=1}^3 ((V_{CESn} \cdot I_{Cn} \cdot d_n) + (V_{fn} \cdot I_{fn} \cdot d_n)) \approx I_f \cdot (V_{CES} + V_f), \quad (1)$$

where V_{CES} – IGBT collector-emitter saturation voltage, I_C – IGBT collector current, V_f – diode forward voltage, I_f – diode forward current, d_n – duty cycle for the n-th period of PWM.

Commutation losses per switch in MC are calculated as product of commutation frequency and total switching energy loss:

$$P_{loss\ com} = 3 \cdot f_{com} \cdot E_{com\ tot}. \quad (2)$$

The total power loss of MC is sum of commutation losses and conduction losses:

$$P_{loss\ tot} = 3 \cdot (P_{loss\ ph\ con} + P_{loss\ com}). \quad (3)$$

The total power loss of each component of one bi-directional switch of MC as a function of frequency is shown in Fig. 4. These graphs are calculated in MATLAB for particular case of 0.3kW converter using STGB10NC60HD IGBT transistors with integrated ultra-fast-recovery anti-parallel diode.

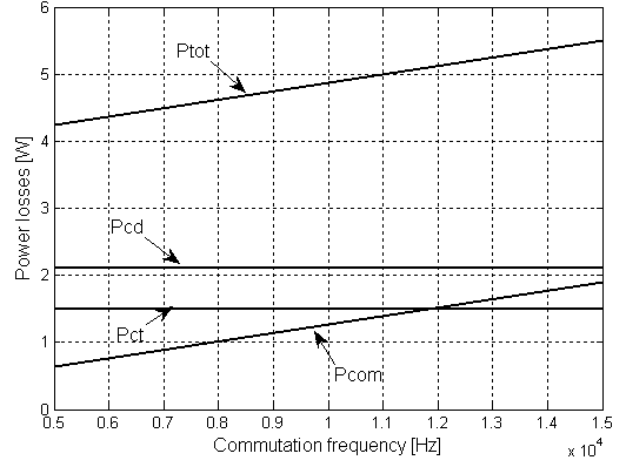


Fig. 4 - Power losses of Matrix Converter where P_{tot} – total power loss, P_{com} – commutation power loss, P_{ct} – transistor conduction loss, P_{cd} – diode conduction loss

In total converter power loss calculation it is assumed that commutation losses occur at every current path change. In [5] a method of reducing the converter losses is proposed. It achieved by reduction of the number of switch state changes that produce switching losses.

4 Thermal considerations

Loss calculations are essential for determination of cooling conditions of the converter. Too much excessive heat due to losses will destroy transistor junction, but over dimensioned cooling system does not allow compact design of converter. This is why a tradeoff between good cooling and compact design must be found.

To determine cooling conditions of MC maximum allowable case temperature must be calculated. Temperature difference between case and junction is calculated as product of total power loss in the transistor $P_{loss\ tot}$ and junction-case thermal resistance $R_{th\ jc}$:

$$\Delta T_{jc} = P_{loss\ tot} \cdot R_{th\ jc}. \quad (4)$$

Because junction-ambient thermal resistance is of much higher value than junction-case it is neglected here.

Maximal junction temperature is determined by properties silicon crystal. For power devices this temperature is determined to be from 125 °C to 150 °C.

For safe operation 125 °C is used in this calculation. Maximum case temperature is calculated as:

$$T_{c\max} = T_{j\max} - \Delta T_{jc}, \quad (5)$$

where $T_{c\max}$ – maximal case temperature, $T_{j\max}$ – maximum junction temperature.

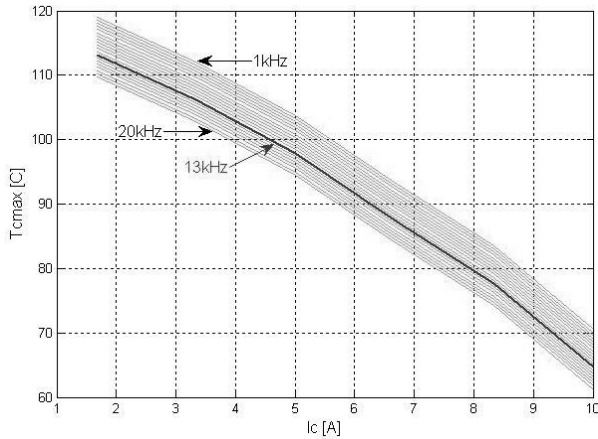


Fig. 5 - Maximum case temperature dependency on current and frequency

Graph in Fig. 5 illustrates maximal case temperature dependency on transistor collector current at different commutation frequencies. The higher commutation frequency the higher commutation losses of the transistor, hence lower the maximum case temperature is allowable.

5 Building a model and simulation

Depending on the control mode and real configuration of the switches the total losses may look quite different. Therefore, the comprehensive thermal analysis asks a huge number of experiments that is not convenient from the practical point of view. For this reason it was decided to use simulation at the initial stages of research. In order to check its accuracy the results of reference simulation was compared with the reference experiment.

A PSpice simulation test bench was build. For the first approach it possible to find an existing subcircuit or internal model for this simulation program. Unfortunately, the model of particular transistor STGB10NC60HD (used in the experiments) was not available. For this reason a similar model (for STGB7NC60HD) was taken and modified to fit needs. It was also found that the model did not contain the intrinsic diode implemented in the real device. To run simulation with conditions as close to real life as possible, the model of ultra fast diode with similar parameter was developed and attached.

The following simulation conditions were kept: 200V DC input voltage, collector current – 1A, load inductance 4mH, commutation frequency - 13kHz, duty cycle – 0.5.

The results of simulation (V_{CE} , I_C and their product, representing the instantaneous power losses) are presented in Fig. 6. The averaging of this product over the switching period gives the total power losses of 1.41W.

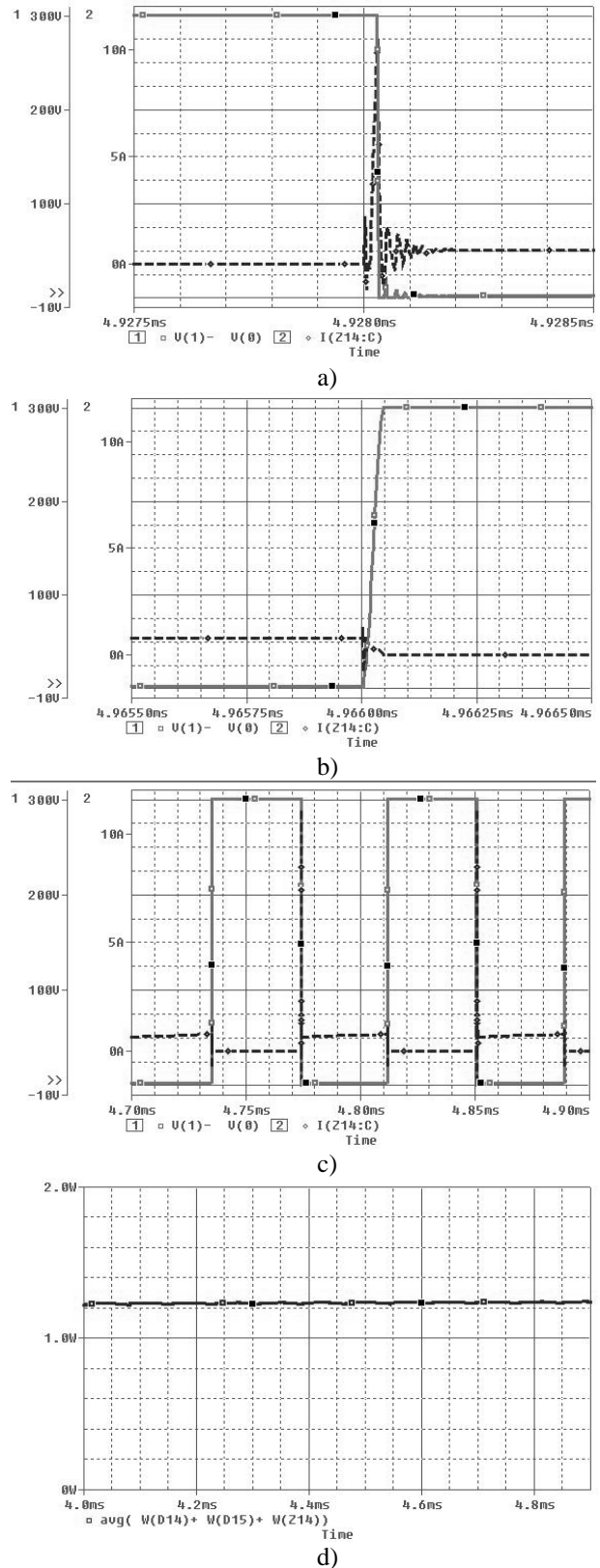


Fig. 6. PSpice simulation of one bi-directional switch a) turn-on; b) turn-off; c) two commutation cycles; d) average total power losses (collector-emitter voltage – solid line, collector current – dashed line)

6 Experimental verification of the model

In order to verify the model experiments with a common emitter bi-directional switch commutated in chopper mode were carried out. Measured instantaneous V_{CE} , I_C of are presented in Fig.7.

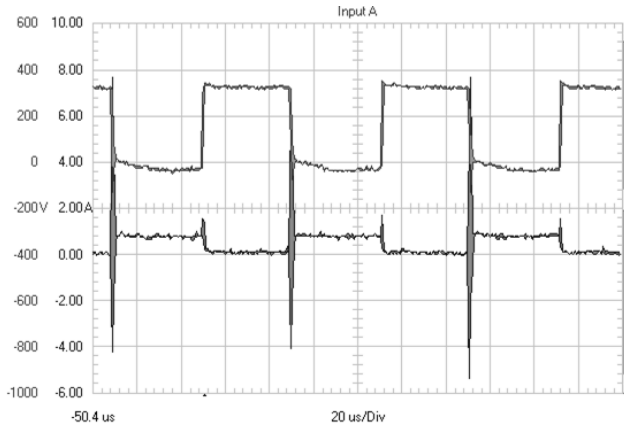
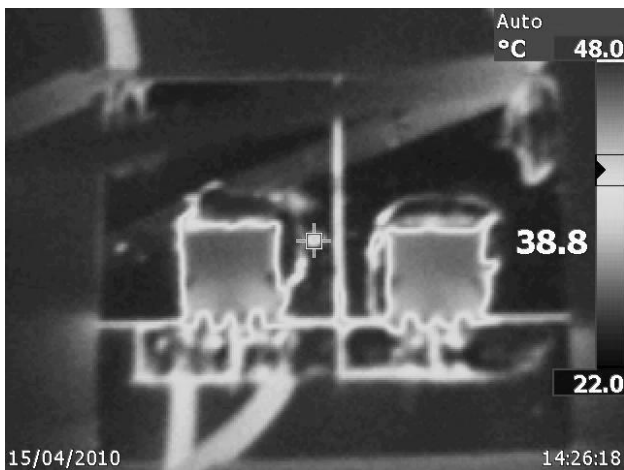
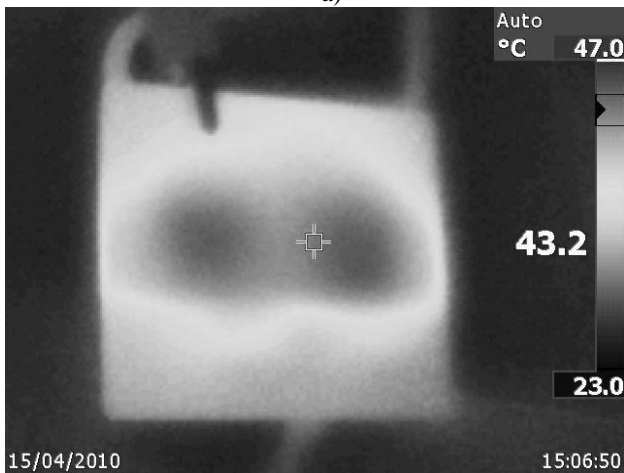


Fig. 7. Experimentally measured switch voltage (top) and current (bottom)



a)



b)

Fig. 8. Temperature of a) bi-directional switch at 1 A at commutation frequency 13 kHz; b) back side of PCB

The obtained data produce the average power losses of about 3,14W. This is 2.2 times more than what simulation results have shown. Case temperature was also captured (Fig. 8-a). Transistor that is commutates current has higher case temperature (Fig. 8.a. left) than transistor where only diode conducts (Fig. 8.a. right). However in MC the conduction is determined by output current polarity hence each sine wave period each switch conducts in both directions and power losses are distributed equally in both devices.

7 Conclusions

The particular detailed model of bi-directional power semiconductor switch was chosen in order to facilitate the thermal design of MC. Power losses in the switch were calculated, simulated and experimentally measured. The simulation results do not agree with experiments. The difference can be explained by the imprecision of the utilized model and idealized simulation conditions. Possible reason for this imprecision is wrong interaction of FET and BJT parts of the model. Exact conclusion regarding this reason requires more detailed analysis of the model and some extra experiments that will be done on the next stage of research.

At the same time, the obtained experimental data provides quite good practical basis for further investigation of thermal behaviour of integrated AC drive with matrix converter.

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