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IGBT Power Losses Calculation Using the Data-Sheet Parameters

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Automotive Power

Never stop thinking.

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1 Abstract

The aim of this Application Note is to provide a tool for a calculation of power losses in IGBT-based power electronics converters used in automotive applications. After a general discussion on power losses calculation using data-sheet parameters, the typical applications will be reviewed in order to extract the application specific parameters important for the loss balance.

2 IGBT and Diode Losses

IGBT and Diode power losses (P_l), as well as power losses in any semiconductor component, can be divided in three groups:

a) Conduction losses (P_{cond})

b) Switching losses (P_{sw})

c) Blocking (leakage) losses (P_b), normally being neglected.

Therefore:

$$P_l = P_c + P_{sw} + P_b \approx P_c + P_{sw}$$

2.1 Conduction Losses

IGBT Conduction losses can be calculated using an IGBT approximation with a series connection of DC voltage source (u_{CE0}) representing IGBT on-state zero-current collector-emitter voltage and a collector-emitter on-state resistance (r_C):

$$u_{CE}(i_C) = u_{CE0} + r_C \cdot i_C$$

The same approximation can be used for the anti-parallel diode, giving:

$$u_D(i_D) = u_{D0} + r_D \cdot i_D$$

These important parameters can be read directly from the IGBT Datasheet (see fig. 1 for the IGBT and fig. 2 for the Diode). In order to take the parameter variation into account, and thus to have a conservative calculation, the u_{ce0} and u_{D0} values read from the diagram have to be scaled with (u_{cemax}/u_{cetyp}) or (u_{Dmax}/u_{Dtyp}) values. Those exact values can be read from the datasheet tables, but for an engineering calculation a typical safety margin value of (1.1-1.2) can be used.

The instantaneous value of the IGBT conduction losses is:

$$p_{CT}(t) = u_{CE}(t) \cdot i_C(t) = u_{CE0} \cdot i_C(t) + r_C \cdot i_C^2(t)$$

If the average IGBT current value is I_{cav}, and the rms value of IGBT current is I_{crms}, then the average losses can be expressed as:

$$P_{CT} = \frac{1}{T_{sw}} \int_0^{Tsw} p_T(t)dt = \frac{1}{T_{sw}} \int_0^{Tsw} (u_{CE0} \cdot i_C(t) + r_C \cdot i_C^2(t))dt = u_{CE0} \cdot I_{cav} + r_C \cdot I_{crms}^2$$

The instantaneous value of the diode conduction losses is:

$$p_{CD}(t) = u_D(t) \cdot i_D(t) = u_{D0} \cdot i_F(t) + r_D \cdot i_D^2(t)$$

If the average diode current is I_{Dav}, and the rms diode current is I_{Drms}, the average diode conduction losses across the switching period (T_{sw}=1/f_{sw}) are:

$$P_{CD} = \frac{1}{T_{sw}} \int_0^{Tsw} p_{CD}(t)dt = \frac{1}{T_{sw}} \int_0^{Tsw} (u_{D0} \cdot i_D(t) + r_D \cdot i_D^2(t))dt = u_{D0} \cdot I_{Dav} + r_D \cdot I_{Drms}^2$$

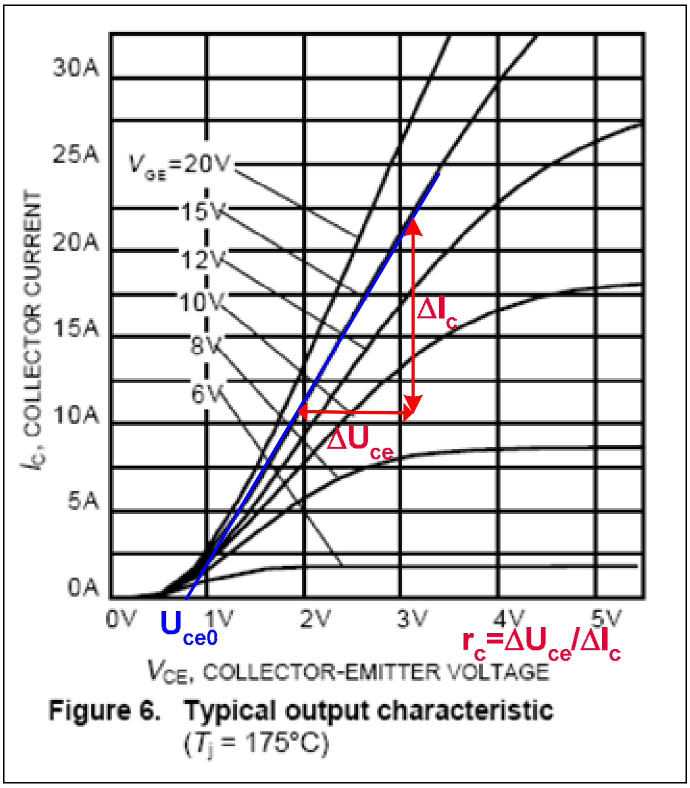

Figure 1 **Reading the u_{CE0} and r_C ($r_C = \Delta U_{ce} / \Delta I_c$) from the data-sheet diagram**

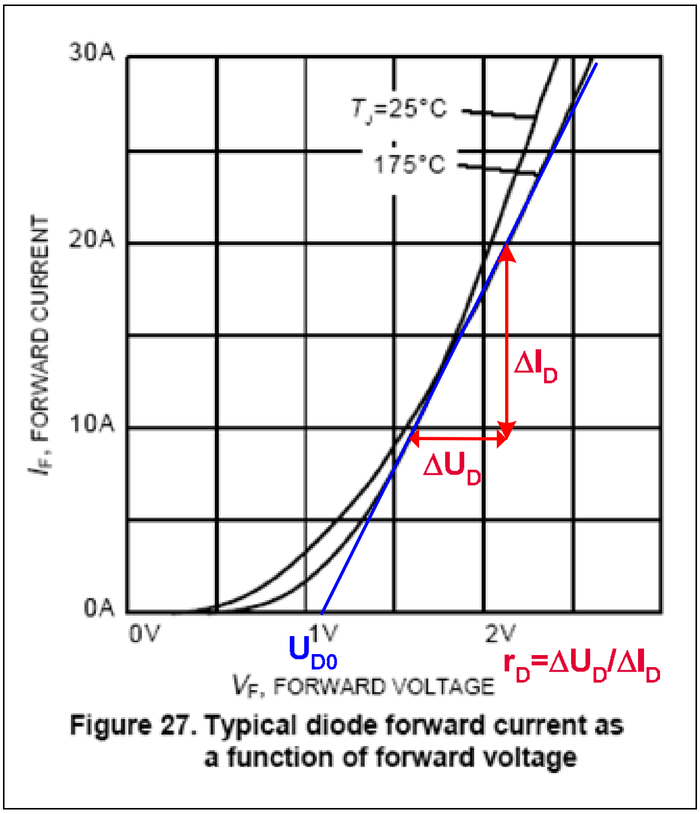

Figure 2 **Reading the u_{D0} and r_D ($r_d = \Delta U_D / \Delta I_D$) from the data-sheet diagram**

2.2 Switching Losses

The circuit for the examination of the IGBT switching losses is presented in fig. 3. It is a single-quadrant chopper supplying an inductive type load. The IGBT is driven from the driver circuit, providing a voltage U_{Dr} at its output. The IGBT internal diode is used as a free-wheeling diode, because in the majority of applications, such as 3-phase AC motor drives, bi-directional DC-motor drives, full-bridge DC/DC converters, etc., the power electronics converter consists of one or more IGBT-based half-bridges. If an external free-wheeling diode is used, the calculations are still valid, provided the diode parameters are taken from the diode data-sheet.

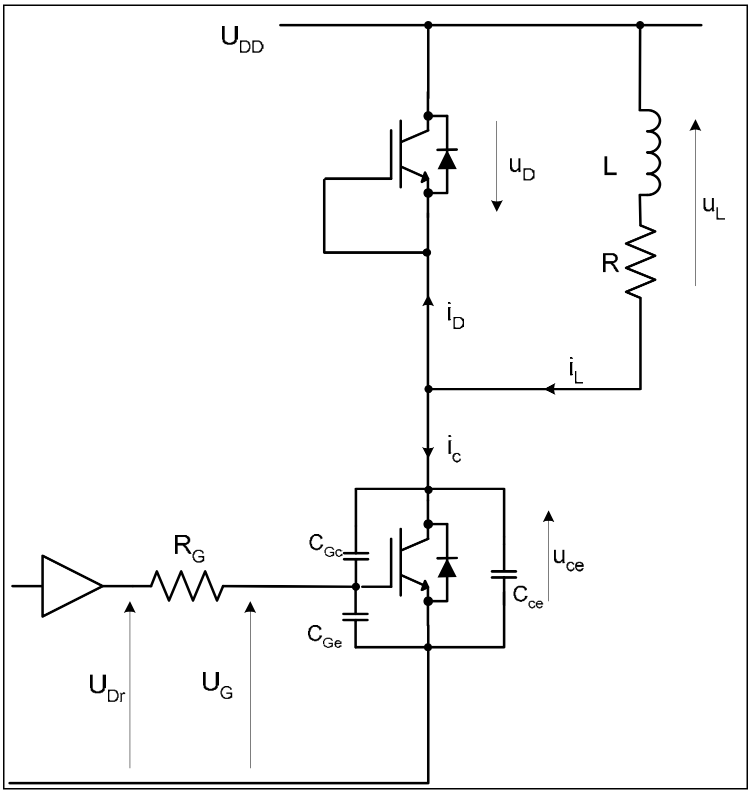

Figure 3 IGBT chopper driving an inductive load

The turn-on energy losses in IGBT (E_{onT}) can be calculated as the sum of the switch-on energy without taking the reverse recovery process into account (E_{onTi}) and the switch-on energy caused by the reverse-recovery of the free-wheeling diode (E_{onTrr}):

$$E_{onT} = \int_0^{tri+tfu} u_{ce}(t) \cdot i_c(t)dt = E_{onMi} + E_{onMrr}$$

The peak of the reverse-recovery current can be calculated as:

$$I_{Drrpeak} = \frac{2 \cdot Q_{rr}}{trr}$$

Turn-on energy in the diode consists mostly of the reverse-recovery energy (E_{onD}):

$$E_{onD} = \int_0^{tri+tfu} u_D(t) \cdot i_F(t)dt \approx E_{onDrr} = \frac{1}{4} \cdot Q_{rr} \cdot U_{Drr}$$

where U_{Drr} is the voltage across the diode during reverse recovery. For the worst case calculation this voltage can be approximated with a supply voltage ($U_{Drr} = U_{DD}$).

The switch-off energy losses in the IGBT can be calculated in the similar manner. The switch-off losses in the diode are normally neglected ($E_{offD} \approx 0$). Therefore:

$$E_{offT} = \int_{0}^{tru+tfi} u_{ce}(t) \cdot i_c(t) dt$$

The switching losses in the IGBT and the diode are the product of switching energies and the switching frequency (f_{sw}):

$$P_{swM} = (E_{onM} + E_{offM}) \cdot f_{sw}$$

$$P_{swD} = (E_{onD} + E_{offD}) \cdot f_{sw} \approx E_{onD} \cdot f_{sw}$$

2.3 Loss Balance

Power losses in the IGBT and the free-wheeling diode can be expressed as the sum of the conduction and switching losses giving:

$$P_T = P_{CT} + P_{swT} = u_{CE0} \cdot I_{cav} + r_C \cdot I_{crms}^2 + (E_{onT} + E_{offT}) \cdot f_{sw}$$

$$P_D = P_{CD} + P_{swD} = u_{D0} \cdot I_{Dav} + r_D \cdot I_{Drms}^2 + E_{onD} \cdot f_{sw}$$

3 Application Specific Parameters

In the following text the typical applications will be revisited together with the typical signal waveforms necessary for the power loss balance calculation.

3.1 Step-down (Buck) Converter

Figures 9 and 10 present the topology and the typical signals in the step-down (buck) converter.

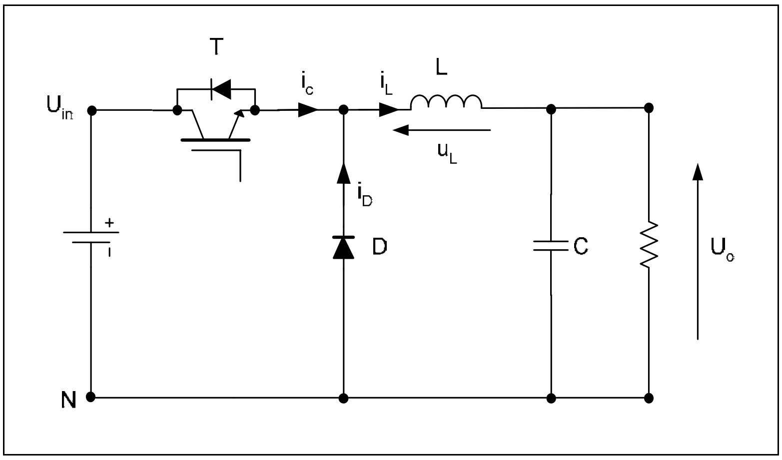

Figure 4 Step-down converter topology

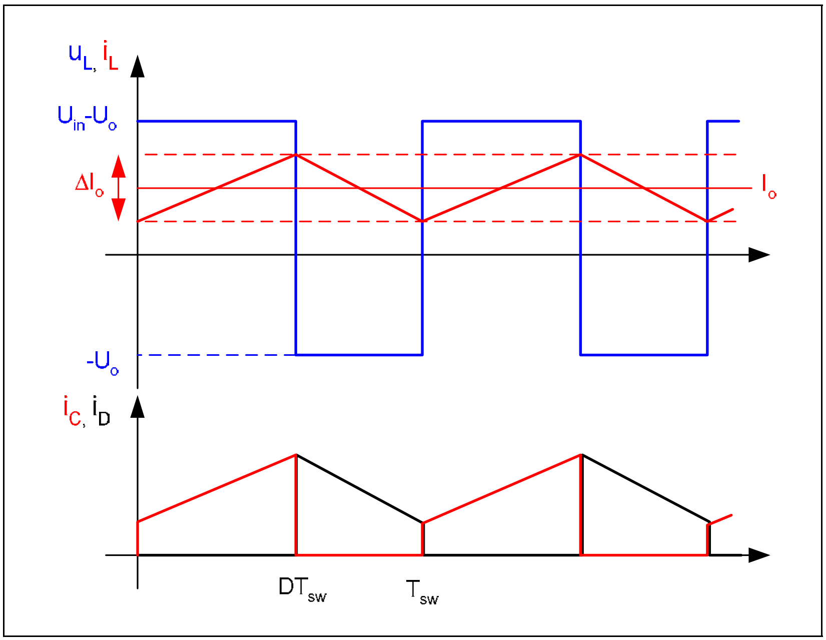

Figure 5 Step-down converter – typical signals

Input parameters for the calculation: Input voltage (U_{in}), output voltage (U_o), output power (P_o), inductor value (L), switching frequency (f_{sw}).

Output current:

$$I_o = \frac{P_o}{U_o}$$

Duty cycle in continuous conduction mode:

$$D = \frac{U_o}{U_{in}}$$

Output current ripple:

$$\Delta I_o = \frac{(1-D)U_o}{L \cdot f_{sw}}$$

The parameters needed for the loss calculation can be determined according to previously calculated values as:

$$I_{con} = I_o - \frac{\Delta I_o}{2}$$

$$I_{coff} = I_o + \frac{\Delta I_o}{2}$$

$$I_{cav} = D \cdot I_o$$

$$I_{crms}^2 = D \cdot I_o^2 = (\sqrt{D} \cdot I_o)^2$$

$$I_{Dav} = (1-D) \cdot I_o$$

$$I_{Drms}^2 = (1-D) \cdot I_o^2 = (\sqrt{1-D} \cdot I_o)^2$$

3.2 Step-up (Boost) Converter

Figures 11 and 12 present the topology and the typical signals in the step-up (boost) converter.

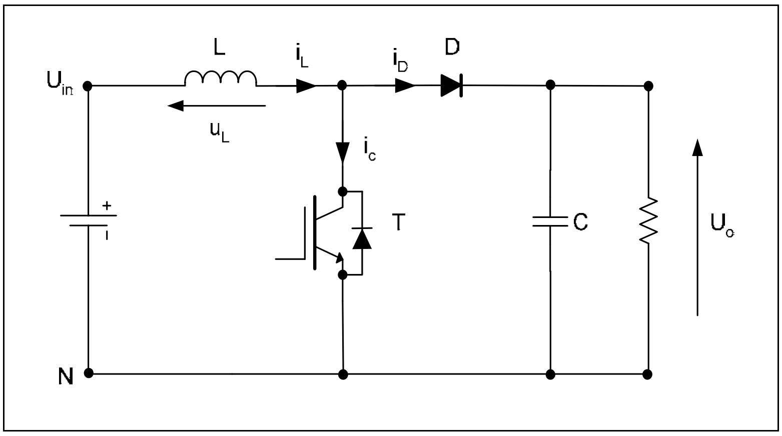

Figure 6 Step-up converter topology

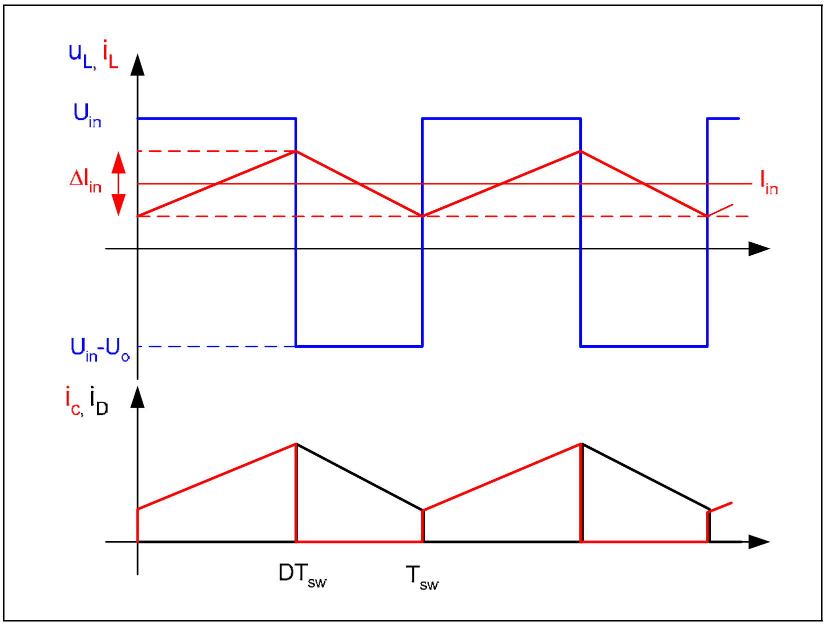

Figure 7 Step-up converter – typical signals

Input parameters for the calculation: Input voltage (U_{in}), output voltage (U_o), output power (P_o), input power (P_{in}), inductor value (L), switching frequency (f_{sw}).

Input current:

$$I_{in} = \frac{P_{in}}{U_{in}}$$

Duty cycle in continuous conduction mode:

$$D = 1 - \frac{U_{in}}{U_o}$$

Input current ripple:

$$\Delta I_{in} = \frac{D \cdot U_{in}}{L \cdot f_{sw}}$$

The parameters needed for the loss calculation can be determined according to previously calculated values as:

$$I_{con} = I_{in} - \frac{\Delta I_{in}}{2}$$

$$I_{coff} = I_{in} + \frac{\Delta I_{in}}{2}$$

$$I_{cav} = D \cdot I_{in}$$

$$I_{crms}^2 = D \cdot I_{in}^2 = (\sqrt{D} \cdot I_{in})^2$$

$$I_{Dav} = (1 - D) \cdot I_{in}$$

$$I_{Drms}^2 = (1 - D) \cdot I_{in}^2 = (\sqrt{1 - D} \cdot I_{in})^2$$

3.3 DC Motor Drive

Figures 13 and 14 present the topology and the typical signals in the single-quadrant chopper for the DC motor drive.

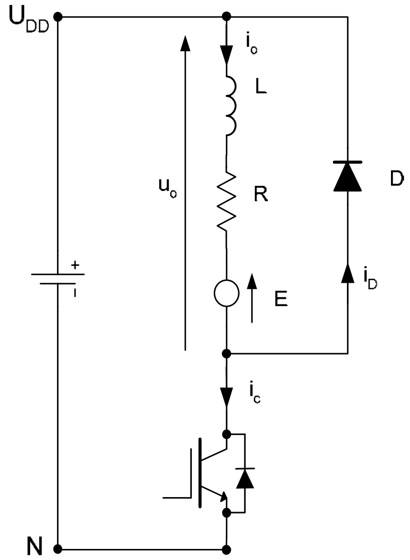

Figure 8 Single-quadrant DC motor drive

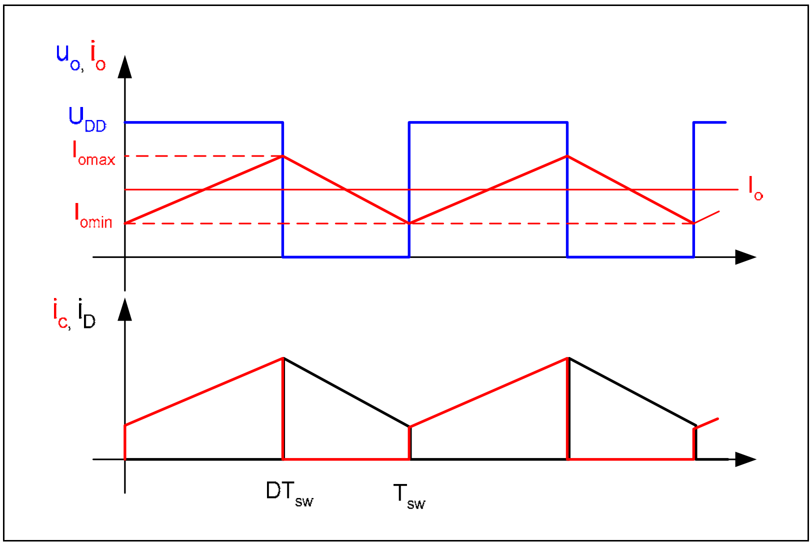

Figure 9 Single-quadrant DC motor drive – typical signals

Input parameters for the calculation: Input voltage (U_{DD}), output voltage (U_o), output power (P_o), armature inductor value (L), armature resistance value (R), motor back-emf value (E), switching frequency (f_{sw}).

Average value of the output current:

$$I_o = \frac{P_o}{U_o}$$

Duty cycle in continuous conduction mode:

$$D = \frac{U_o}{U_{DD}}$$

Minimum output current:

$$I_{o\min} = \frac{U_{DD}}{R} \frac{1 - e^{\left(\frac{D}{fsw \cdot \frac{L}{R}}\right)}}{1 - e^{\left(\frac{1}{fsw \cdot \frac{L}{R}}\right)}} - \frac{E}{R}$$

Maximum output current:

$$I_{o\max} = \frac{U_{DD}}{R} \frac{1 - e^{\left(-\frac{D}{fsw \cdot \frac{L}{R}}\right)}}{1 - e^{\left(-\frac{1}{fsw \cdot \frac{L}{R}}\right)}} - \frac{E}{R}$$

Output current ripple:

$$\Delta I_o = I_{o\max} - I_{o\min}$$

The parameters needed for the loss calculation can be determined according to previously calculated values as:

$$I_{con} = I_o - \frac{\Delta I_o}{2}$$

$$I_{coff} = I_o + \frac{\Delta I_o}{2}$$

$$I_{cav} = D \cdot I_o$$

$$I_{crms}^2 = D \cdot I_o^2 = (\sqrt{D} \cdot I_o)^2$$

$$I_{Dav} = (1 - D) \cdot I_o$$

$$I_{Drms}^2 = (1 - D) \cdot I_o^2 = (\sqrt{1 - D} \cdot I_o)^2$$

Figures 15…17 present the topology and the typical signals in the four-quadrant chopper for the DC motor drive. Fig. 16 shows the case of the bipolar PWM, while the fig. 17 shows the case of the unipolar PWM. Appropriate values can be determined following the same procedure as for the single-quadrant chopper, taking into account that for the bipolar PWM the voltage excursion on the load is $2U_{DD}$.

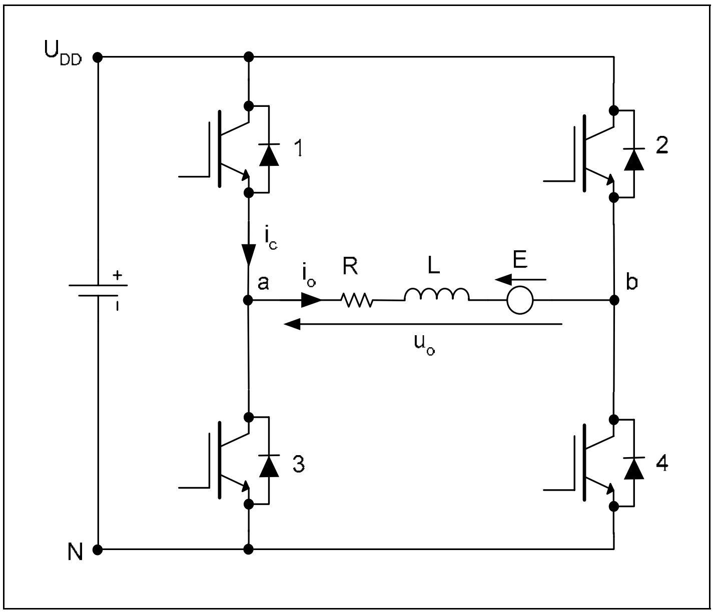

Figure 10 Four-quadrant DC motor drive

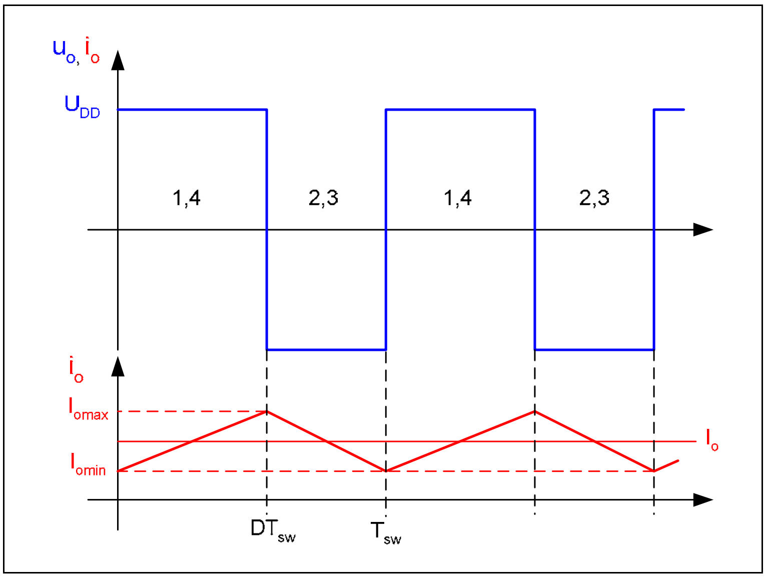

Figure 11 Four-quadrant DC motor drive – typical signals with bipolar PWM

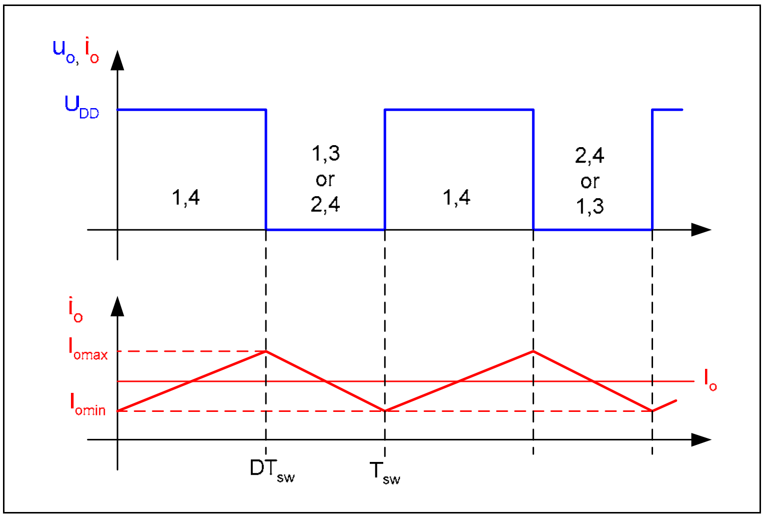

Figure 12 Four-quadrant DC motor drive – typical signals with unipolar PWM

3.4 Three-Phase AC Motor Drive

Figures 17 and 18 present the topology and the typical signals in the three-phase inverter for the AC motor (permanent magnet synchronous, brushless DC, induction motor) drive.

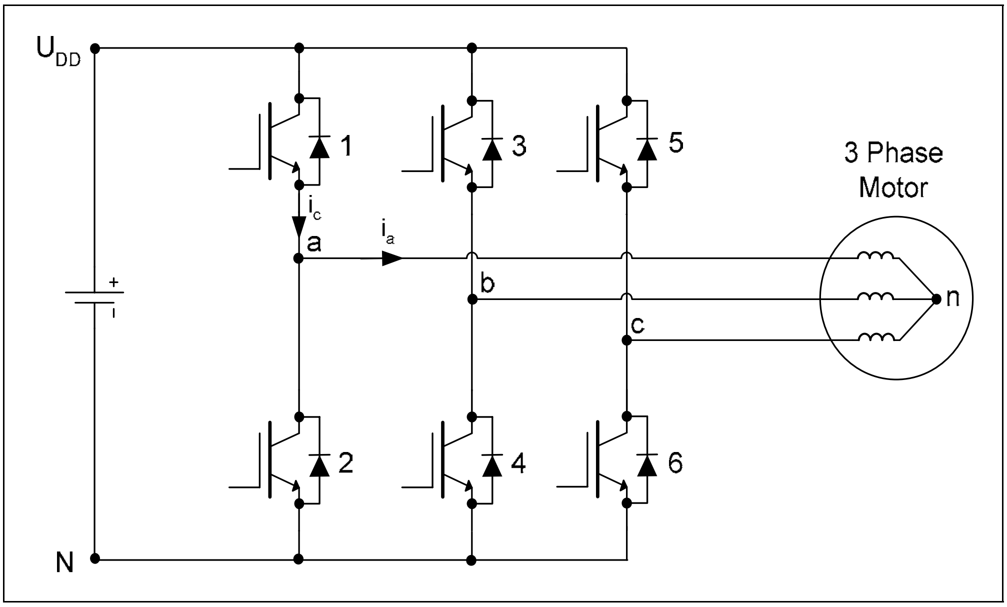

Figure 13 Three-phase AC motor drive

Input parameters for the calculation: Input voltage (U_{DD}), output line-to-line voltage (U_o) or output phase voltage (U_{an1}), rms value of the output current (I_{orms}) or output apparent power ($S_o=3U_{an1}I_{orms}$), motor displacement factor ($\cos\phi 1$), equivalent stator inductance (L), switching frequency (f_{sw}), output (motor electrical) frequency f_o and an inverter amplitude modulation index m_a

Output current ripple:

$$\Delta I_a = \frac{(U_{DD} - \sqrt{2} \cdot U_o) \cdot U_o}{2 \cdot L \cdot U_{DD} \cdot f_{sw}}$$

Peak value of the output current:

$$I_o = \sqrt{2} \cdot I_{orms}$$

IGBT conduction losses:

$$P_{CT} = u_{ce0} \cdot I_{cav} + r_c \cdot I_{crms}^2 = u_{ce0} \cdot I_o \cdot (\frac{1}{2 \cdot \pi} + \frac{m_a \cdot \cos \phi 1}{8}) + r_c \cdot I_o^2 \cdot (\frac{1}{8} + \frac{m_a \cdot \cos \phi 1}{3 \cdot \pi})$$

Diode Conduction losses:

$$P_{CD} = u_{D0} \cdot I_{Dav} + r_D \cdot I_{Drms}^2 = u_{D0} \cdot I_o \cdot (\frac{1}{2 \cdot \pi} - \frac{m_a \cdot \cos \phi 1}{8}) + r_D \cdot I_o^2 \cdot (\frac{1}{8} - \frac{m_a \cdot \cos \phi 1}{3 \cdot \pi})$$

In order to find a simple solution for the switching loss calculation, it is supposed that the losses generated in the inverter in one half-wave of the output frequency (1/(2 f_o)) correspond to the losses generated if instead of AC output current a DC equivalent output current is applied. The equivalent DC output current value is:

$$I_{DC} = \frac{1}{\pi} \cdot I_o$$

This value can be used for [I_{Ton}, I_{Toff}] in the switching loss calculation as described in detail in the chapter 2.3.

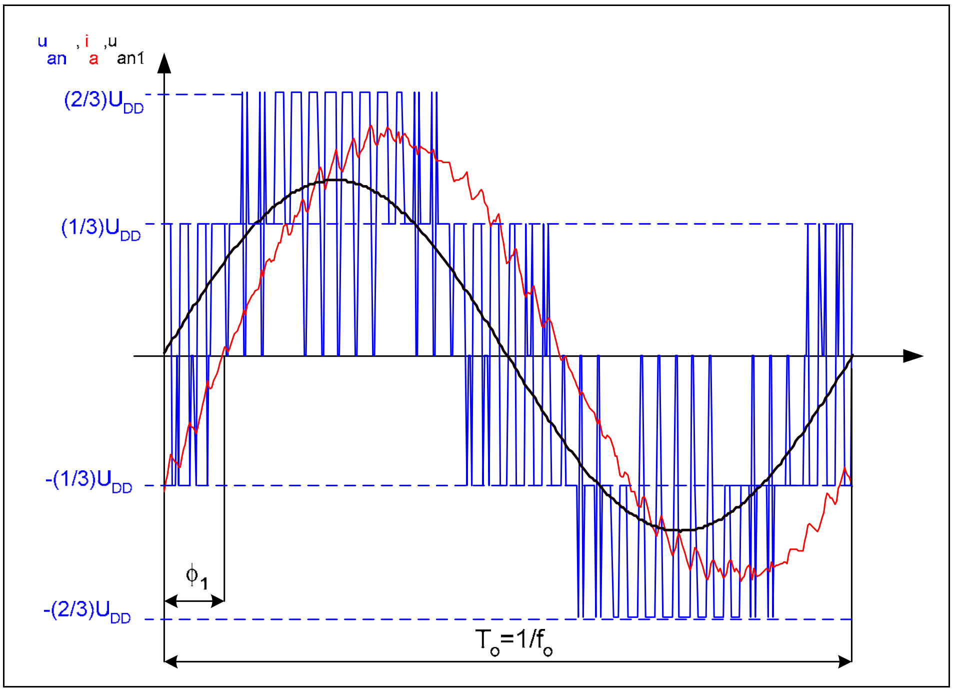

Figure 14 Three-phase AC motor drive – typical signals

3.5 Switched Reluctance Motor Drive

Figures 20, 21 and 22 present the topology and the typical signals in the two-quadrant chopper for one phase of the switched reluctance motor drive. The complete converter consists of more two-quadrant converters, the number of which depends on the number of the motor phases. The procedure for the power loss calculation is practically the same as with the DC motor drive and therefore the same equations can be used.

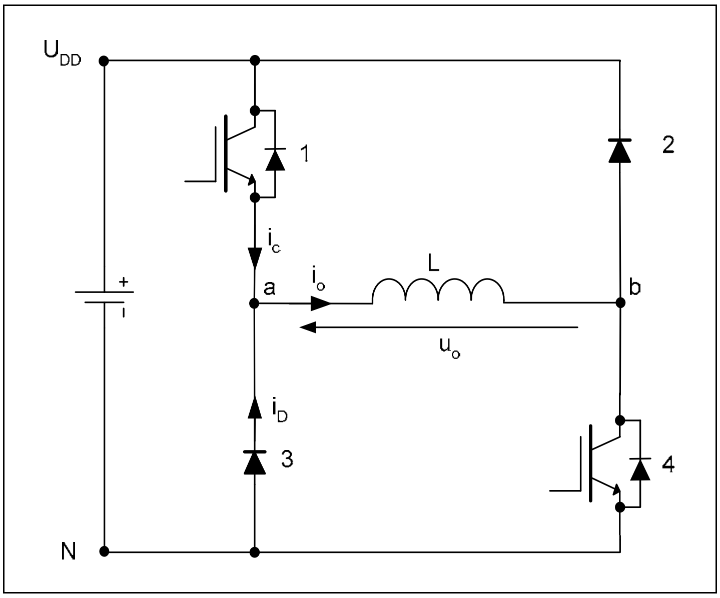

Figure 15 Two-quadrant converter for one phase winding of the switched reluctance motor drive

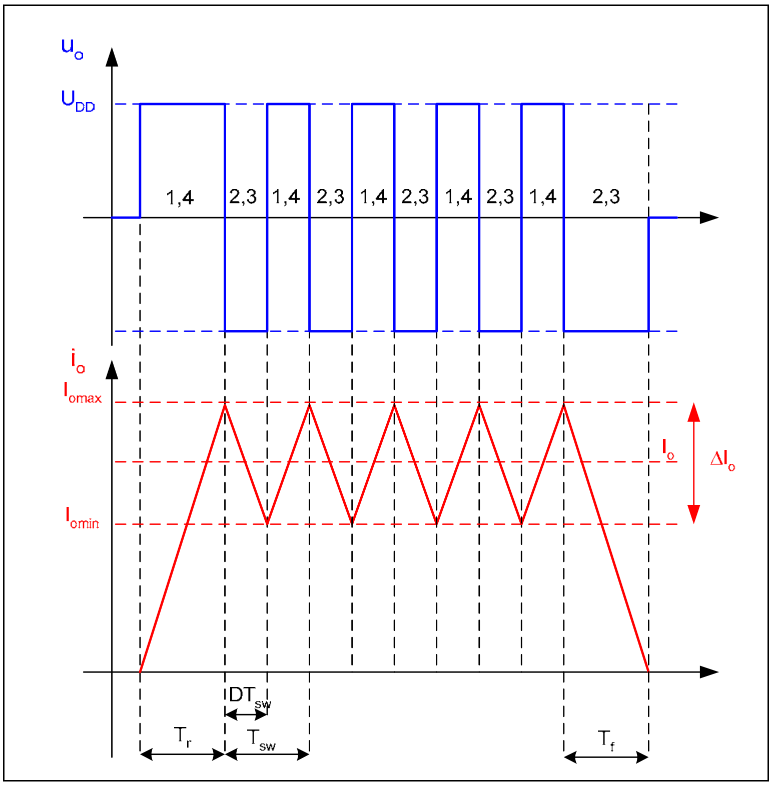

Figure 16 Switched reluctance motor drive – typical signals with bipolar PWM

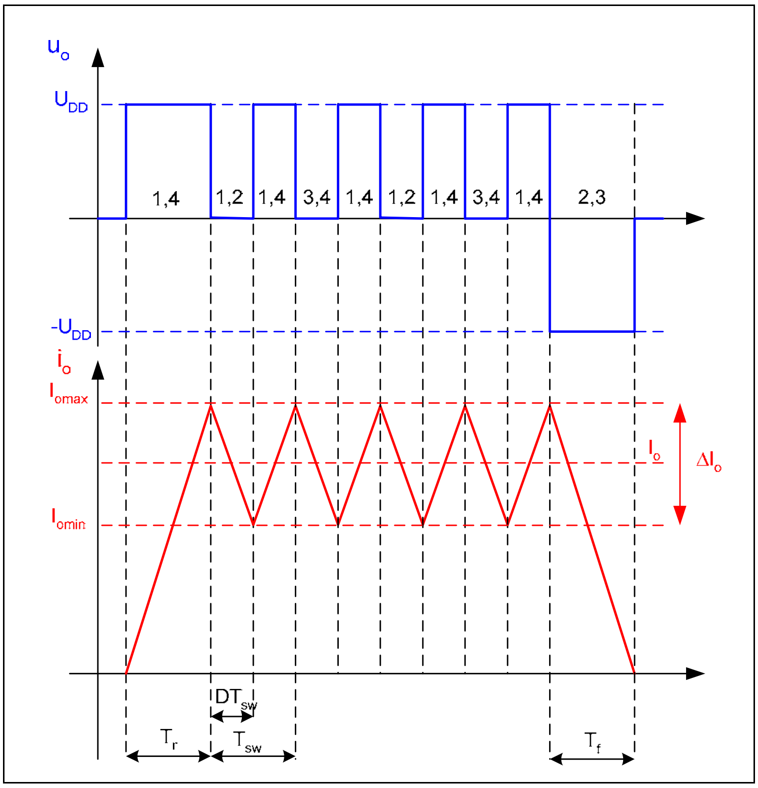

Figure 17 Switched reluctance motor drive – typical signals with unipolar PWM

3.6 Piezo-Electric Actuator

Figures 23 and 24 present the topology and the typical signals in the two-quadrant DC/DC converter for the piezo-electric actuator, used, for example, in direct injection systems. The procedure for the power loss calculation is the same as with the step-down (buck) converter during charging and the same as with the step-up (boost) converter during the discharging. Namely, while the actuator is charging, the system behaves like a step-down converter (IGBT 1 and Diode 2 are active) and the energy flows from U_{DD} to C_A and the energy flow reverses while the C_A is discharging (IGBT 2 and Diode 1 are active).

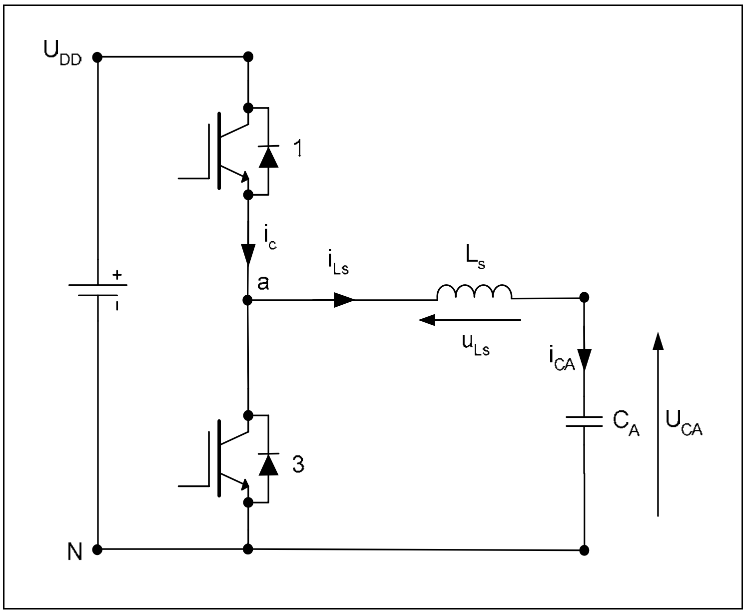

Figure 18 Two-quadrant converter for piezo-electric actuator

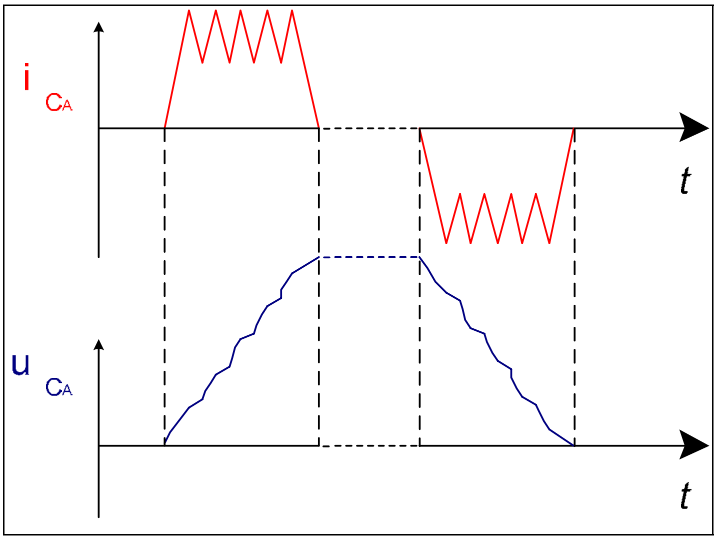

Figure 19 Converter for piezo-electric actuator – typical signals

4 Conclusion

This Application Note presented a mathematical tool for the calculation of power losses in IGBT-based power electronics converters used in automotive applications. Mathematical model for the power loss balance calculation using the data-sheet parameters was presented. The typical automotive applications were reviewed and the application specific parameters important for the loss balance were extracted.

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