

MOSFET Power Losses Calculation Using the Data- Sheet Parameters

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1 Abstract

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

2 MOSFET and Diode Losses

Power losses (P_l) in any component operating in the switch-mode can be divided in three groups:

- a) Conduction losses (P_c)
- 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

Conduction losses in power MOSFET can be calculated using an MOSFET-approximation with the drain-source on-state resistance ($R_{DS(on)}$):

$$u_{DS}(i_D) = R_{DS(on)}(i_D) \cdot i_D$$

u_{DS} and i_D are drain-source voltage and the drain current, respectively. The typical $R_{DS(on)}$ can be read from the data-sheet diagram, as shown in Fig. 1, where I_D is the MOSFET on-state current as defined by the application.

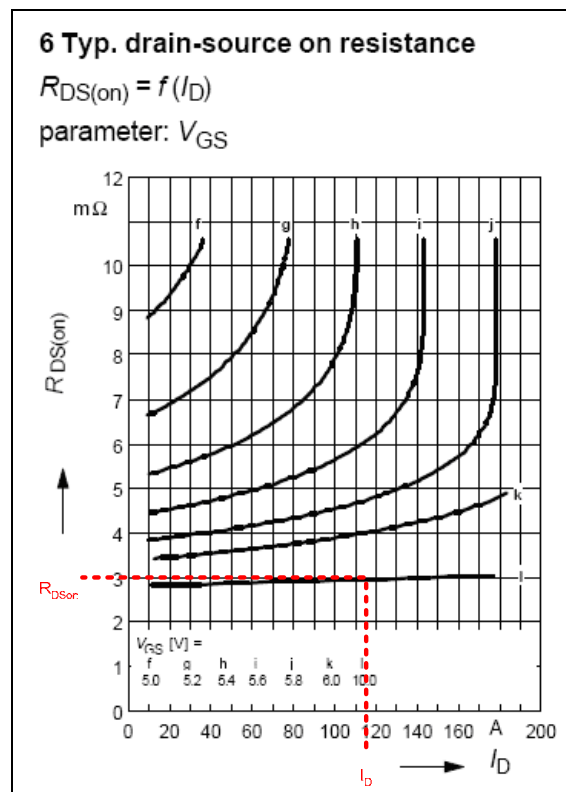


Figure 1 Drain source resistance as a function of drain current (at $T_J=25^\circ\text{C}$)

Therefore, the instantaneous value of the MOSFET conduction losses is:

$$p_{CM}(t) = u_{DS}(t) \cdot i_D(t) = R_{DSon} \cdot i_D^2(t)$$

Integration of the instantaneous power losses over the switching cycle gives an average value of the MOSFET conduction losses:

$$P_{CM} = \frac{1}{T_{sw}} \int_0^{T_{sw}} p_{CM}(t) dt = \frac{1}{T_{sw}} \int_0^{T_{sw}} (R_{DSon} \cdot i_D^2(t)) dt = R_{DSon} \cdot I_{Drms}^2$$

where I_{Drms} is the rms value of the MOSFET on-state current.

The conduction losses of the anti-parallel diode can be estimated using a diode approximation with a series connection of DC voltage source (u_{D0}) representing diode on-state zero-current voltage and a diode on-state resistance (R_D), u_D being the voltage across the diode and i_F the current through the diode:

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

These parameters can be read from the diagrams in the MOSFET datasheet as shown in fig. 2. In order to take the parameter variation into account, and thus to have a conservative calculation, the u_{D0} value read from the diagram have to be scaled with (u_{Dmax}/u_{Dtyp}) . Those exact values can be read from the datasheet tables, but for an engineering calculation a typical safety margin value of (10%-20%) can also be used.

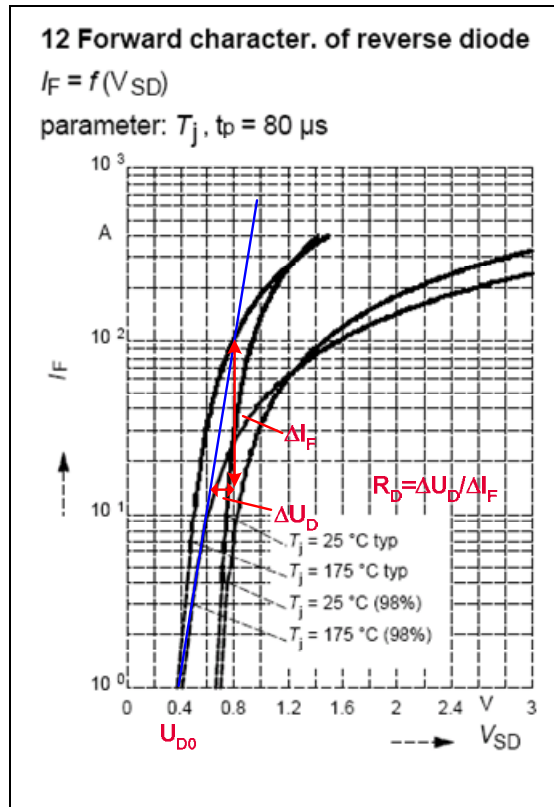


Figure 2 Diode resistance as a function of the diode current

The instantaneous value of the diode conduction losses is:

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

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

$$P_{CD} = \frac{1}{T_{sw}} \int_0^{T_{sw}} p_{CD}(t) dt = \frac{1}{T_{sw}} \int_0^{T_{sw}} (u_{D0} \cdot i_F(t) + R_D \cdot i_F^2(t)) dt = u_{D0} \cdot I_{Fav} + R_D \cdot I_{Frms}^2$$

2.1.1 R_{DSon} - Taking the Temperature and Production Variations into Account

The procedure for R_{DSon} determination, shown in figure 1, refers to the R_{DSon} typical values. While this procedure should be satisfying for the majority of applications, the R_{DSon} value can be calculated by taking into account the temperature and production variations. It can be done using following equation:

$$R_{DSon}(T_J) = R_{DSonMAX}(25^\circ C) \cdot \left(1 + \frac{\alpha}{100}\right)^{T_J - 25^\circ C}$$

where T_J is the junction temperature and $R_{DSonMAX}(25^\circ C)$ is the maximum value of R_{DSon} at $25^\circ C$, which can be read from the product summary table in the data-sheet as shown in the fig. 3. The temperature coefficient α can be calculated in the following manner: Two sets of values (T_{J1} , R_{DSon1}) and (T_{J2} , R_{DSon2}) can be read from the data sheet as shown in fig. 4. These values can be used with the last equation to determine α .

Product Summary		
V_{DS}	40	V
$R_{DS(on),max}$ (SMD version)	3.3	m Ω
I_D	100	A

Figure 3 Reading $R_{DSonMAX}(25^\circ C)$ from the data-sheet

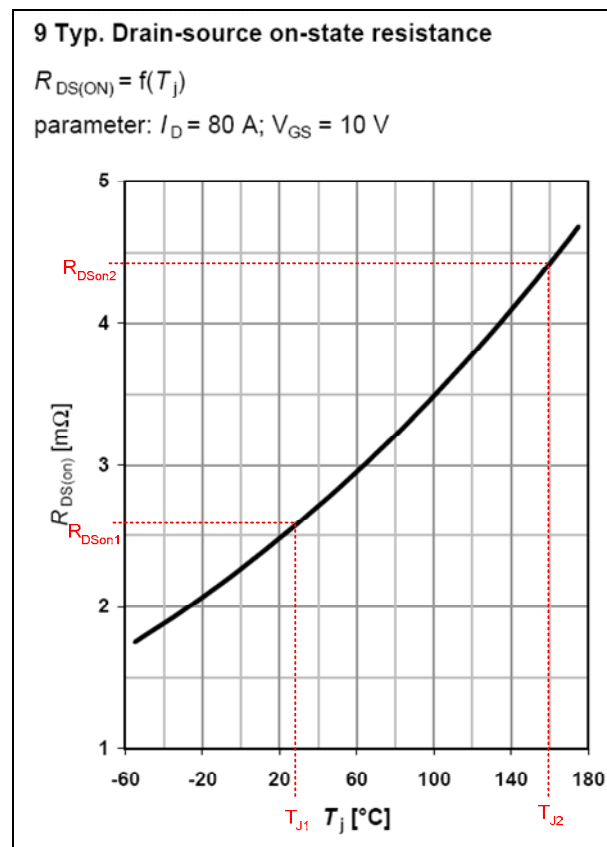


Figure 4 Reading T_J/R_{DSon} from the data-sheet

2.2 Switching Losses

The circuit for the examination of the MOSFET switching losses is presented in fig. 5. It is a single-quadrant chopper supplying an inductive type load. The MOSFET is driven from the driver circuit, providing a voltage U_{Dr} at its output. The MOSFET internal diode is used as a free-wheeling diode, because in the majority of applications, such as 3-phase AC motor drives, DC-motor drives, synchronous DC/DC converters, etc., the power electronics converter consists of one or more MOSFET-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.

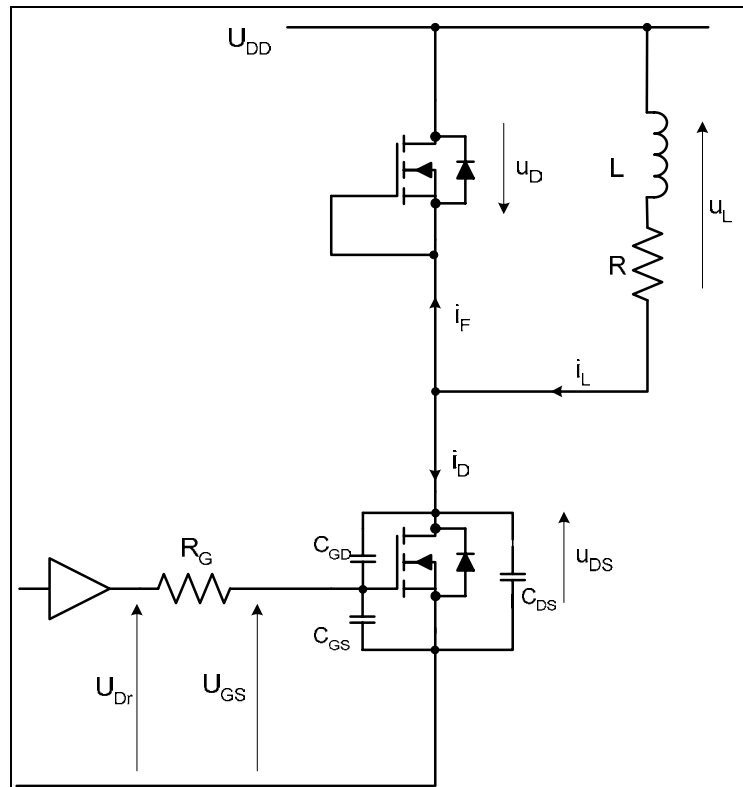


Figure 5 MOSFET chopper with an inductive load

For the engineering calculations of the power loss balance, a linear approximation of the MOSFET switching process is sufficient and, as will be shown later, presents the worst case calculation. The idealised switching process of the power MOSFET is presented in Fig. 6. The uppermost part (A) presents the gate voltage (u_{GS}) and current (i_G); the next one (B) shows the drain-source voltage (u_{DS}) and the drain current (i_D) without taking the reverse recovery of the free-wheeling diode into account. The part C gives a qualitative overview of the power losses, while the part D shows the reverse-recovery effects on the switching losses.

2.2.1 Switch-on transient

- Driver circuit changes its state from 0V to U_{Dr} , the gate voltage rises to the threshold voltage ($U_{GS(th)}$), with the time-constant defined by the gate resistor and the equivalent MOSFET input capacitance ($C_{iss}=C_{GD}+C_{GS}$). Until the gate voltage reaches the $U_{GS(th)}$, the output does not change.
- After the $U_{GS(th)}$ has been reached, the drain current rises and takes over the load current. The worst case value of the current rise-time (t_{ri}) between zero and I_{Don} (defined by the application) can be read from the MOSFET data-sheet, as shown in fig. 7. During the current rise-time, the free-wheeling diode is still conducting and the drain-source voltage is U_{DD} .
- In order for the diode to switch off, all the minority carriers stored in it have to be removed (see fig. 6D). This reverse-recovery current has to be absorbed by the MOSFET, causing additional power losses. The worst-case values of the reverse-recovery charge (Q_{rr}) and duration (t_{rr}), which will be used in the power loss calculation, can again be read from the MOSFET data-sheet (see fig. 8)

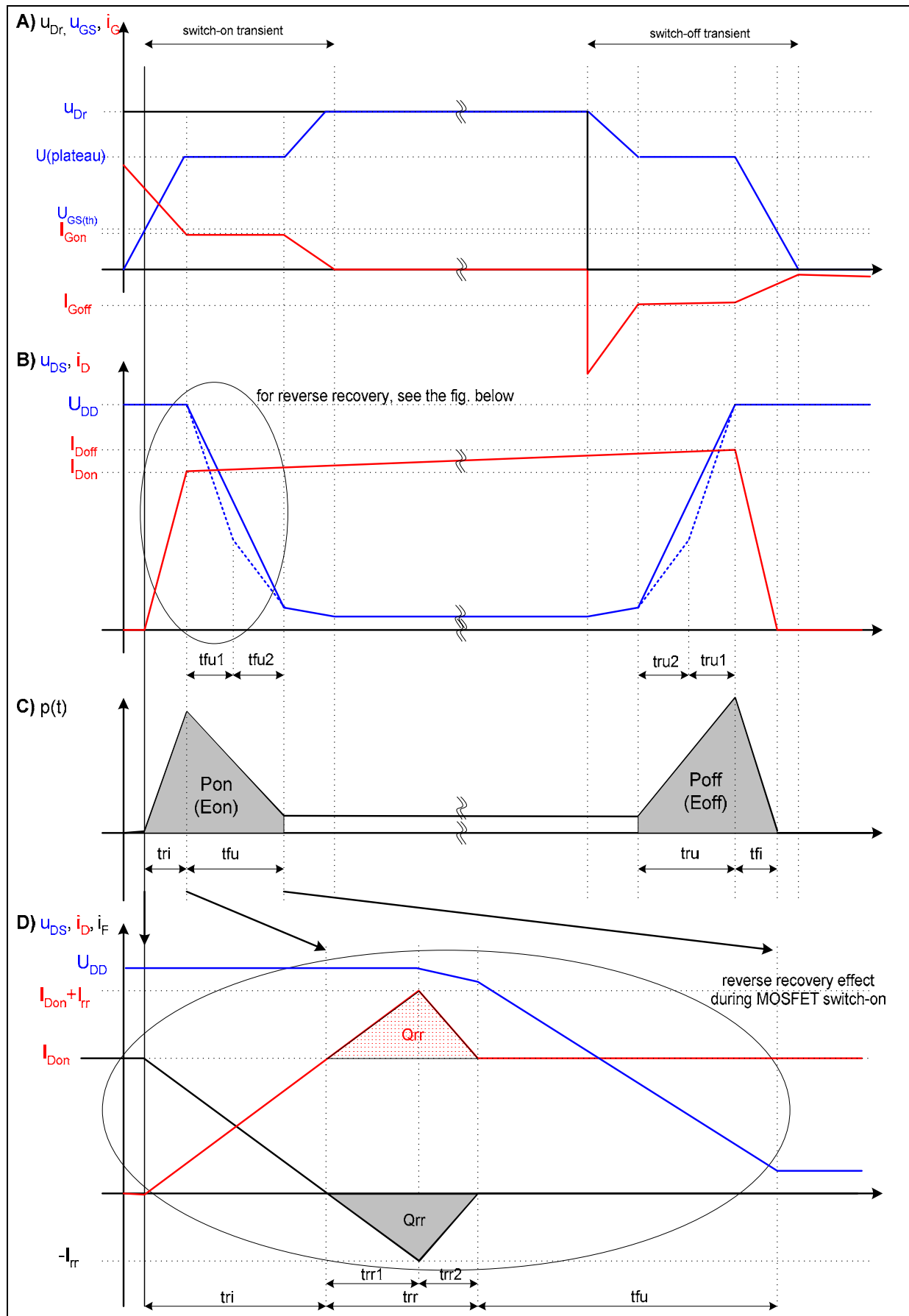


Figure 6 Switching transients of the power MOSFET

Electrical Characteristics						
Parameter	Symbol	Conditions	Values			Unit
			min.	typ.	max.	
Dynamic Characteristics						
Transconductance	g_{fs}	$V_{DS} \geq 2 \cdot I_D \cdot R_{DS(on)max}$, $I_D = 100A$	73	146	-	S
Input capacitance	C_{iss}	$V_{GS} = 0V$, $V_{DS} = 25V$, $f = 1MHz$	-	5430	-	pF
Output capacitance	C_{oss}		-	1915	-	
Reverse transfer capacitance	C_{rss}		-	400	-	
Turn-on delay time	$t_{d(on)}$	$V_{DD} = 20V$, $V_{GS} = 10V$,	-	22	-	ns
Rise time	t_r	$I_D = 100A$,	-	54	-	
Turn-off delay time	$t_{d(off)}$	$R_G = 2.2\Omega$	-	63	-	
Fall time	t_f		-	53	-	

Figure 7 Reading the current rise- (red) and fall-time (blue) from the data-sheet

Reverse Diode						
Inverse diode continuous forward current	I_S	$T_C = 25^\circ C$	-	-	100	A
Inv. diode direct current, pulsed	I_{SM}		-	-	400	
Inverse diode forward voltage	V_{SD}	$V_{GS} = 0V$, $I_F = 80A$	-	0.9	1.3	V
Reverse recovery time	t_{rr}	$V_R = 20V$, $I_F = I_S$,	-	66	-	ns
Reverse recovery charge	Q_{rr}	$di_F/dt = 100A/\mu s$	-	153	-	nC

Figure 8 Reading the reverse recovery time (red) and charge (blue) from the data-sheet

- After the diode has been switched off, the drain-source voltage is falling from $u_{DS} = U_{DD}$ to its on-state value $u_{DS} = R_{DS(on)} \cdot I_{on}$. The Miller effect takes place and the gate-source voltage is clamped at the $u_{GS} = U_{(plateau)}$ (see fig. 9). The slope of the drain-source voltage is dictated through the gate current flowing through the gate-drain capacitance ($C_{GD} = C_{rss}$). In order to calculate the voltage fall-time (t_{fu}) with a reasonable accuracy, the non-linearity of the gate-drain capacitance has to be taken into account. The typical dependence of the gate-drain capacitance on the drain-source voltage is shown in the fig. 10. Such non-linearity can not be easily incorporated into the engineering calculations. That is why a two-point approximation is used. It is supposed that if the drain-source voltage is in the range $u_{DS} \in [U_{DD}/2, U_{DD}]$, then the gate-drain capacitance takes value of $C_{GD1} = C_{GD}(U_{DD})$. On the other hand, if the drain-source voltage is in the range $u_{DS} \in [0V, U_{DD}/2]$, then the gate-drain capacitance takes value of $C_{GD2} = C_{GD}(R_{DS(on)} \cdot I_{on})$. The way to determine those capacitances is shown in fig. 10. The drain-source voltage during the fall time, the two-point approximation being taken into account, is shown in fig. 6B with the dotted line. Since this approximation is used only to determine the voltage fall time (as well as the rise time during switch off) and the drain-source voltage is assumed to have the linear form (solid line in fig. 6B), it becomes clear that this analysis presents the worst-case for the switching losses calculation.

The gate current during t_{fu} can be calculated as:

$$I_{Gon} = \frac{U_{Dr} - U_{(plateau)}}{R_G}$$

The voltage fall time can now be calculated as a median of the fall times defined through the gate current and the capacitances C_{GD1} and C_{GD2} .

$$t_{fu} = \frac{t_{fu1} + t_{fu2}}{2}$$

where:

$$tfu1 = (U_{DD} - R_{DSon} \cdot I_{Don}) \frac{C_{GD1}}{I_{Gon}} = (U_{DD} - R_{DSon} \cdot I_{Don}) \cdot R_G \cdot \frac{C_{GD1}}{(U_{Dr} - U_{(plateau)})}$$

$$tfu2 = (U_{DD} - R_{DSon} \cdot I_{Don}) \frac{C_{GD2}}{I_{Gon}} = (U_{DD} - R_{DSon} \cdot I_{Don}) \cdot R_G \cdot \frac{C_{GD2}}{(U_{Dr} - U_{(plateau)})}$$

Gate Charge Characteristics						
Gate to source charge	Q_{gs}	$V_{DD}=32V, I_D=100A$	-	28	37	nC
Gate to drain charge	Q_{gd}		-	53	80	
Gate charge total	Q_g	$V_{DD}=32V, I_D=100A,$ $V_{GS}=0 \text{ to } 10V$	-	129	172	
Gate plateau voltage	$V_{(plateau)}$	$V_{DD}=32V, I_D=100A$	-	5.2	-	V

Figure 9 Reading the plateau voltage from the data-sheet

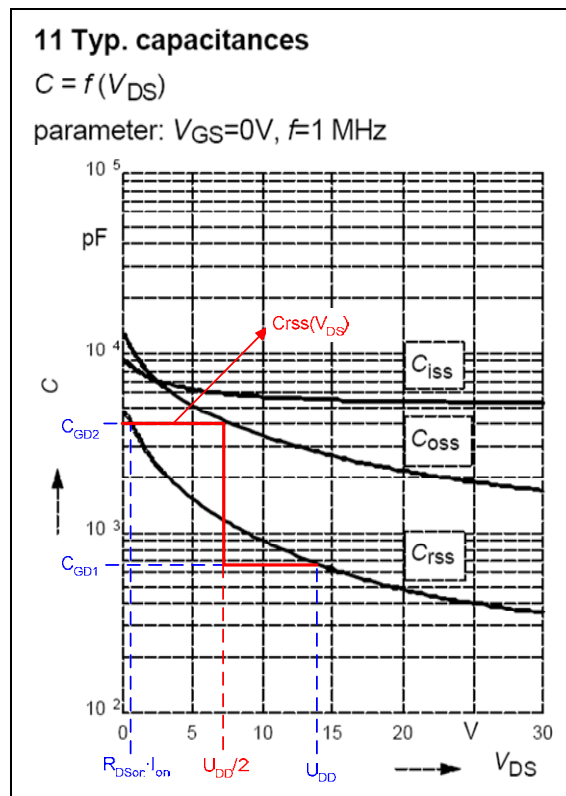


Figure 10 Two-point representation of the gate-drain capacitance

2.2.2 Switch-off transient

Switch-off process corresponds to the switching-on process of the MOSFET in the reverse order and will thus not be discussed in detail. Two important differences are:

- No reverse recovery takes place
- The gate current and the voltage rise time can be expressed as:

$$I_{Goff} = -\frac{U_{(plateau)}}{R_G}$$

$$tru = \frac{tru1 + tru2}{2}$$

$$tru1 = (U_{DD} - R_{DSon} \cdot I_{Don}) \frac{C_{GD1}}{I_{Goff}} = (U_{DD} - R_{DSon} \cdot I_{Don}) \cdot R_G \cdot \frac{C_{GD1}}{U_{(plateau)}}$$

$$tru2 = (U_{DD} - R_{DSon} \cdot I_{Don}) \frac{C_{GD2}}{I_{Goff}} = (U_{DD} - R_{DSon} \cdot I_{Don}) \cdot R_G \cdot \frac{C_{GD2}}{U_{(plateau)}}$$

2.2.3 Switching Energies and Losses

According to previous considerations, the worst case turn-on energy losses in power MOSFET (E_{onM}) can be calculated as the sum of the switch-on energy without taking the reverse recovery process into account (E_{onMi}) and the switch-on energy caused by the reverse-recovery of the free-wheeling diode (E_{onMrr}):

$$E_{onM} = \int_0^{tri+tfu} u_{DS}(t) \cdot i_D(t) dt = E_{onMi} + E_{onMrr} = U_{DD} \cdot I_{Don} \cdot \frac{tri + tfu}{2} + Q_{rr} \cdot U_{DD}$$

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

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

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

$$E_{offM} = \int_0^{tru+tfi} u_{DS}(t) \cdot i_D(t) dt = U_{DD} \cdot I_{Doff} \cdot \frac{tru + tfi}{2}$$

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

$$P_M = P_{CM} + P_{swM} = R_{DSon} \cdot I_{Drms}^2 + (E_{onM} + E_{offM}) \cdot f_{sw}$$

$$P_D = P_{CD} + P_{swD} = u_{D0} \cdot I_{Fav} + R_D \cdot I_{Frms}^2 + E_{onD} \cdot f_{sw}$$

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 11 and 12 present the topology and the typical signals in the step-down (buck) converter.

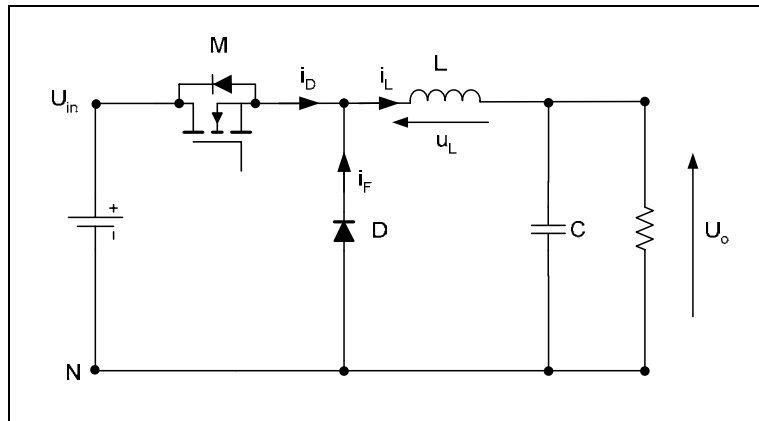


Figure 11 Step-down converter topology

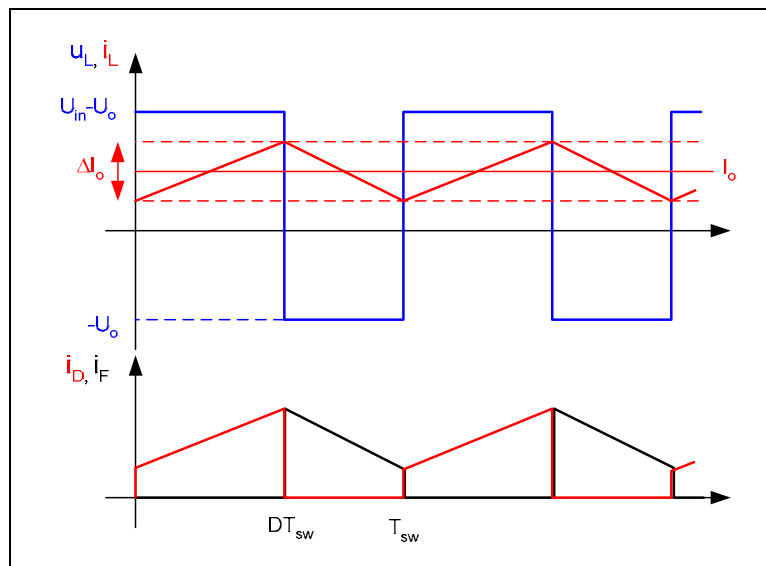


Figure 12 Step-down converter – typical signals

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:

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

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

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

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

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

3.2 Step-up (Boost) Converter

Figures 13 and 14 present the topology and the typical signals in the step-up (boost) converter.

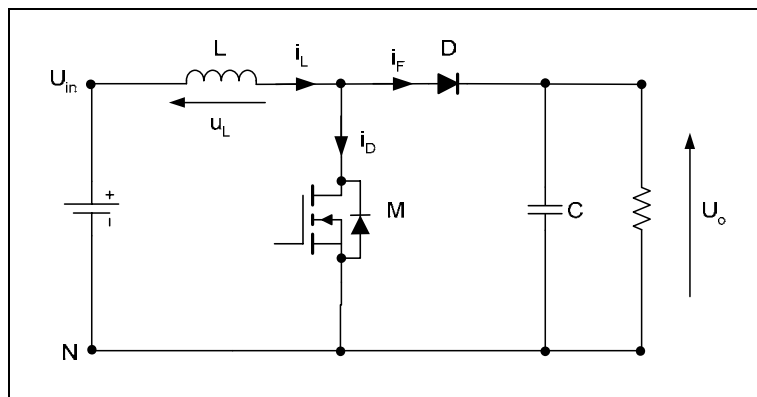


Figure 13 Step-up converter topology

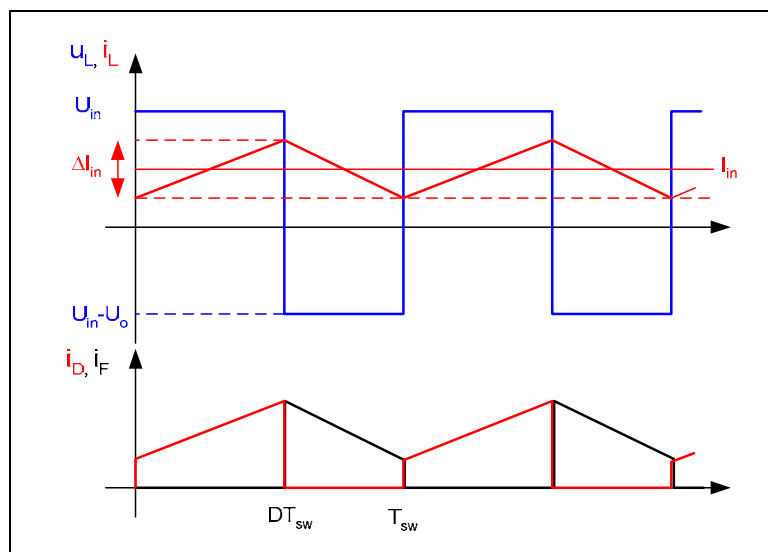


Figure 14 Step-up converter – typical signals

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:

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

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

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

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

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

3.3 DC Motor Drive

Figures 15 and 16 present the topology and the typical signals in the single-quadrant chopper for the DC motor drive.

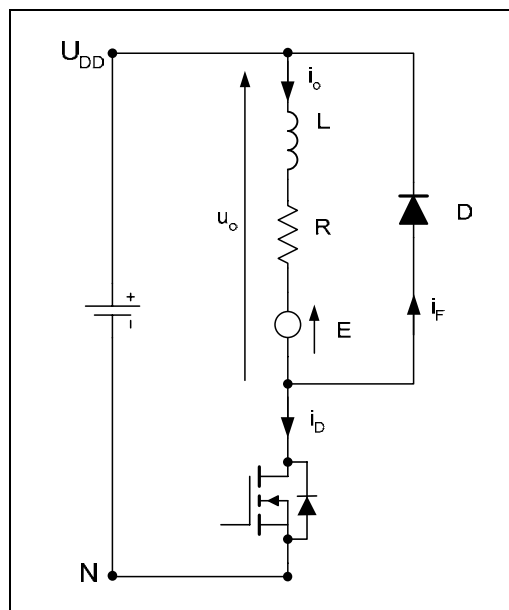


Figure 15 Single-quadrant DC motor drive

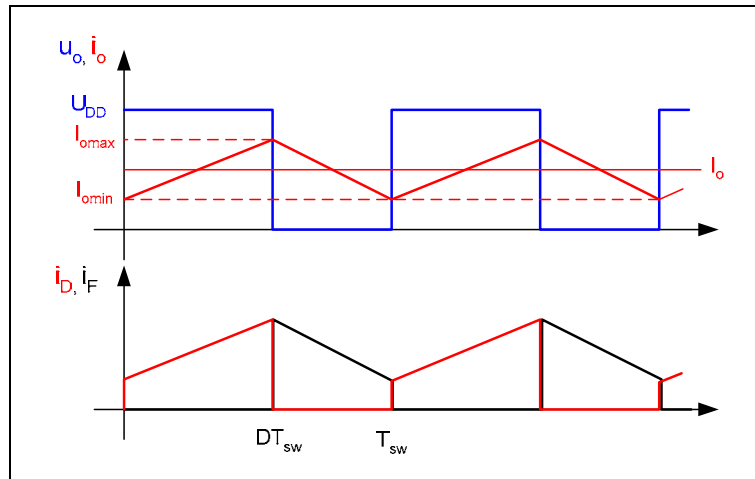


Figure 16 Single-quadrant DC motor drive – typical signals

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:

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

Maximum output current:

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

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:

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

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

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

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

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

Figures 17...18 present the topology and the typical signals in the four-quadrant chopper for the DC motor drive. Fig. 18 shows the case of the bipolar PWM, while the fig. 19 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 $2U_{DD}$.

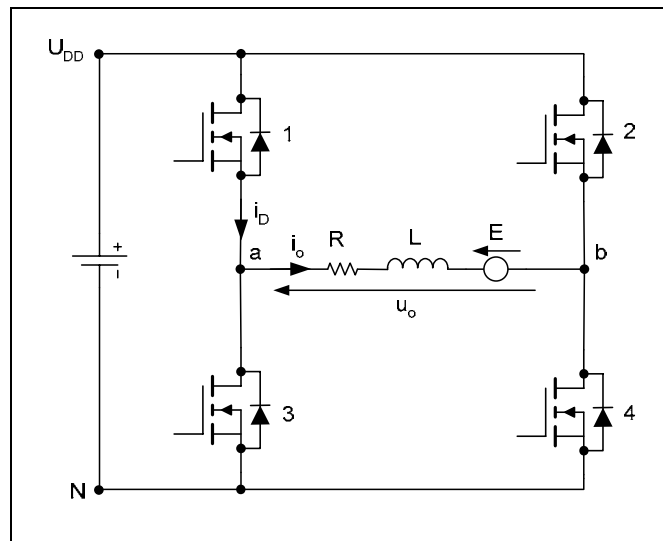


Figure 17 Four-quadrant DC motor drive

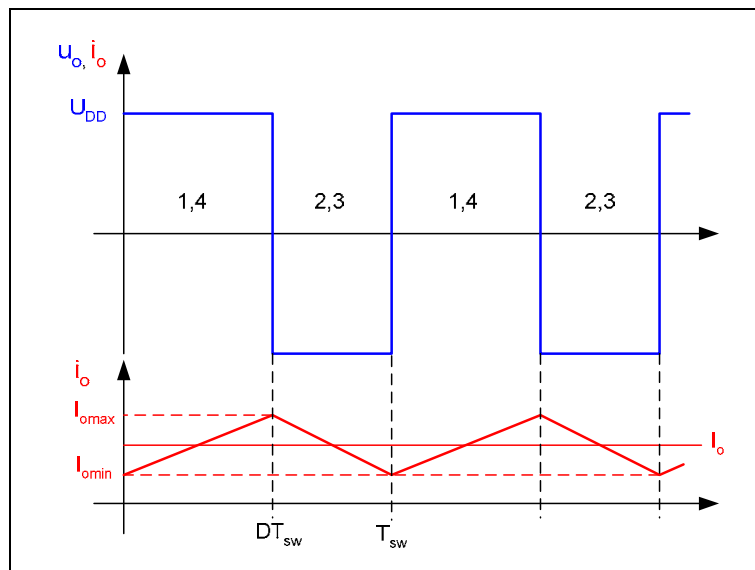


Figure 18 Four-quadrant DC motor drive – typical signals with bipolar PWM

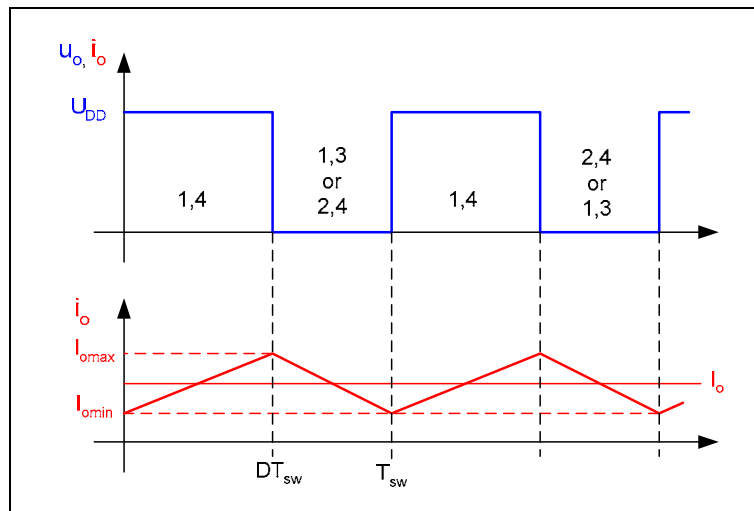


Figure 19 Four-quadrant DC motor drive – typical signals with unipolar PWM

3.4 Three-Phase AC Motor Drive

Figures 19 and 20 present the topology and the typical signals in the three-phase inverter for the AC motor (permanent magnet synchronous, brushless DC, induction motor) drive. Typical applications are: electric power steering (EPS), Starter-Generator (Alternator), fans, blowers, HVAC etc.

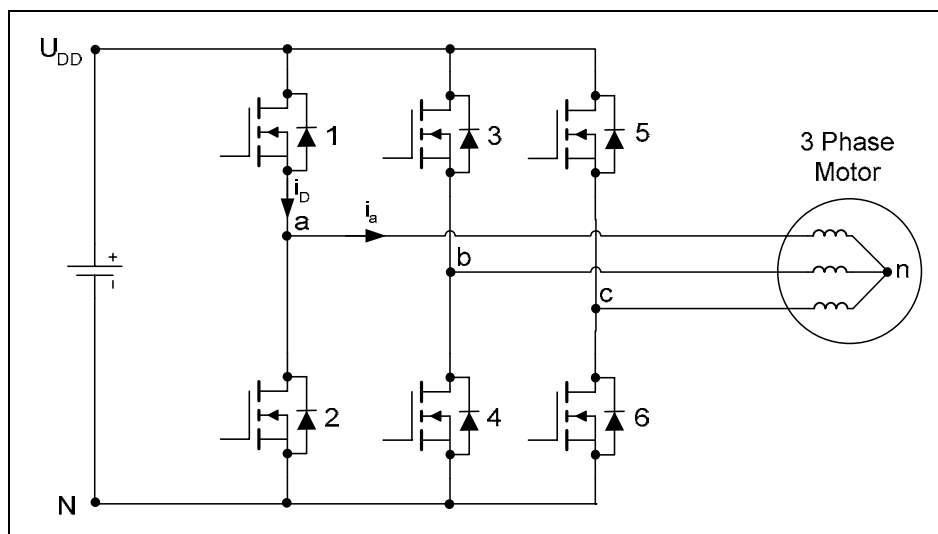


Figure 20 Three-phase AC motor drive

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:

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

MOSFET conduction losses:

$$P_{CM} = R_{DSon} \cdot I_{Drms}^2 = R_{DSon} \cdot I_o^2 \cdot \left(\frac{1}{8} + \frac{m_a \cdot \cos \phi_1}{3 \cdot \pi} \right)$$

Diode Conduction losses:

$$P_{CD} = u_{D0} \cdot I_{Fav} + R_D \cdot I_{Frms}^2 = u_{D0} \cdot I_o \cdot \left(\frac{1}{2 \cdot \pi} - \frac{m_a \cdot \cos \phi_1}{8} \right) + R_D \cdot I_o^2 \cdot \left(\frac{1}{8} - \frac{m_a \cdot \cos \phi_1}{3 \cdot \pi} \right)$$

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 $[I_{Don}, I_{Doff}]$ in the switching loss calculation as described in detail in the chapter 2.3.

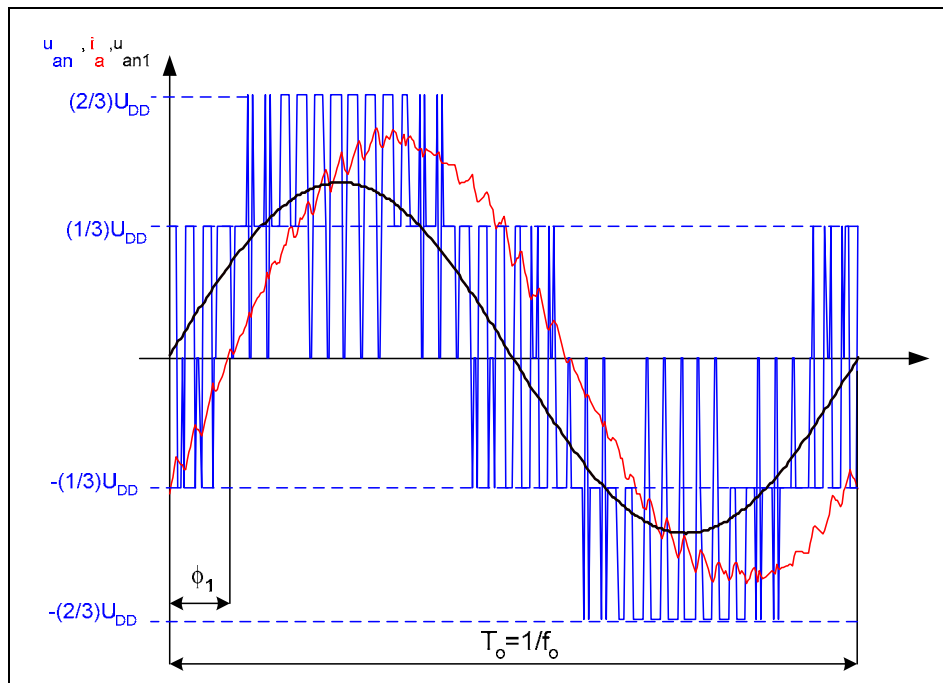


Figure 21 Three-phase AC motor drive – typical signals

3.5 Switched Reluctance Motor Drive

Figures 22, 23 and 24 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.

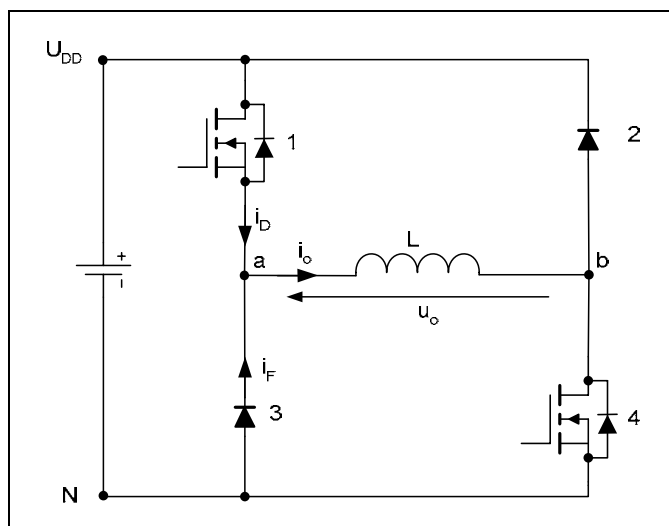


Figure 22 Two-quadrant converter for one phase winding of the switched reluctance motor drive

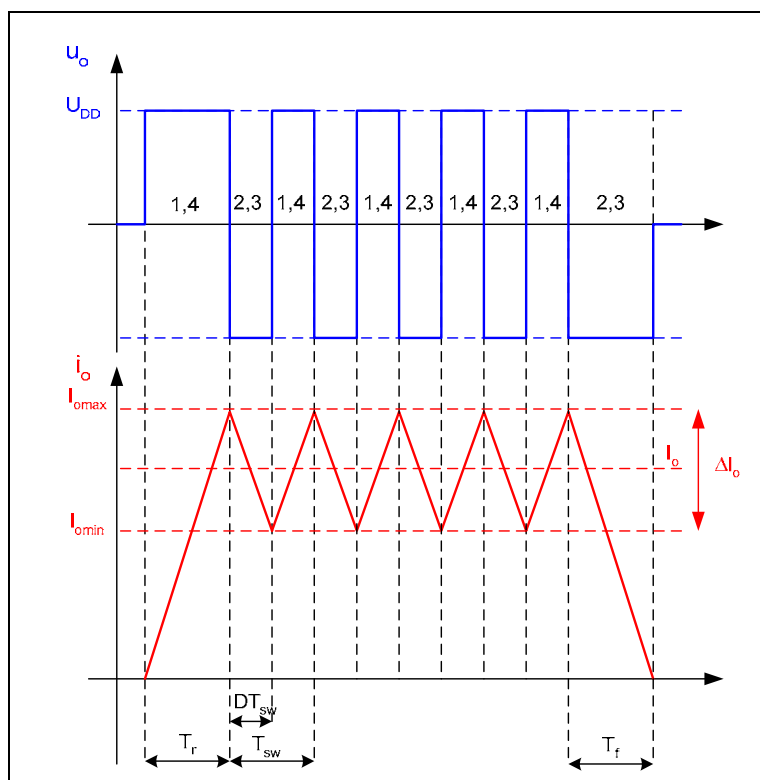


Figure 23 Switched reluctance motor drive – typical signals with bipolar PWM

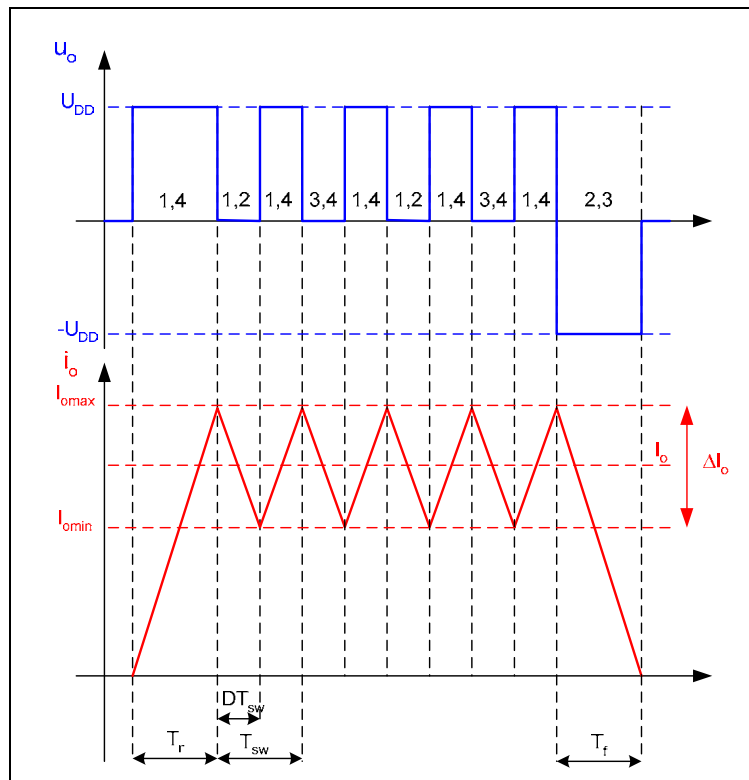


Figure 24 Switched reluctance motor drive – typical signals with unipolar PWM

3.6 Piezo-Electric Actuator

Figures 25 and 26 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 (MOSFET 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 (MOSFET 2 and Diode 1 are active).

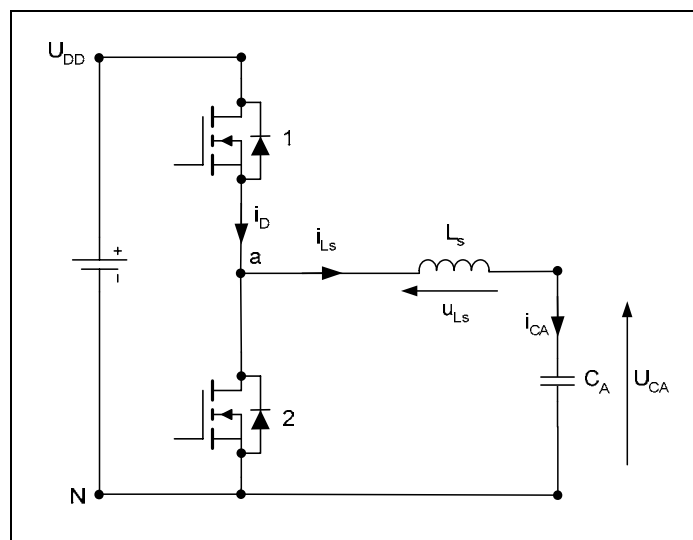


Figure 25 Two-quadrant converter for piezo-electric actuator

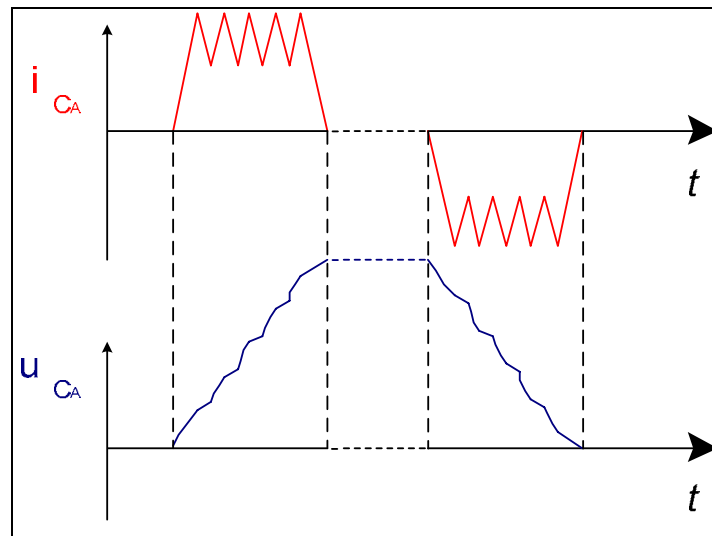


Figure 26 Converter for piezo-electric actuator – typical signals

4 Conclusion

This Application Note presented a mathematical tool for the calculation of power losses in MOSFET-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.

5 Abbreviations

P_I	Power losses
P_c	Conduction losses
P_{sw}	Switching losses
P_b	Blocking (leakage) losses
p_{CM}	Instantaneous value of the MOSFET conduction losses
P_{CM}	Average value of the MOSFET conduction losses
p_{CD}	Instantaneous value of the diode conduction losses
P_{CM}	Average value of the diode conduction losses
P_{swM}	MOSFET switching losses
P_{swD}	Diode switching losses
P_M	MOSFET losses
P_D	Diode losses
P_o	Converter output power
E_{onM}	MOSFET switch-on energy
E_{onMi}	MOSFET switch-on energy without taking the reverse recovery process into account
E_{onMrr}	MOSFET switch-on energy caused by the reverse-recovery of the free-wheeling diode
E_{onD}	Diode energy during MOSFET switch-on transient
E_{offM}	MOSFET switch-off energy
u_{DS}	Drain-source voltage
u_D	Voltage across the diode
u_{D0}	Diode on-state zero-current voltage
U_{Dr}	Driver output voltage
U_{GS}	Gate-source voltage
U_{GSth}	Gate-source threshold voltage
$U_{(plateau)}$	Plateau voltage
U_{Drr}	Voltage across the diode during reverse recovery
U_{DD}	Converter supply (DC bus) voltage
U_{in}	Converter input voltage
U_o	Converter output voltage
u_L	Voltage across the load
i_D	Drain current
I_{Drms}	RMS value of the drain current
i_F	Current through the diode
I_{Fav}	Average diode current
I_{Frms}	RMS value of the diode current
I_{rr}	Reverse recovery current
$I_{Frrpeak}$	Peak value of the diode reverse recovery current

I_G	Gate current
i_L	Load current
I_{in}	Converter input current
I_o	Converter output current
R_{DSon}	Drain source on-state resistance
R_D	Diode on-state resistance
R_G	Gate resistor
C_{GS}	Gate-source capacitance
C_{GD}	Gate-drain capacitance
C_{DS}	Drain-source capacitance
Q_{rr}	Reverse recovery charge
R	Load resistor
L	Load Inductance
T_j	Junction temperature
α	Temperature coefficient
T_{sw}	Switching period
f_{sw}	Switching frequency
t_{ri}	Current rise time
t_{fi}	Current fall time
t_{ru}	Voltage rise time
t_{fu}	Voltage fall time
t_{rr}	Reverse recovery time
D	Duty cycle

Edition 2006-07-31

**Published by Infineon Technologies AG,
Am Campeon 1-12,
85579 Neubiberg, Germany**

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