Evaluation method Figure of Merit for semiconductors and magnetics components and impact on the switching power supply efficiency

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Abstract - The paper deals with FoM parameter analysis of power semiconductor system’s components. This parameter can be used as optimization tool of quality indicators for power supply systems. The main advantage of using FoM assessment technique for certain system’s components is the elimination of simulation and physical experiments for effectiveness evaluation, how as was confirmed in the paper[1]. This paper consist of description of FoM assessment process for perspective converter structures as GaN and SiC for various working conditions and the appropriateness of using this method is also verified by simulation experiments on models with high degree of validity. FoM parameter is finally evaluated in the way of efficiency investigation of proposed LLC converter, where also different materials of core transformers 3F4, 3F45 have been verified, as well as their influence on the efficiency.

Keywords
Figure of Merit, FoM, power losses, GaN, SiC, LLC converter, magnetics materials

1. Introduction

Demands on high efficiency and power density of electrical devices have been lately extremely high. This is the reason why electronic components such as diodes, transistors and transformers are accentuated and why there was set the scientific discipline Figure of Merit (FoM) dealing with this problematics. FoM is in fact the non-dimensional quantity which serves as the qualitative indicator for electrical components: the lower the resulting FoM value is, the better is the qualitative parameter of a transistor [1]-[3].

One of the ways how to increase the qualitative parameters of power semiconductor system is the choice of optimal semiconductor components. Another very important step to properties’ enhancement of a power semiconductor converter is the appropriate choice of magnetic materials and other components [4]-[7]. This paper deals with several ways that can be used to choose the optimal semiconductor components and a high-frequency transformer, which would be suited for standards specifications given for quality indicators of power supply. For that reason it is necessary to choose the appropriate material which would be the transformer made of. For that purpose several magnetic materials used for transformers operating in high switching frequencies are analysed.

Using the techniques mentioned above, it is possible to design switched mode power supplies (SMPS) with perspective converter’s structure LLC, which would be suited to upcoming standard specifications called ENERGY STAR.

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

- $U_{IN} = 390\text{V}$
- $U_{OUT} = 48\text{V}$
- $I_{OUT} = 20\text{A}$
- $f_{SW} = 1\text{MHz}$

2. FoM for diodes

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

$$P_{\text{loss(CON)}} = I_D \times V_F \quad (1)$$
$$P_{\text{loss(SW)}} = Q_{rr} \times V_D \times f_s \quad (2)$$

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:

$$\text{FoM} = Q_n \cdot V_F$$

(3)

SiC diodes are not defined with the reverse recovery parameter and therefore the FoM evaluation is not considered with $Q_n$ parameter. Instead of that, the capacitive charge $Q_c$ comes into consideration, whereby its value is much smaller compared to $Q_n$. Due to this fact, switching losses of SiC diodes should be smaller [8]-[9].

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

$$\text{FoM} = Q_c \cdot V_F$$

(4)

3. FoM for MOSFETR transistors

3.1 Detailed FoM for hard-switching

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

$$p_{loss} = \frac{1}{2} \left( \frac{Q_{GD} + Q_{DS}}{V_{DS} - V_{DS(on)}} \right) f_{sw} + \frac{1}{2} \left( \frac{Q_{DS} + Q_{DS(on)}}{V_{DS} - V_{DS(on)}} \right) f_{sw} + \frac{1}{2} R_{DS(on)} I_{DS} + Q_c V_F$$

(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 values, namely excitation losses in gate circuit $K_{GS}$ (6).

$$K_{GS}(U_{DS}) = 1 + \frac{U_{DS}}{U_{PLT} - U_{TH}} - \frac{2 U_{PLT} (U_{DS} - U_{TH})}{U_{TH} I_o R_G}$$

(6)

, where

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

After that it is possible to calculate FoM parameter for hard-switching commutation mode (see equation (7)). The equation considers all the powers losses which occur during transistor switching [10] - [11].

$$\text{FoM} = (Q_{GD} + K_{GS}^* Q_{GS})^* R_{DS(on)}$$

(7)

3.2 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 equation (5) should be modified as follows:

$$p_{loss,ZVS} = \frac{1}{2} \left( \frac{Q_{GD} + Q_{DS}}{V_{DS} - V_{DS(on)}} \right) f_{sw} + \frac{1}{2} R_{DS(on)} I_{DS} + Q_c V_F$$

(8)

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

$$K_{loss} = 1 + \frac{U_{GS}}{U_{PLT} - U_{TH}} - \frac{2 U_{PLT} (U_{GS})}{U_{TH} I_{off} R_G}$$

(9)

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

$$\text{FoM} = (Q_{GD} + K_{loss}^* Q_{GS})^* R_{DS(on)}$$

(10)

4. FoM procedure for selection of magnetic material

When evaluating FoM analysis and choosing the appropriate material suitable for chosen application field, the parameters introduced in table below should be taken into consideration.

<table>
<thead>
<tr>
<th>Material</th>
<th>$B_{sat}$ (mT)</th>
<th>$\mu_i$</th>
<th>$p$ (Ω.m)</th>
<th>$T_c$ (°C)</th>
<th>Thermal conductivity (W/(m.K))</th>
<th>Frequency range (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3F3(MnZn)</td>
<td>440</td>
<td>2000</td>
<td>2</td>
<td>&gt;200</td>
<td>3.5~5</td>
<td>0.1-0.5</td>
</tr>
<tr>
<td>3F35</td>
<td>500</td>
<td>1400</td>
<td>10</td>
<td>&gt;240</td>
<td>3.5~5</td>
<td>0.5-1</td>
</tr>
<tr>
<td>3F4(MnZn)</td>
<td>410</td>
<td>900</td>
<td>10</td>
<td>&gt;220</td>
<td>3.5~5</td>
<td>1.2</td>
</tr>
<tr>
<td>3F45(MnZn)</td>
<td>420</td>
<td>900</td>
<td>10</td>
<td>&gt;300</td>
<td>3.5~5</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Tab. 1. Parameters for different materials

where

- $B_{sat}$ is saturation induction
- $\mu_i$ is initial permeability
- $p$ is the electrical resistance
- $T_c$ is the Curie temperature

Based on the values form the table above, several materials appropriate for frequency range 1MHz were chosen and for comparison of materials development for transformers operating under high switching frequencies the material 3F3 was also chosen.

Dependence of saturation induction from frequency and temperature for materials 3F3-3F45 can be seen from characteristics of selected materials in datasheets. The higher the operating frequency, the lower the value of saturation induction and the value of core losses does not change considerably. Recommended value of value losses is about 100kW/m³.
Let’s consider the core’s temperature about 60°C, which indicates that the value of maximal saturation induction is $B_{\text{max}} = 14\, \text{mT}$, and in case of double-acting converters the induction rise is $\Delta B = 28\, \text{mT}$. As it can be seen in Fig. 1, for the same value of $\Delta B = 28\, \text{mT}$ are the volume losses for material 3F45 much lower comparing to all other generations of materials. This assumes, that this material will be the most appropriate one from the point of view of improving the qualitative indicators of power supplies.

In Fig. 2 the FoM parameter of ferrite materials can be seen. It is represented by multiplication of operating frequency and saturation induction. When comparing, it is obvious that the most optimal choice for parameters of objective application are the materials 3F4 and 3F45. Materials 3F5 and 4F1 are not satisfying.

### 5. Evaluation of FoM of selected diodes and transistors

FoM parameter of selected diodes was calculated using eq. (3) for Si diode IDP15E65D1 with reverse recovery and therefore with envisaged $Q_r$ charge and eq. (4) for SiC diode IDH12G65C5, UJD06510T with no reverse recovery diode, and therefore only charge $Q_c$ was allowed [12].

<table>
<thead>
<tr>
<th>Material</th>
<th>$Q_c$ [uC]</th>
<th>$Q_r$ [uC]</th>
<th>$V_f$</th>
<th>FoM</th>
</tr>
</thead>
<tbody>
<tr>
<td>IDP15E65D1</td>
<td>0,37</td>
<td>1,35</td>
<td>0,4995</td>
<td></td>
</tr>
<tr>
<td>IDH12G65C5_SiC</td>
<td>0,018</td>
<td>1,5</td>
<td>0,027</td>
<td></td>
</tr>
<tr>
<td>UJD06510T_SiC</td>
<td>0,016</td>
<td>1,5</td>
<td>0,024</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3. FoM evaluation for diodes

Figure 4 shows switching losses on diodes during load changes – this confirms the FoM prediction which assumed the lowest power losses at SiC diode UJD12G65 and the highest losses at Si diode IDP15E65D1 for frequency 1MHz. During the maximal load $I_{\text{load}} = 20\, \text{A}$ is the difference of power losses between IDP15E65D1 and UJD12G65 more than 10W.
The evaluation of selected transistors was done for zero-voltage commutation mode due to the fact that at considered LLC topologies the ZVS technique was applied. Several different types were evaluated, with focus on the best-class transistors now available on the market. Such transistors are CoolMOS IPW60R165CP, SPP20N60C3, perspective GaN transistors from two manufactures and SiC transistors 2N7638-GA. As it is mentioned above, if a selection of transistor needs to be evaluated more complexly, then it is necessary to consider also gate drive loss $K_{GS}$ (6) for hard switching and $K_{loss}$ for soft switching. This part becomes quite important when very-high frequency operation is considered [13]-[15].

Based on relations (7) and (10) and based on the parameters of objective application, the FoMs and FoM$_{ZVS}$ were determined, and are listed in Table II.

<table>
<thead>
<tr>
<th>Transistor</th>
<th>$K_{GS}$</th>
<th>$K_{loss}$</th>
<th>FoM$_{ZVS}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IPW60R165CP</td>
<td>1,098</td>
<td>1,013</td>
<td>3,317</td>
</tr>
<tr>
<td>SPP20N60C3</td>
<td>1,290</td>
<td>1,203</td>
<td>8,785</td>
</tr>
<tr>
<td>2N7638-GA</td>
<td>1,250</td>
<td>1,033</td>
<td>5,332</td>
</tr>
<tr>
<td>EPC2027</td>
<td>1,177</td>
<td>1,090</td>
<td>0,361</td>
</tr>
<tr>
<td>GS66506T</td>
<td>1,128</td>
<td>1,071</td>
<td>0,239</td>
</tr>
<tr>
<td>GS66508T</td>
<td>1,128</td>
<td>1,02</td>
<td>0,232</td>
</tr>
<tr>
<td>GS66508P</td>
<td>1,128</td>
<td>1,071</td>
<td>0,241</td>
</tr>
</tbody>
</table>

As it can be seen, the lowest value of FoM parameter is for GS66506T transistor (the lower the value is, the better performance of transistor may be achieved). In order to verify this claiming, the power losses for all types of transistors with increasing current load were counted. Following parameters were used:

$$U_{in} = 400 \text{ V} \quad I_{load} = 1-10 \text{ A} \quad f_{SW} = 1\text{MHz} \quad U_{GS} = 10\text{V}$$

As it can be seen in Fig. 5, GaN transistors have the lowest power losses for soft switching, which confirms the fact, that FoM parameter is the relevant pointer of effective components choice.

6. Core loss determination of selected magnetic materials

Before the evaluation of core losses, it is necessary to choose the specific type of core which would be suited for designed LLC converter. The converter parameters are as follows:

$$U_{IN} = 85-265\text{VAC}, U_{IN} =390\text{VDC} \text{ (output from PFC)}$$

$$U_{OUT}= 48\text{V} \quad I_{OUT} = 20\text{A} \quad P_{OUT} = 1\text{kW} \quad f_{SW} = 1\text{MHz} \quad D=0,5$$

The minimal area of a core $A_F$ for $\Delta B = 28\text{mT}$ was counted:

$$A_F = \frac{(2\pi \times 28)^2}{L_{E=0.5}} = \frac{2 \times 19 \times 28}{0.019} = 1,195 \times 10^{-8} \text{m}^4 = 11950\text{mm}^4$$

This condition satisfies the core EQ38/8/25 (chosen from the producers’ catalogue) with effective volume 7.9 cm$^3$, which can be made of all selected materials. After this, the core losses depending on the type of material used should be analysed. Following value of power losses in core (for volume in cm$^3$) are given in datasheets.

$$K_{fe3F3}=9\text{W/cm}^3 \quad K_{fe3F3}=3\text{W/cm}^3$$

$$K_{fe3F4}=0,1\text{W/cm}^3 \quad K_{fe3F4}=0,06\text{W/cm}^3$$

It is obvious that the highest losses in core for material 3F3 are much higher than preferred material 3F45. Next section verifies this claiming by simulation model, where the material of core of transformer is changed in designed converter.

7. Efficiency investigation of proposed LL converter

A simulation LLC model with above mentioned parameters and with various materials of core of transformer was constructed and the efficiency of the converter was analysed when changing the material of core. This should show that type of magnetic material as
well as the shape of core significantly influence the qualitative parameters of converters.

In order to compare the efficiency with analysed materials, first the core with ideal coupling $K_{\text{linear}} = 1$. As it can be seen in Fig. 6, the converter gains relatively high efficiency and the most similar to this value is the core with material 3F45, so this one is considered to be the best alternative for core of transformer. In order to compare the converter’s efficiencies following components were used: CoolMOS transistors IPW60R165CP and on the secondary side power SiC shottky’s diodes with small conduction and switching losses.

![Fig. 6. Converters efficiency for various materials of core of transformer](image)

### 8. Conclusion

Aim of this paper was to summarize the important knowledge for possibility of increasing the qualitative parameters of switching power supplies for front-end DC/DC converters. Selected components underwent the FoM analysis and their appropriateness for certain objective application was compared. The simulation and analytical results confirmed the significant progress of GaN technology in case of switching components. This technology minimizes the values of parasitic elements and is suitable for high switching frequencies as well as it decreases the power losses up to 70%. Other task was to compare the diodes with silicon structure and silicon carbide. In this case we found out that the SiC diodes do not have reverse recovery and so their power losses are lower approximately about 50% depending on the current load. Further analysis aimed to proper selection of core material for transformer. A huge progression of novel materials was found out – such materials are for example 3F4, 3F45 with suitable properties for higher performance and frequency.

All this technical knowledge was also verified at simulation model of LLC converter, using SiC diodes on secondary side. The efficiency of transformer was measured when changing the materials of its core and so we confirmed, that with magnetic materials 3F4 and 3F45 the converter suits the upcoming standard specifications ENERGY STAR.

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### References

[1] B. Kozacek, M. Frivaldsky, J. Kostal, M. Piri, “Figure of Merit of Semiconductor Structures, Determination of impact on the system efficiency of LLC converter” 20th International Conference : Czech Republic, September 8-10, 2015


BORIS KOZACEK, EVALUATION METHOD FIGURE OF MERIT FOR SEMICONDUCTORS AND MAGNETICS COMPONENTS AND IMPACT ON THE SWITCHING POWER SUPPLY EFFICIENCY


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