

4. Switches, semiconductors and passive elements

4.1 Switches

In the original sense the word 'switch' is used for mechanical elements which open or close an electrical circuit. Some switches are activated manually others by an electrical coil. The latter were called relay or contactors.

For all switching elements the following four states are interesting:

1. turned off
2. turn on process
3. turned on
4. turn off process

The exact behavior of switches can be rather complicated. In most cases the turned off state (switch open) can be modeled by an infinite resistance. Turned on (switch closed) can be represented by a small resistance.

The turning on and off processes include a delay between the control signal and the real opening or closing of the contacts. Especially, with higher voltages arcing can occur.

Switching actions often consist of a number of on / off's due to bouncing of the contacts. The effects of arcing and bouncing are reduced with RC-snubbers.

4.2 Semiconductors

The word 'power electronics' is derived from the use of 'electronic-elements' for power application. In small to medium size power supplies the semiconductors are diodes, Field Effect Transistors (FET) and Insulated Gate Bipolar Transistors (IGBT). For high power applications Thyristors and Thyristors with Gate Turn Off capability, GTO's and IGCT's are used.

In the field of power electronics the power semiconductors have to be operated in the 'switching mode' to avoid excessive losses and damage: they are either turned on or off. Compared to mechanical switches semiconductors are much faster and are capable of an 'unlimited' number of switching actions. The four states of a semiconductor shall be discussed shortly.

- a) In the turned off state a semiconductor is well represented by a very high resistance. A small leakage current can exist. But, this current is usually neglected. The limited voltage blocking capacity has to be taken into account.
- b) While turning on (an action that lasts some 10ns for FET's and about 1us for IGBT's) current through and voltage across the element occur. This leads to the 'turn on losses'. There is a small delay between the turn on signal and the actual turning on. Begin and end of the turn on process are gradually.
- c) Turned on, the FET represents a simple resistor. The IGBT can be modeled with a resistor in series with a voltage source. In this state the conducting losses are generated. The current carrying capacity of the elements is limited.
- d) Turning off is a transient state with similar duration as the turn on process. Current through and voltage across the element occur for a short time simultaneously, which leads to the 'turn off losses'. Especially for IGBT's the end of the turn off process is gradually which leads to the → current tail. A turn off delay occurs between the control signal and the falling off the current.

For an exact model of the semiconductor internal capacitances and stray inductances have to be considered too. Depending on the quality of the data sheets of the semiconductor it is often difficult to find all the mentioned data. Depending on the used simulation tool more or less data for the description of the elements is needed.

As a general rule it is valid: *The simpler the model the faster the simulation.*

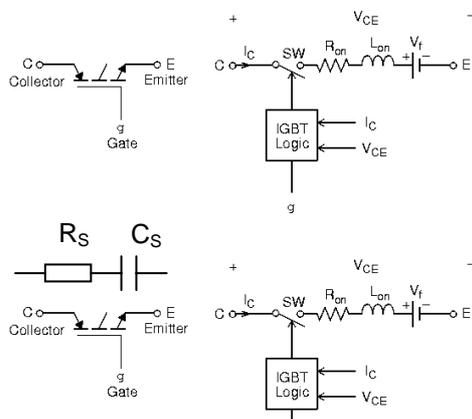
→ It is part of the art to find the simplest model that fulfills the needs of a simulation.

As an Example the block parameters for an IGBT are shown.

Description



The IGBT block implements a semiconductor device controllable by the gate signal. The IGBT is simulated as with a switch controlled by a logical signal ($g > 0$ or $g = 0$).



Block Parameters: IGBT	
-IGBT (mask) (link)	
Implements an IGBT device in parallel with a series RC snubber circuit. In on-state the IGBT model has internal resistance (R_{on}) and inductance (L_{on}). In off-state the IGBT model has infinite impedance. The internal inductance cannot be set to zero. Discretization of the IGBT is available only through the Universal Bridge block.	
Parameters	
Resistance R_{on} (Ohms):	0.001
Inductance L_{on} (H):	1e-6
Forward voltage V_f (V):	1
Current 10% fall time T_f (s):	1e-6
Current tail time T_t (s):	2e-6
Initial current I_c (A):	0
Snubber resistance R_s (Ohms):	1e5
Snubber capacitance C_s (F):	inf
<input checked="" type="checkbox"/> Show measurement port	
<input type="button" value="OK"/> <input type="button" value="Cancel"/> <input type="button" value="Help"/> <input type="button" value="Apply"/>	

4.3 Snubbers

Due to the fast turn off capability of switches and power semiconductors, the inductances in series to the elements are very critical. Most elements do also have an internal inductance. These inductances are the reason for the need of RC-snubbers connected across the semiconductor. The modeling of inductance and snubber are critical in simulations!

4.4 Passive elements

In power supplies, as in other power electronic circuits, passive elements are needed. Most real passive elements do have a non ideal behavior. The non ideal effects shall be listed:

Resistors: The models are usually pure ohmic. Real elements can be:

- temperature dependant
- frequency dependant (skin effect, proximity effect)
- inductive

Capacitors: They show:

- current dependant losses ('Equivalent Serial Resistance ESR')
- voltage dependant losses (especially electrolytic capacitors)
- serial inductance

Inductances: These can be very demanding elements..... They are:

- ohmic (losses!)
- frequency dependant
(skin and proximity effect → increase of the resistance; decrease of the inductance)
- amplitude dependant (saturation)
- capacitive (especially for higher frequencies)

For larger magnets these effects can be very troublesome! It can be necessary to generate models which take some of these effects into account (RLC-ladders).

Coupled inductances (transformers): It is important to understand the definition of the model. In some simulation programs the models did not operate correct in the past.

5. 'Fast' models for switched power stages

The core of a magnet power supply consists of the power semiconductors! In case of a buck converter this is typically a single FET or IGBT and a diode; in case of a 4Q-converter there are 4 FET's or IGBT's with their associated diodes. Depending on the goal of the simulation the power part can be modeled differently:

Electrical circuit design:

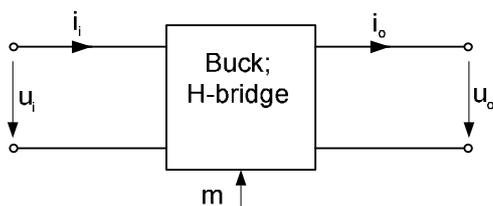
For the design of the circuit a good model of the semiconductors is necessary. Therefore, the semiconductor models, as discussed before, have to be implemented in the circuit. The simulation results of such a model are good. But, the simulation of an exact switched model is time consuming, due to the switching actions!

Controller design:

The design of the controller starts when the electrical design is finished. Longer time intervals are being investigated. Hence, a 'faster' model is desirable.

For the controller design the frequency components of the switching frequency are filtered so well, that they are no longer of interest. Therefore, a time continuous description of the power semiconductor part is interesting – time continuous simulations are fast!

The *time continuous description* of H-bridge and buck converter can be done with two mathematical equations (i: input; o: output; m: modulation index):



$$u_o = m \cdot u_i \quad \text{buck} : 0 \leq m \leq 1$$

$$i_i = m \cdot i_o \quad \text{H-bridge} : -1 \leq m \leq 1$$

In Matlab /Simulink the following structure for the converter results:

