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A COMPARATIVE STUDY ON SILICON CARBIDE MOSFET AND IGBT SWITCHING LOSSES USING WAVELET

[1]Vijay Patil, [2]Prof.A.M.Mulla

[1]Research Scholar, [2]Principal
[1]Electrical Engineering Department,
[1]Shivaji University, Kolhapur, Maharashtra, India
[2]Electrical Engineering Department,
[2]Dr. Daulatrao Aher College of Engineering, Karad, Maharashtra, India

Abstract: Switching loss calculation in IGBT and Silicon Carbide *(*SiC*)* MOSFET requires device parameters like turn-on and turn-off time, input and output capacitances, parasitic inductances and circuit parameters like voltage, current and operating frequency. Using these parameters switching loss is calculated with given approximate mathematical formulae. This paper presents a wavelet based method for switching loss calculation. It requires only the voltage and current waveforms during switching and calculates the power loss and also provides the frequency content during switching. The information regarding frequency content can be utilized for designing snubber as well as for EMI analysis. Multi Resolution Analysis (MRA) is used to decompose signals in wavelet domain and the signals are transformed in different frequency bands. The power is calculated in each band by multiplication of current and voltage wavelet coefficients. Simulation are presented for both Silicon Carbide MOSFET and IGBT with inductive load and a comparative study of the obtained output are analyzed.

***Index Terms* – MOSFET, IGBT, multi resolution analysis, switching power loss, wavelets, simulink.**

I. INTRODUCTION

The switching loss of power Silicon Carbide *(*SiC*)* MOSFETs and IGBTs becomes a dominant factor in the total power loss of power electronics converters when the switching frequency is increased to improve dynamic performance and reduce size. A simple yet reasonably accurate method of estimating power MOSFET switching losses using device datasheet information is highly desirable for predicting maximum junction temperatures and overall power converter efficiencies. However, the complex switching behavior and switching losses of a power are difficult to model analytically due to the nonlinear characteristics of Silicon Carbide *(*SiC*)* MOSFET and IGBT parasitic capacitances.

Currently, the silicon-based metal-oxide-semiconductor field-effect transistor (MOSFET) is the preferred semiconductor device in low to medium-powered high-frequency power processing applications. This kind of transistor represents one of the major sources of power losses and heating in such applications often requiring a proper cooling system to be integrated into the static converter. According to the tendency of higher switching frequencies of such converters, device switching losses need to be very well modelled in order to achieve a good quality design [1].

Loss modelling methods can be categorized into three main types for these devices, starting with the simplest analytical models, SPICE-based models and then moving to the more complex physical-modelling realm [2]. The estimation or calculation of the switching losses in power Silicon Carbide *(*SiC*)* MOSFETs and IGBTs has been a major matter of investigation in the technical literature, although it is not yet a consolidated subject, mainly because of the inaccuracy or complexity of some methods. This topic is important because a more accurate assessment regarding such losses may reduce the design and optimization time of a power converter without the need to build various prototypes for experimental comparison [3]. Considering that the analytical methods of switching losses usually present low accuracy, several works have been proposed in the technical literature to improve the key issues on the matter, namely simulation time, computational effort and accuracy [4, 5].

II. LITERATURE REVIEW

Transeint nature of voltage and current during switching instants of solid state devices like Silicon Carbide *(*SiC*)* MOSFETs and IGBTs makes it difficult to calculate the switching power loss with conventional mathematical models. Various methods of switching power loss have been proposed in literature.

Z. John Shen et.al.[6] investigate the internal physics of Silicon Carbide *(*SiC*)* MOSFET switching processes using a physically based semiconductor device modeling approach, and subsequently examines the existing switching loss estimation method based on the new physical insight. They also claim that in calculation of losses the output capacitance loss term is redundant and erroneous.

Yuming Bai et.al.[7] calculate the losses taking into account the effect of parasitic like L_s and derive the expression for drain to source voltage V_{ds} which includes the inductance L_s. The power loss is calculated by taking the integral of the product of drain to source voltage and drain current over the period of interest.

E. Hiraki et.al.[8] discuss the switching power loss analysis with a feasible power loss analysis simulator. It makes use of feasible switching loss data- based table accumulated from the measured transient switching operation and periodic steady state conduction voltage and current operating waveforms of semiconductor switching devices used in power electronic converters.

J.S. Lai et.al.[9] utilize well established mathematical formulae based on voltage and current ratings, device parameters and switching frequency.

Cavalcanti et.al.[10] propose energy based second order polynomial equation which takes into account the parameter variations, such as temperature for power loss calculation. These methods are based upon device parameter like input and output capacitances, parasitic inductance of the Silicon Carbide (SiC) MOSFETS and their physical modeling. In these calculations information regarding the snubber to be added in the practical circuits, their losses and also the oscillation during transients due to parasitic is not mentioned. Also, information regarding frequency content is missing in all the above mentioned loss analysis, which is useful for snubber design and analysis of EMI during switching. Wavelet is being used for transient analysis and wide range of frequency contents in it.

Heydt et.al.[11] analyzed wavelet transform application for transient signal with its advantages and disadvantages. L.J. Driesen et.al. [12] have quantified transient power by complex wavelet transform. E.Y. Hamid et.al. [13] provide a theoretical basis of using wavelet packet transform for power measurement in different frequency bands.

III. PROPOSED SYSTEM

This paper proposes the wavelet based method for switching power loss calculation. The proposed method calculates the power loss with accuracy as compared to the simple integration method and also gives information about the frequency content of voltage and current waveforms during transients. Multi resolution analysis using wavelets, makes it possible to identify and locate the frequency content of these transients. Multi resolution analysis is used to decompose signals in wavelet domain. The voltage and current signals are transformed in different frequency bands which accommodate transient frequencies. The power is calculated in each frequency band by multiplication of current and voltage wavelet coefficients. The total power is sum of all the sub band power.

3.1 Clamped Inductive Load Circuit

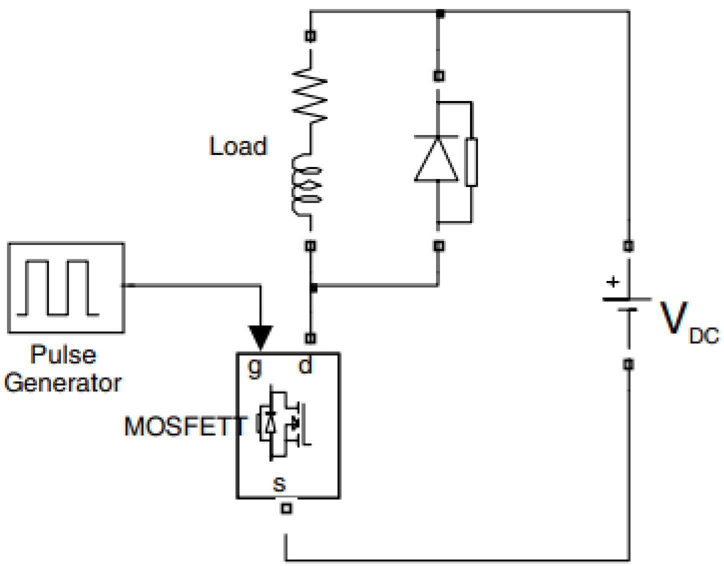

Fig.1. Clamped Inductive load circuit

Fig.1 shows the inductive load circuit for Silicon Carbide (SiC) MOSFET under test.There is no switching loss during Silicon Carbide (SiC) MOSFET turn off transition due to substantial output capacitance c_{ds} of the Silicon Carbide (SiC) MOSFET. This capacitance holds the voltage v(t) close to zero while the Silicon Carbide (SiC) MOSFET turns off. However, when the Silicon Carbide (SiC) MOSFET, induced by diode reverse recovery and by output capacitances of Silicon Carbide (SiC) MOSFET and diode. Significant ringing is observed in the MOSFET voltage waveform when substantial inductance is present in series with the Silicon Carbide (SiC) MOSFET. The ringing caused by these inductances is visible in the Silicon Carbide (SiC) MOSFET voltage and current. The method proposed takes into account all these effects and calculates the power loss depending upon the actual waveforms in the Silicon Carbide (SiC) MOSFET.

3.2 Simulation Parameters

Table 1 Simulation Parameters

Parameters	**Values**
V_{DC}	400V
Load	40 ohm in series with 0.5µH
C_{ds}	380pF
C_{gs}	2260pF
C_{ds}	340pF
f_s	200kHz
C_s	0.1nF
Snubber Resistance	50 ohm
Snubber Inductance	231nH

3.3 Wavelet Transform

The wavelet series representation of the signal f(x) is given by:

$$f(x) = \sum_k c_{N,k}\phi_{N,k}(x) + \sum_{m=1}^{N}\sum_k d_{m,k}\psi_{m,k}(x) \quad \ldots (1)$$

$$c_{m,k} = \sum_k f(x)\bar{\phi}_{m,k}(x) \quad \ldots (2)$$

$$d_{m,k} = \sum_k f(x)\bar{\psi}_{m,k}(x) \quad \ldots (3)$$

where $\bar{\phi}$ (x) and $\bar{\psi}$ (x) are the conjugate functions corresponding to scaling function ϕ(x) and mother wavelet ψ(x), respectively. $c_{m,k}$ and $d_{m,k}$ are approximate and detail component of signal f(x) respectively. The filter coefficients are found by solving dilation equation given as:

$$\phi(x) = \sqrt{2}\sum_{n=-\infty} h_n \phi(2x-n), \qquad x \in R \quad \ldots (4)$$

where h_n is filter coefficients of the scaling function $\phi(x)$. The mother wavelet filter coefficients are found by solving wavelet equation:

$$\psi(x) = \sqrt{2}\sum_{n=-\infty} g_n \phi(2x-n) \quad \ldots (5)$$

where g_n is filter coefficients of the mother wavelet function $\psi(x)$.

The filter coefficients for orthogonal wavelet transforms are related by given equation:

$$g(k) = (-1)^k \bar{h}(1-k) \quad \ldots (6)$$

The multi resolution concept forms the basis of a mathematical framework for wavelets. One can decompose a function f(x) into coarse version $c_{m,k}$ plus a residual $d_{m,k}$ and then iterate this to infinity as shown in Fig.2 for one scale of decomposition If properly done, this can be seen that a wavelet transform decomposes a signal f(x) into trends and detail coefficients. Fig.3 shows the spectrum of multi resolution analysis of signal. $\psi_1 - \psi_4$ represent spectrum of different mother wavelet dilation.

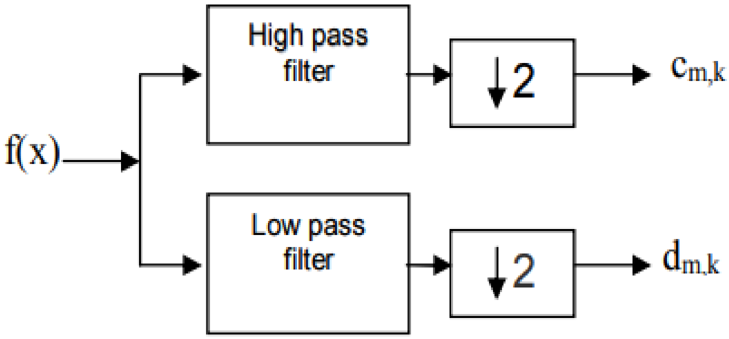

Fig.2. One level decomposition of signal f(x)

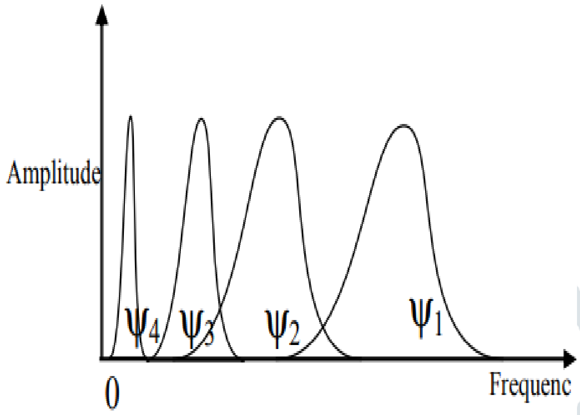

Fig.3. Spectrum of multi resolution Analysis

3.4 Power Measurement

The transient power is measure by concurrent value of voltage and current. The voltage and current can be represented by wavelet basis function as shown in equation:

$$i(t)=\sum_{k} c_{N,k}\phi_{N,k}(t)+\sum_{m=1}^{N}\sum_{k} d_{m,k}\psi_{m,k}(t) \quad \text{.......(7)}$$

$$v(t)=\sum_{k} c'_{N,k}\phi_{N,k}(t)+\sum_{m=1}^{N}\sum_{k} d'_{m,k}\psi_{m,k}(t) \quad \text{.......(8)}$$

where

$$c_{m,k}=\sum_{k} i(t)\bar{\phi}_{m,k}(t) \text{ and } d_{m,k}=\sum_{k} i(t)\bar{\psi}_{m,k}(t)$$

$$c'_{m,k}=\sum_{k} v(t)\bar{\phi}_{m,k}(t) \text{ and } d'_{m,k}=\sum_{k} v(t)\bar{\psi}_{m,k}(t)$$

The power is calculated as an averaged sum of the power transfer over transient period:

$$P=\frac{1}{T}\int v(t).i(t)dt = P_{j,0}+\sum_{j\ge j_0}^{N-1} P_j$$

$$=\frac{1}{2^N}\left(\sum c_{j_0,k}c'_{j_0,k}+\sum\sum d_{j,k}d'_{j,k}\right) \quad \text{.......(9)}$$

IV. Simulation Results and Discussions

To verify the accuracy of the method proposed, analysis of power measurement using instantaneous values of voltage and current, power measured by Simulink block and power measured by wavelets has been carried out on simulated waveform. Fig.4 and Fig.5 shows the Simulink block used for power calculation of Silicon Carbide *(*SiC*)* MOSFET and IGBTs.

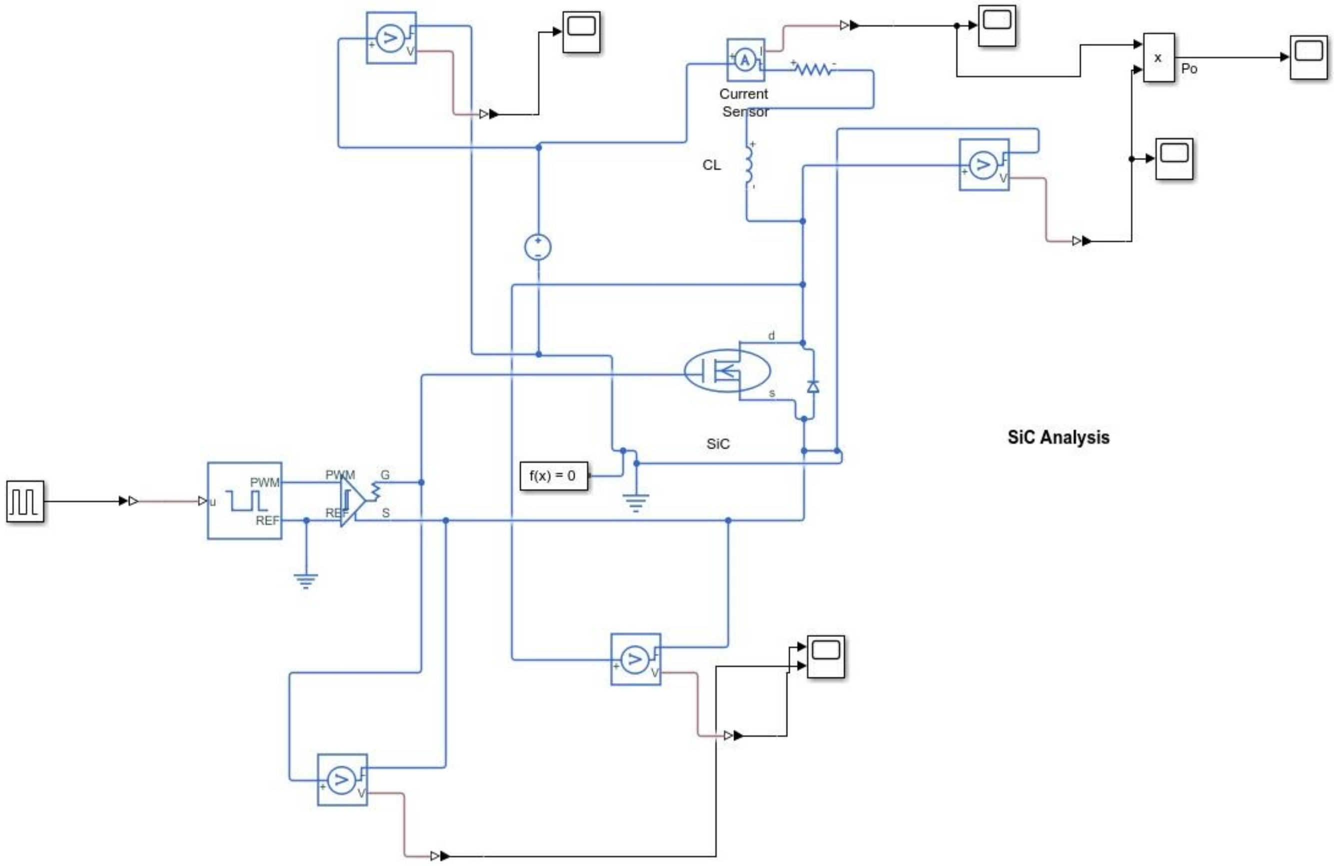

Fig.4. Simulink block for power measurement using Silicon Carbide *(*SiC*)* MOSFET

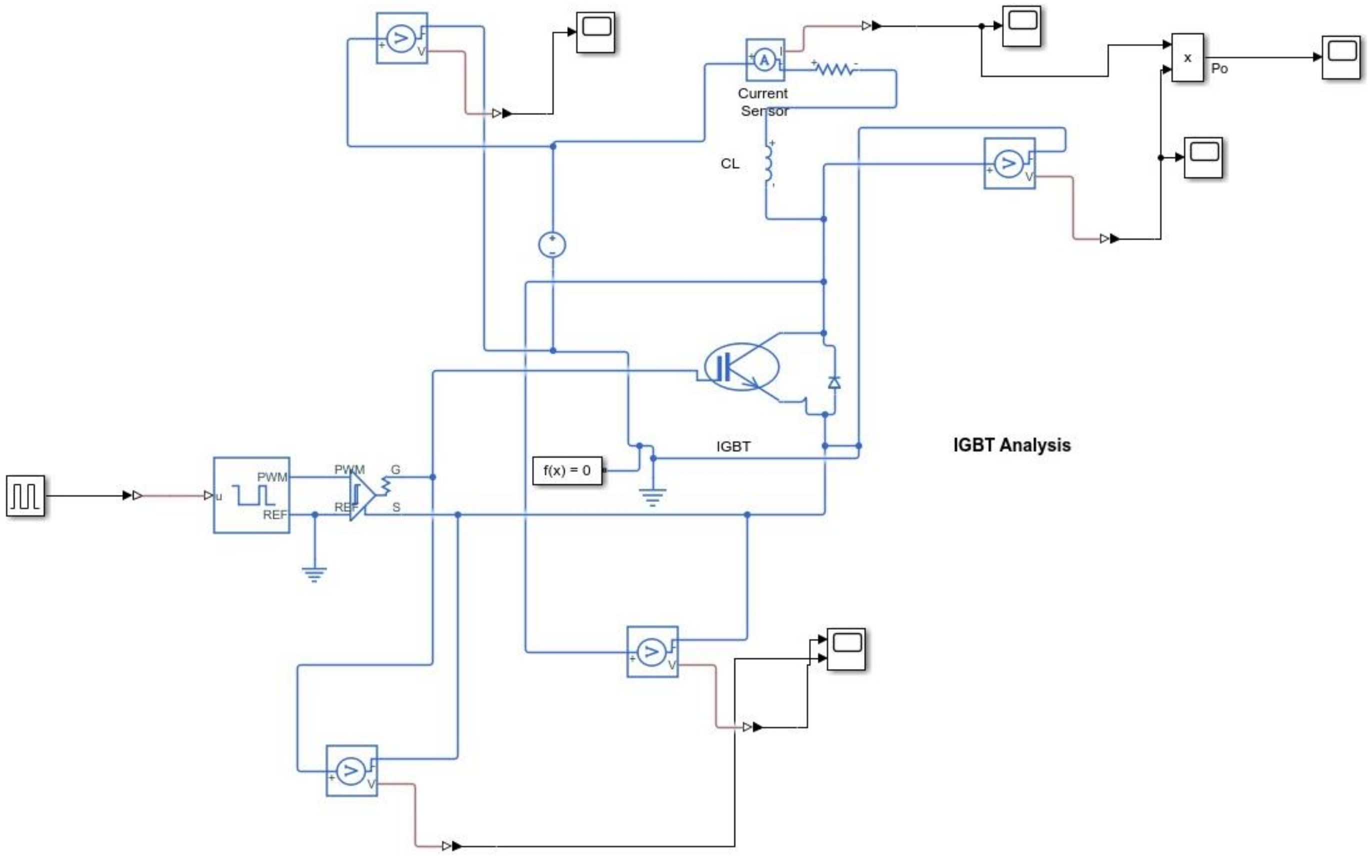

Fig.5. Simulink block for power measurement using IGBT

For comparison purpose power calculated using Simulink and Wavelet are taken for analysis and their output results for Silicon Carbide *(*SiC*)* MOSFET and IGBTs are shown in the Table 2 and Table 3 respectively.

Table 2 Result of Silicon Carbide (SiC) MOSFET and IGBT power measurement using Wavelet Method

Types of Wavelets	Power Loss (Watt)	
	SiC MOSFET	IGBT
Sampling Frequency f_s = 5Khz		
db1	0.000001458103	0.061749
db2	0.000001471014	0.061768
db3	0.000001470959	0.061794
db10	0.000001474324	0.061976
db20	0.000001488929	0.062249
Sampling Frequency f_s = 10Khz		
db1	0.000002780813	0.061669
db2	0.000002791620	0.061687
db3	0.000002791856	0.061711
db10	0.000002797076	0.061884
db20	0.000002813582	0.062165
Sampling Frequency f_s = 15Khz		
db1	0.000004079989	0.061605
db2	0.000004090657	0.061617
db3	0.000004090885	0.061634
db10	0.000004095950	0.061757
db20	0.000004111920	0.061980
Sampling Frequency f_s = 20Khz		
db1	0.000005392033	0.061572
db2	0.000005402115	0.061582
db3	0.000005402331	0.061596
db10	0.000005407337	0.061693
db20	0.000005423229	0.061880

Table 3 Result of Silicon Carbide (SiC) MOSFET and IGBT power measurement using Simulink Method

SIMULINK	Power Loss (Watt)	
Sampling Frequency f_s	SiC MOSFET	IGBT
5Khz	0.0000014706	0.061757
10Khz	0.0000027813	0.06166
15Khz	0.0000040923	0.061603
20Khz	0.0000054027	0.0611574

It is clearly seen that power measured by wavelets is more accurate than the power calculated by Simulink methods. Also the compared results of switching power losses of both Silicon Carbide (SiC) MOSFET and IGBT shows that the switching power losses are very low in Silicon Carbide (SiC) MOSFET than IGBTs.

V. Conclusion

This paper uses a physically-based device modeling approach to analyze power Silicon Carbide (SiC) MOSFET and IGBT switching losses. The switching power loss estimation method widely accepted by the power electronics community is carefully examined based on the new physical insights. In this study, a new method based on wavelet packet transform for power measurement was proposed. The method does not need constant window functions, trigonometric and complex number calculations. The validity of the proposed method was demonstrated via simulations and experimental works. The results of switching power losses for both Silicon Carbide (SiC) MOSFET and IGBTs were compared. It is concluded that the widely accepted output capacitance loss term in the existing calculation method is redundant and erroneous, and the current method of approximating switching times with the power Silicon Carbide (SiC) MOSFET and IGBT gate charge parameters grossly overestimates the switching power loss. As the switching power losses of SiC MOSFET are ten times lower than the IGBTs, the Silicon Carbide (SiC) MOSFET outperforms the IGBTs.

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