Figure of Merit of Semiconductor Structures

Determination of the impact on the system efficiency of LLC converter

Boris Kozacek, Michal Frivaldsky, Juraj Kostal, Marek Piri
Department of Mechatronics and Electronics, University of Zilina
Institute of Electrical Engineering ,University of Zilina
Zilina,Slovakia
michal.frivaldsky@fel.uniza.sk

Abstract – **This article has been realized in order to show simplified design procedure on how to meet the standards for dc-dc converters, which are being constantly increased. Hence we decided to analyze several generations of power semiconductor MOSFET and diode structures. With the use of simulation we've analyzed power losses (switching losses and conduction losses) during Zero Voltage Switching commutation mode. Parametric simulations were carried out at the conditions that meet electrical parameters of switched mode power supplies suited for distributed power systems. The aim of determination of switching losses at different conditions during ZVS mode is to see, whether determination of figure of merit (FOM) parameter can be considered as reliable indicator for proper device selection for target application. Consequently the FOM parameter for selected types of transistors and diodes in terms of several FOM methodologies has been determined. This parameter shall represent a measure of semiconductor suitability for high frequency power transistor application. The relevancy of FOM parameter will be finally evaluated in the way of efficiency (one of qualitative indicator) investigation of proposed LLC converter.**

Based on the evaluation of simulation analysis and on efficiency investigation of proposed LLC converter the confirmation of FOM relevancy will be confirmed.

Keywords-figure of merit; power losses; CoolMOS; GaN;efficiency; LLC converter

I. INTRODUCTION (HEADING 1)

Nowadays demand for efficiency and high density of electronic device is high. Therefore, great emphasis is placed on the properties of electronic components such as diodes, transistors, transformers and more. Hence the scientific discipline was created Figure of Merit (FOM) which is dealing with this issue.

FOM is numeric value representing power parameter of components and other important factors, which affect this parameter. The development of switching power supply significantly moved forward. Requested parameters of switched mode power supplies (SMPS) are reduction of the size and reduction of power losses (increase of efficiency). In this article we decided to analyse several methods of FOM for the power diodes and for the power MOSFET transistors.

In order to meet coming standards and normative, switching frequency continuously increases, because this step present one of the solution how to meet requirements and qualitative indexes of SMPS. Simultaneously it is important to minimize switching losses for example by zero current switching (ZCS) or zero voltage switching (ZVS). Due to these facts, we decided to investigate this parameter for soft switching converters that are using ZVS technique.

If we want to work with FOM method it's very important to know internal parasitic parameters.

Diodes have a parasitic components such as C_d in the forward direction, barrier capacity C_b in reverse direction, differential resistance r_d due to the influence of series resistance Rs, which forms together with the inductance L_s and the parasitic capacity C_p main element of the package of diode (Fig. 1). For SMPS the most important, or most critical parameters are capacitive charge Q_c and reverse recovery charge Q_{rr}. These parameter are limiting dynamic properties of diode structure, and hence utilization if high frequency operation.

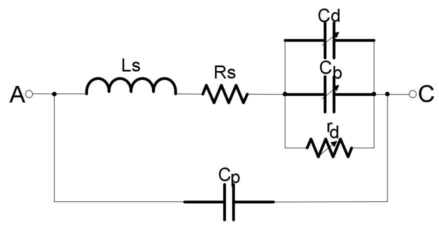

Figure 1. Diode with internal parasitic elements

MOSFET transistors, through unipolar structure, belong to the fastest power semiconductor component. Dynamic parameters are limited by internal parasitic components (Fig. 2). R_G is internal resistance of gate terminal, C_{GS} capacity of separate gate terminal from source electrode. This capacitance has constant value in full range of U_{GS}. Capacity C_{DS} is nonlinear and together with the parasitic inductance L_D and L_S creates resonant circuit which causes oscillation during turn-off process . The most important is C_{GD} capacity, also called Miller's capacity, which represents capacity of the space charge Q_{GD}. This value is heavily dependent from U_{DS}. Next very important parameter is resistance $R_{DS(ON)}$. This parameter defines the amount of conduction losses. The values of these parameters are given in components datasheets and are dependent on the internal structure of MOSFET and on its technology (manufacture).

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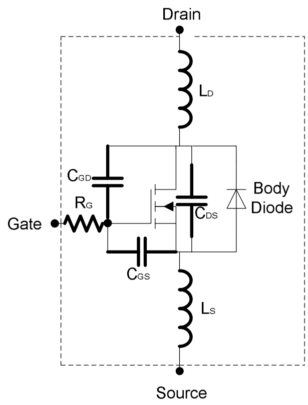

Figure 2. Transistor with internal parasitic elements

In this article we will further describe the different methods FOM evaluation which will be subsequently verified with the use of simulation analysis.

II. FoM for Diodes

A. Diode FoM

Power losses of the diode structure comprises from conduction losses and from switching losses. For their determination, the following equations are valid:

$$P_{loss(CON)} = I_D * V_F \quad (1)$$

$$P_{loss(SW)} = Q_{rr} * V_D * f_s \quad (2)$$

These equations are primary valid for Si diodes, where:

- I_D is continuous forward current of diode
- V_F is the forward voltage drop for diode,
- Q_{rr} is the reverse recovery charge for diode
- V_D is blocking voltage for diode and
- f_{sw} is switching frequency.

The equation for evaluation of FOM parameter for the Si diode is as follows:

$$FoM = Q_{rr} * V_F \quad (3)$$

SiC diodes are not defined with the reverse recovery parameter, and therefore FOM evaluation is not considered with Q_{rr} parameter. Instead of it, the capacitive charge Q_c comes into consideration, whereby its value is much smaller compared to Q_{rr}. Due to this, switching losses of SiC diodes shall be smaller[1]-[2].

Equations for the calculation FoM for the SiC diodes is follows:

$$FoM = Q_c * V_F \quad (4)$$

III. FoM for MOSFET Transistors

B. Detailed FoM for Hard-Switching

If it is necessary to evaluate the performance of the transistor, in terms of more precise choice, then more detailed information are needed where effect of turn-on, turn-off, conduction loss and loss due to gate excitation of transistor are considered (5).

$$P_{loss} = \frac{U_{in}.I_O}{2}.\frac{(Q_{GD}+Q_{GS}).R_G}{(U_{GS}-U_{PLT})}.f_{SW} + \frac{U_{in}.I_O}{2}.\frac{(Q_{GD}+Q_{GS})R_G}{U_{PLT}}.f_{SW} + I_O^2 R_{DS(ON)}.\frac{U_O}{U_{in}} + Q_G U_{GS} f_{SW} \quad (5)$$

, where

- U_{PLT} is leading voltage of gate drive,
- I_O is nominal value of current taken from datasheet
- f_{SW} is nominal switching frequency.

Furthermore, it is necessary to adopt new value namely excitation losses in gate circuit K_{GS} (6).

$$K_{GS}(U_{DR}) = 1 + \frac{U_{DR}}{U_{PLT} - U_{TH}}.\frac{2U_{PLT}(U_{DR} - U_{PLT})}{U_{IN} I_O R_G} \quad (6)$$

, where

- U_{DR} is value of excitation voltage
- U_{TH} is threshold voltage.

After that it is possible to calculate FOM parameter for hard switching commutation mode (7). Following equation considers with all parts of the power losses which are occurring during transistor switching [3] - [4].

$$FoM = (Q_{GD} + K_{GS}*Q_{GS})*R_{DS(ON)} \quad (7)$$

C. Detailed FoM for Soft-Switching

With the use of ZVS commutation mode it is possible to minimize turn-on loss of power transistors. In order to evaluate FOM for ZVS mode, the relation (5) shall be modified as follows[5]:

$$P_{loss\_ZVS} = \frac{U_{in}.I_O}{2}.\frac{(Q_{GD}+Q_{GS})R_G}{U_{PLT}}.f_{SW} + \frac{I_O^2}{n^2}.\frac{\pi^2}{4} R_{DS(ON)} + Q_G U_{GS} f_{SW} \quad (8)$$

To determine the parameter FOM for the ZVS it is necessary to introduce an additional variable, which represents gate drive losses:

$$K_{loss} = 1 + \frac{U_{GS}}{U_{PLT} - U_{TH}}.\frac{2U_{PLT}(U_{GS})}{U_{IN} I_{OFF} R_G} \quad (9)$$

, where I_{OFF} is current strength at the time off parts. The resulting relationship FoM for the ZVS technique is:

$$FoM = (Q_{GD} + K_{loss}*Q_{GS})*R_{DS(ON)} \quad (10)$$

IV. Evaluation of FOM of Selected Diodes and Transistors

FoM parameter selected diodes were calculated using eq. (3) for Si diode IDP15E65D1 to be reverse recovery and therefore envisaged Q_{rr} charge and eq. (4) for SiC diode IDH12G65C5, UJD06510T with no reverse recovery diode, and therefore only allows charge Qc[6]-[7].

TABLE I. Figure of Merit For Diode

	Qc[uC]	Qrr[uC]	Vf	FOM
IDP15E65D1		0,37	1,35	0,4995
IDH12G65C5_SiC	0,018		1,5	0,027
UJD06510T_SiC	0,016		1,5	0,024

The evaluation of selected transistors was done for hard-switching commutation mode, as well as for ZVS mode. Three different types were evaluated, whereby we focused on best in class transistors, which are nowadays available on the market. These are CoolMOS IPW60R165CP, CoolMOS, SPP20N60C3, and GaN EPC2027. As was already mentioned, if we need to evaluate selection of transistor more complexly, then it is necessary to consider also gate drive loss K_{GS} (6). This part becomes very important when very-high frequency operation is considered [8].

Table II shows datasheet values of parameters which are necessary for determination of K_{GS}. Next, based on (7) and (10) and based on the parameters of target application, the FOM_{HS} and FOM_{ZVS} were determined, and are listed in Table III.

The main electrical parameters of proposed SMPS in LLC topology, which is suited for distributed power systems, are:

- U_{INMAX} = 400 V, U_{INMIN} = 300V, U_{OUT} = 48 V
- P_{OUT} = 480 W, f_{SW} = 500 kHz

TABLE II. THE CIRCUIT AND TRANSISTOR PARAMETERS FOR FOM EVALUATION BASED ON METHODOLOGY C

	UTH[V]	UDR[V]	UPLT[V]	Io[A]	UIN[V]	RG[Ω]
IPW60R165CP	3	15	5	10	100	1,9
SPP20N60C3	3	15	5,5	10	100	0,54
EPC2027	1,4	15	2	10	100	0,4

TABLE III. FIGURE OF MERIT FOR HARD AND SOFT SWITCHING

	KGS	FOM	Kloss	FOM_ZVS
IPW60R165CP	1,39	3,83	1,59	4,09
SPP20N60C3	2,16	10,78	2,83	12,19
EPC2027	4,25	0,11	4,75	0,12

As can be seen, the lowest value of FOM parameter is for EPC2027 transistor (the lower the value is the better performance of transistor may be achieved). In next chapter, the investigation of switching performance for selected transistors will be shown. Here in this article we have focused just on simulation analysis of ZVS commutation mode. This is also due to fact that the relevancy of FOM parameter will be finally evaluated in the way of efficiency (one of qualitative indicator) investigation of proposed LLC converter.

The hard switching performance was already done, whereby detailed information can be seen at [9] [12].

V. SIMULATION ANALYSIS OF SOFT-SWITCHING COMMUTATION MODE FOR SELECTED MOSFET TRANSISTORS

The simulation analysis of ZVS commutation mode has been performed at the same circuit parameters as FOM was computed and as target application is defined.

The simulation analysis served for the analysis of dynamic properties during soft-switching of selected power transistors. GaN device represents new technology enhancement mode Galium Nitride device. CoolMOS transistors exhibit currently best in class performance for power applications (for example solar inverters, renewable energy, telecom/servers, front-end converters etc…). Selection of CoolMOS transistors shall point out current trend in the design and development of power semiconductor devices. Key electrical parameters of selected transistors are listed in table IV.

TABLE IV. PARAMETERS OF SELECTED TRANSISTORS

Parameter / transistor	**SPP20N60C3**	**IPW60R165CP**	**EPC2027**
U_{DS} [V]	650	650	450
I_D [A] 25°C	20	21	4
I_{Dpulse} [A] 25°C	62	61	12
P_{TOT} [W]	208	192	-
R_{DS} [Ω] 25°C	0.19	0.15	0,4
R_{DS} [Ω] 150°C	0.43	0.4	-
C_{ISS} [pF]	2400	2000	180
C_{OSS} [pF]	780	100	23
Qg [nC]	87	39	1,7
Q_{RR}[uC]	11	7,5	0
Q_{GS}[nC]	11	9	0,6
Q_{GD}[nC]	33	13	0.25

The simulation analysis for FOM evaluation has been realized at these parameters:

- U_{DC} = 400 V
- I_{load} = 1 - 10 A
- f_{sw} = 500 kHz

Principal schematic for the analysis is shown on fig. 3. The switching performance of SPP20N60C3 transistor is shown on fig. 4, where energy loss for one switching period is being shown (turn - on loss, conduction loss and turn – off loss).

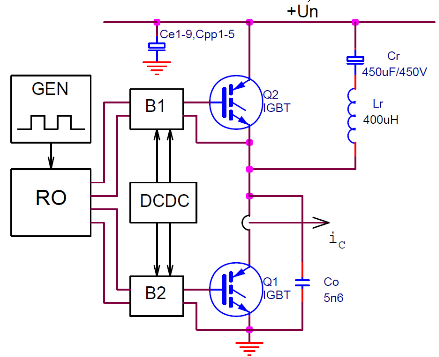

Figure 3. Principal schematics for measurement of transistor´s switching losses

As is being shown on fig. 4, the values for several parts of transistor’s power losses have been subtracted from the value of energy loss. The value of energy loss was consequently multiplied by the value of switching frequency. In this way, $P_{(on)}$, $P_{(off)}$ and $P_{(con)}$ have been determined [13] – [15].

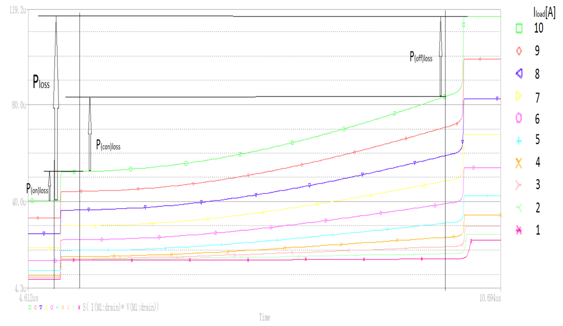

Figure 4. Energy loss for one switching period of SPP20N60C3 transistor

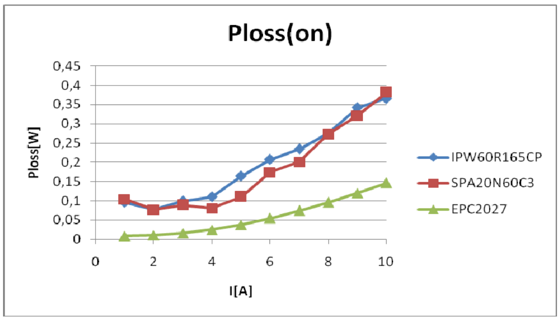

Figure 5. Turn-on losses in dependency on current flowing through transistor structure (RMS value)

Fig. 5 is showing graphical interpretation of the turn-on losses for all selected transistors in dependency on transistor's current. As we can see the smallest power loss has EPC2027. This is caused due to fact, that Q_{GS} is considerably smaller compared to the value of other transistors.

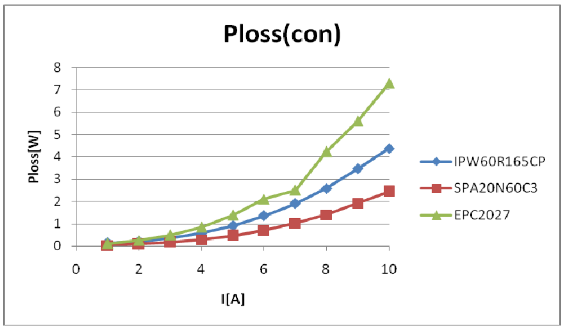

Figure 6. Conduction losses in dependency on current flowing through transistor structure (RMS value)

Significant difference is vissible when we compare the value of conduction losses (Fig. 6). Due to technology of EPC2027, whose Si MOSFET part is enriched with Galium Nitride element, the value of $R_{DS(ON)}$, which influences conduction losses is much higher compared to the technology of CoolMOS devices.

Fig. 7 is showing dependency of turn-off losses on transistor's current. The interesting is that the value of turn-off losses for EPC2027 has almost neglible dependency on the value of current.

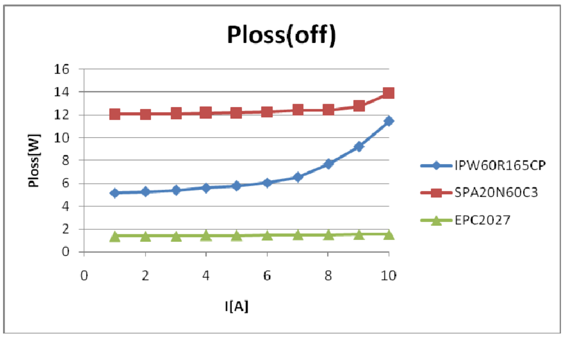

Figure 7. Turn-off losses in dependency on current flowing through transistor structure (RMS value)

The main parametrical difference for investigated devices can be noticed when Miller-Capacitance is investigated more in detail. The value of this capacitance and the voltage dependency of this is the lowest in the case of GaN (EPC2027). Almost due to this fact, the turn-off loss shows negligible dependency on the turn-off current of transistor.

Finally the evaluation of total losses from simulation analysis has been done (Fig. 8). Together with ZVS mode, also hard switching mode has been evaluated in order to see, how big the reduction of switching losses is. The comparisons between CoolMOS devices and GaN shows, that transistor EPC2027 acts as proper solution for SMPS, which must meet coming standards and normative (system efficiency)[16].

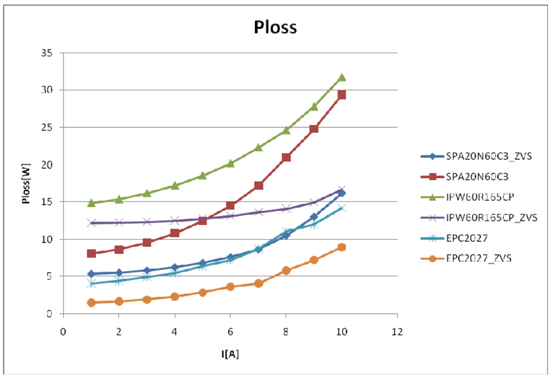

Figure 8. Compare total losses hard and soft (ZVS) switching for transistor structure (RMS value)

Based on previous results we can say, that continual improvement of quality of modern power supplies, can be done with the use of perspective power semiconductor devices. Simulation analysis validated, that FOM evaluation can be used as a merit for proper selection of semiconductor structure for dedicated application,. Because the research and development process must be continuously accelerated (due to market requirements), the FOM methodology seems to be very valuable and perspective procedure for transistor's as well as for diode's quality evaluation.

In next chapter, the confirmation of FOM evaluation for diodes, as well as for transistors will be performed in the way of efficiency determination of proposed LLC converter, where individual parts will be sequentially utilized.

VI. EFFICIENCY INVESTIGATION OF PROPOSED LLC CONVERTER

The efficiency of LLC converter using diodes and transistors is compared in this section. The aim of this study is to confirm the FOM method, where the structures with the lowest FOM value are expected to improve efficiency of proposed converter in the whole regulation range[17]-[18]. Comparison of the efficiency was realized on the converter using ZVS technique and its parameters were as follows:

- Uin = 400V
- Uout = 48 V
- Iout = 20 A
- fsw = 1 MHz

A. *Comparison of the efficiency LLC converter using selected transistors*

The best efficiency of LLC converter was investigated depending on the changes of transistors, whereas the SiC diodes UJD06510T were used on the secondary side of converter.

When using a transistor EPC 2027, the simulation model reached the highest values of efficiency and output power as it can be seen in Figure 9. As confirmed by the analysis of losses, this transistor had the smallest conductivity and switching losses depending on the current I_D. This was also confirmed by the analysis of the FOM, in which the transistor showed lower values in comparison with other types of transistors and the values of parameters FOM are changing minimally with increasing current I_D, and temperature. Based on simulation results, it can be evaluated that the transistors made of GaN are the best choice in terms of efficiency and amount of losses.

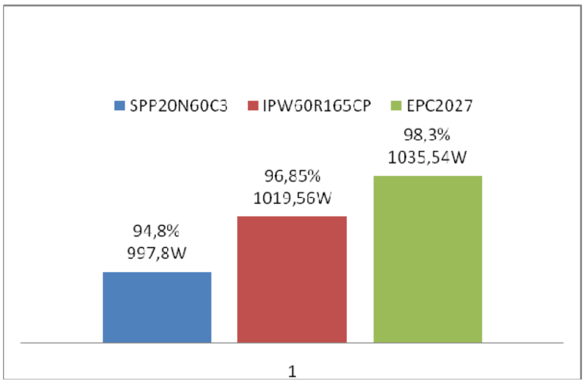

Figure 9. Power output of LLC converter using different switching transistors

B. *Comparison the efficiency of LLC converter using selected diodes*

Selected models of semiconductor diodes were used in the simulation model of LLC converter as rectifier diodes on the secondary side. The selection of suitable types of diodes is expected to improve the efficiency of converter and to reduce the losses on the secondary side.

The simulation analysis shows the influence of the diodes on the efficiency and amount of output performance on simulation model of LLC converter. When using a SiC diode UJD06510T, the converter gained the best output parameters. The validity of the analysis of the FOM parameter, Qrr and switching losses was also confirmed, as this diode obtained the best results.

Silicon diode IDP15E65D1 most significantly influenced the output parameters. The efficiency of converter was decreased the most compared to the previous diode. Figure 10. shows graphical comparison of the influence of three diodes used on the efficiency and power output of the LLC converter simulation model.

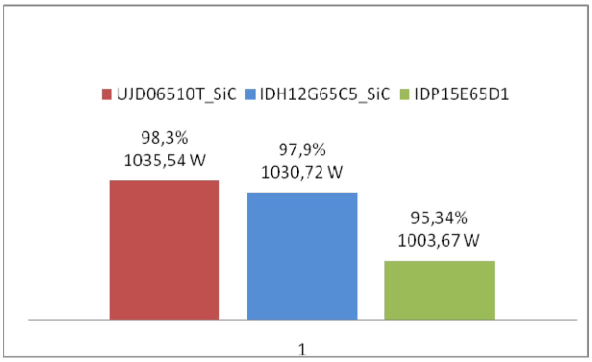

Figure 10. Effect of selected rectifier diodes on efficiency and power output of simulation model of LLC converter.

VII. CONCLUSION

The main aim of this paper was the confirmation of FOM methodologies for the evaluation of the quality of power transistors from “efficiency” point of view. For this purposes simulation analysis of soft-switching commutation mode for several generations of MOSFET transistors was provided with the use of OrCAD Cadence 16.6. Just this software dispose with very exact a precisely made simulation models of power transistors, including necessary physical and electro-thermal processes. For selected electrical parameters, the evaluation of switching and conduction losses was done for all of selected transistors (IPW60R165CP, SPP20N60C3, EPC2027). Consequently the calculation of FOM based on presented methodologies (A-C) was done. The value of FOM is a power merit of devices, whose value indicates quality of semiconductor device. The lower this value is, the better the performance shall be. After comparisons between simulation results and results from FOM calculation, it can be said, that FOM methodologies presents very perspective solution for the selection of proper power device for selected power application.

ACKNOWLEDGMENT

The authors wish to thank to Slovak grant agency VEGA for project no. 1/0558/14 - Research of methodology for optimization of lifetime of critical components in perspective electronic appliances through the use of system level simulation.

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