0 Operation principle of power semiconductors

0.1 Basic switching processes

Apart from a few special applications, power semiconductors are mainly used in switching applications. This leads to some basic principles and operation modes which apply to all power electronics circuitries. The most important goal of all efforts in developing the product range of power semiconductors and their applications in circuits is to reach minimum power losses. Limit conditions for the ideal switch are characterized as follows:

ideal switch

- On-state: $v_S = 0; -\infty < i_S < \infty$
- Off-state: $i_S = 0; -\infty < v_S < \infty$
- Switching behaviour: no conversion of energy during active turn-on/ turn-off

The application of such ideal switches and, consequently, the use of power semiconductors is therefore subject to restrictive switching conditions.

Switches in inductive circuits (impressed current)
A switch applied in an inductive circuit (Fig. 0.1) can actively be turned on, i.e. it can be turned on at any time. There is no power loss under the condition of infinite switching time, since the bias voltage may drop directly over the line inductance.
If the circuit is live, turn-off is not possible without conversion of energy, since the energy stored in L has to be converted. For this reason, turn-off of the switch without any energy conversion is only possible if $i_s = 0$. This is also called passive turn-off, since the switching moment is dependent on the current flow in the circuit. A switch that is running under these switching conditions is called zero-current-switch (ZCS).

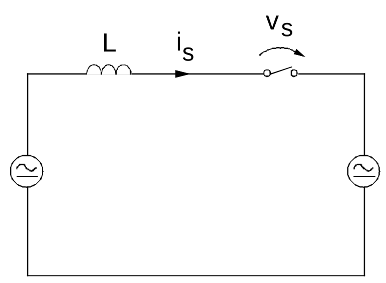
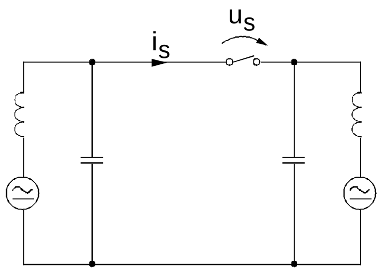


Figure 0.1 Switch in an inductive circuit

- On-state: $v_S = 0; -\infty < i_S < \infty$
- Off-state: $i_S = 0; -\infty < v_S < \infty$
- Switching behaviour: active turn-on at $|v_S| > 0$; passive turn-off at $i_S = 0$

Switch between capacitive nodes (impressed voltage)

Nondissipative turn-on of a switch under a impressed voltage is only possible if $v_s = 0$. This is called passive turn-on, since the voltage waveform and, thus, the zero crossing is determined by the outer circuit. Active turn-off, however, will be possible at any time. Switches running under those switching conditions are called zero-voltage-switches (ZVS).



- On-state: $v_s = 0$; $-\infty < i_s < \infty$
- Off-state: $i_s = 0$; $-\infty < v_s < \infty$
- Switching behaviour: active turn-off at $|i_s| > 0$
  passive turn-on at $v_s = 0$

Figure 0.2 Switch between capacitive nodes

Figure 0.3 shows current and voltage waveforms during the basic switching processes described above. The use of real power semiconductors as switches will lead to the following conditions.

Before active turn-on, the current-transferring semiconductor is under positive voltage. Voltage may drop, if, triggered by the controller, the current increases by a certain rate given by the turn-on mechanism of the power semiconductor.
This turn-on mechanism together with the series inductance is limiting the current rise and voltage distribution within the circuit between power semiconductor and inductance. Turn-on power losses of the given power semiconductor are diminished to a minimum value by increase of inductance.
During passive turn-off of a live power semiconductor carrying current in positive direction, current drops to zero due to the voltage polarity of the outer circuit. Current is conducted back as reverse current by the charge carriers still stored in the semiconductor until the semiconductor has recovered its blocking capability to take up the negative circuit voltage.

Active turn-off of a live power semiconductor will, first of all, produce a voltage rise in positive direction triggered by the controller. Then, the effective parallel capacitance will take over the current flow given by the turn-off mechanism of the power semiconductor. The energy loss caused by the turn-off procedure is reduced by the increase of capacitance for the given power semiconductor.

A passively switched power semiconductor is under negative voltage before turn-on. If this voltage changes polarity due to processes in the outer circuit, the power semiconductor will take up current in positive direction, which will lead to turn-on overvoltage in case of impressed current rise.

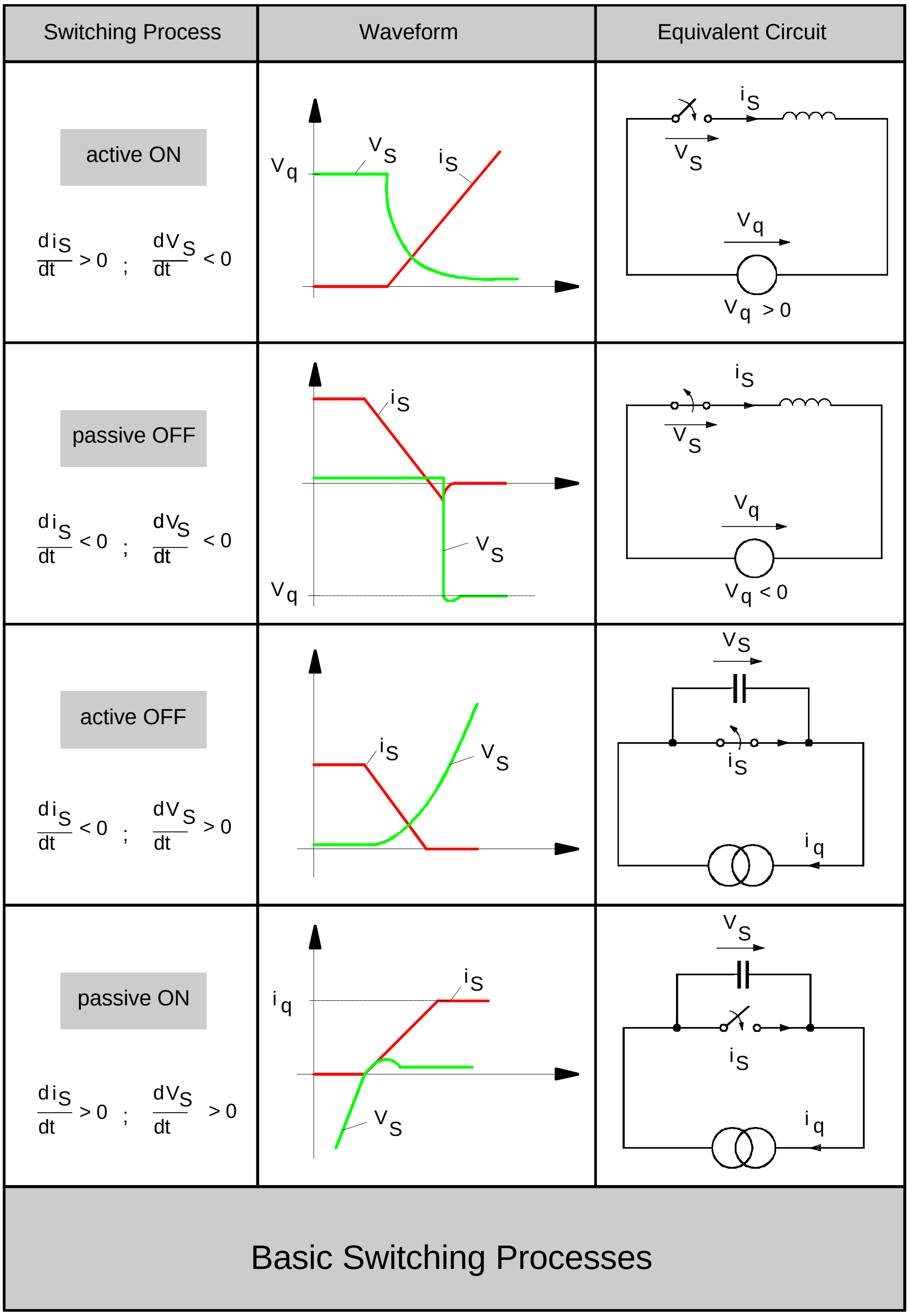


Figure 0.3 Basic switching processes

Every power electronic system works according to two basic function principles:

- firstly, turn-on and turn-off of connection leads between energy exchanging circuitries by means of one switch each - called **cyclic switching** of single switches

and

- secondly, alternating switching of two switches each, alternating current- and voltage-carrying - called **commutation**.

Both basic principles may be integrated into one circuit and the circuit split into several different operation modes.

0.2 Operation principle of power semiconductors

The operation principle of power semiconductors is clearly defined in the previously explained active and passive switching procedures during cyclic switching of single switches and inductive or capacitive commutation. Figure 0.4 shows a summary of the relationships between current and voltage during the different possible switching procedures.

Hard switching (HS, Figure 0.7)

Hard turn-on is characterized by an almost total v_K voltage drop over the current-carrying switch S_1 at a current commutation time t_K causing considerable power loss peaks within the power semiconductor. Commutation inductance is at its minimum value at that moment, i.e. the turned on semiconductor determines the current increase. Current commutation is terminated by passive turn-off of switch S_2. Commutation and switching time are almost identical.
In case of hard turn-off, voltage over S_1 increases up to a value exceeding voltage v_K while current continues flowing. Only then current commutation is started by passive turn-on of S_2. The commutation capacitance is very low, so that the voltage increase is mainly determined by the features of the power semiconductor. Therefore, switching and commutation time are almost the same and there are very high power loss peaks within the switch.

Soft switching (ZCS, ZVS, Figures 0.8 and 0.9)

In the case of soft turn-on of a zero-current-switch the switch voltage will drop relatively fast to the forward voltage drop value, if L_K has been dimensioned sufficiently. Thus, power losses in the switches are almost avoidable during current commutation. Current increase is determined by the commutation inductance L_K. Current commutation is terminated by passive turn-off of S_2, which will cause an increase of the commutation time t_K compared to the switching time t_S.
Active turn-off of S_1 will initialize soft turn-off of a zero-voltage-switch. The decreasing switch current commutates to the capacitance C_K and initializes the voltage commutation process. C_K is bigger than C_{Kmin}, which has considerable influence on the voltage increase rate. Power losses will be reduced by the delayed voltage increase at the switch.

Resonant switching (ZCRS, ZVRS, Figures 0.10 and 0.11)

We are talking about resonant turn-on, if a zero-current-switch is turned on at that moment when current i_L almost drops to zero. Switching losses are still reduced compared to soft switching. Since the switch cannot actively determine the time of zero-current crossing, the controllability is slightly restricted.
On the other hand, we are talking about resonant turn-off of a zero-voltage-switch, if the commutation voltage almost drops to zero during the turn-off process. Once again, switching losses are reduced compared to soft turn-off of the zero-voltage-switch accepting the loss of one control possibility.

Neutral switching (NS, Figure 0.12)

If the switch voltage as well as the switch current are zero at the moment of switching, this is called neutral switching. This is mostly the case with the application of diodes.

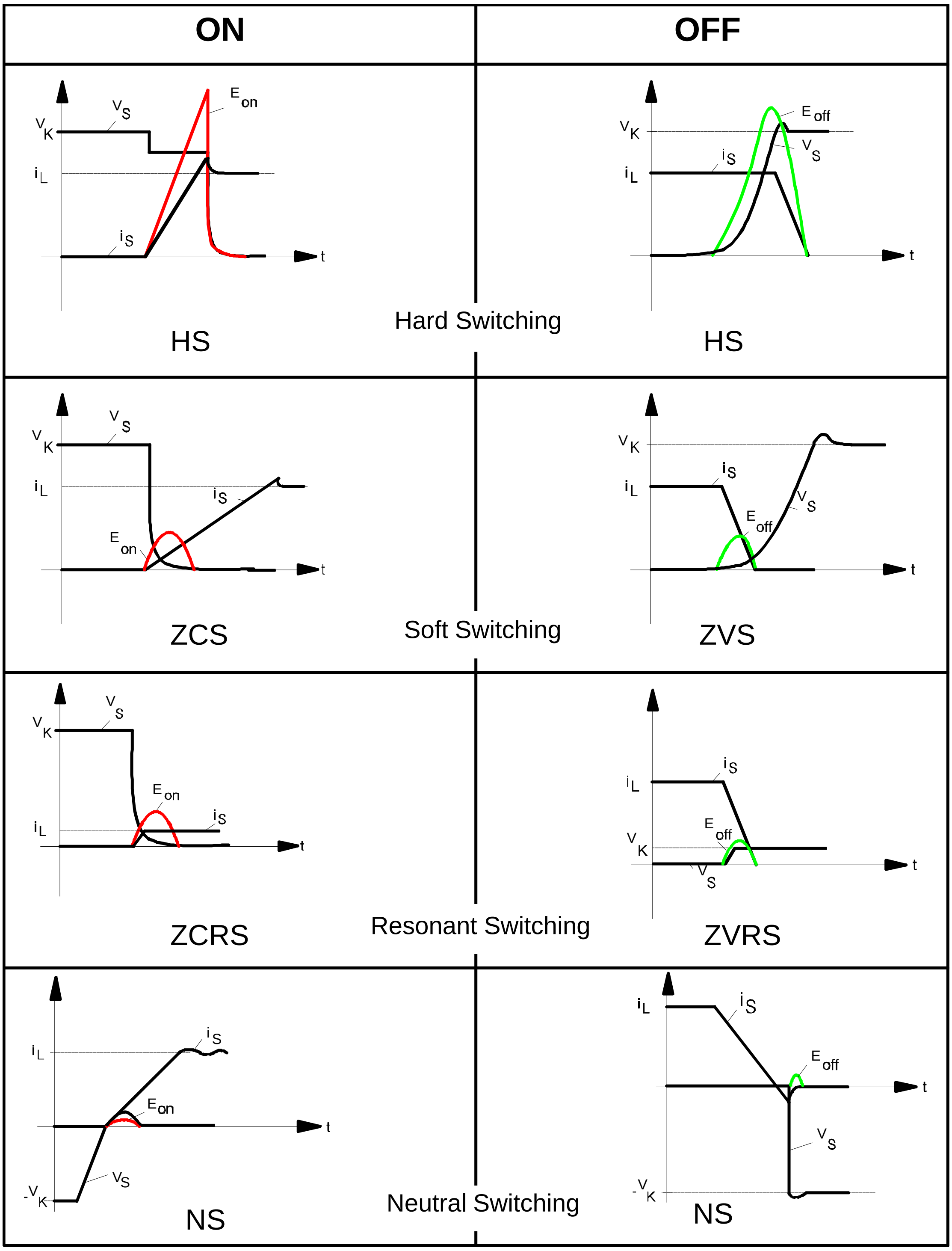


Figure 0.4 Switching procedures (v_K = driving commutation voltage, i_L = load current)