Modelling of SiC Power MOSFET in Matlab, Simulink, and LTSpice

Marah Alhalabi
College of Engineering
Abu Dhabi University
Abu Dhabi, UAE
marah.t.alhalabi@gmail.com

Abdelrahman Rashed
College of Engineering
Abu Dhabi University
Abu Dhabi, UAE
abdelrahman0609@gmail.com

Nusrat Binte Iqbal
College of Engineering
Abu Dhabi University
Abu Dhabi, UAE
n.iqbal-adjunct@adu.ac.ae

Anas Al Tarabsheh
College of Engineering
Abu Dhabi University
Abu Dhabi, UAE
anas.altarabsheh@adu.ac.ae

***Abstract*—SiC power MOSFETs are an integral component of many electrical designs. At present, such designs are validated using various software tools such as Cadence and PSPICE. However, this paper proposes an improved model of the SiC Power MOSFET using MATLAB. The research aims to detail the mathematical formulation of the MOSFET in MATLAB followed by simulating the same in LTSpice and Simulink. The static and dynamic characteristics of the MOSFET are studied i.e. the effect of channel length modulation and temperature followed by the switching process throughout the different time periods is simulated and explained in detail. The paper concludes with an illustration of the results of the simulations obtained and the discussion based on them.**

***Keywords*—SiC Power MOSFET; Static Parameters; Dynamic Characteristics; Matlab; Simulink; LTSpice**

I. Introduction

The progression of the technological world into a compact, faster, and more efficient devices and systems are made possible with the advance in integrated circuit technology. Silicon Carbide (SiC) power MOSFETs with its array of advantages allows exploration into sophisticated circuitry that caters to the needs of better-performing devices and designs. These advantages include maintaining a particular voltage over a wide a wide range of temperatures; thus, reduction of switching loses leading to better and compact designs. This is also due to the presence of a wider band-gap than normal silicon MOSFETs. Furthermore, the SiC power MOSFET also display a low on-state resistance which allows for greater efficiency requiring less cooling. The outstanding switching ability of these MOSFETs along with their significant advantages make them quite desirable in circuit designs requiring such characteristics. Hence, our paper attempts to model the SiC using MATLAB and then verifying them using Simulink and LTSpice. [1], [2]

Currently, most of the available SiC MOSFET simulation models are PSpice-based such as in [3]–[5]. Authors of [6] have proposed a compact MOSFET physics-based CAD model for simulating the I-V characteristics of both long and short-channel MOSFETs. Authors of [7] employ a novel model to simulate the n-MOSFETs rebound effect for the 60 Manometer highly-scaled node circuits with an irradiation up to 1Grad. The utilisation of standard CAD tools limits the modification of certain physical parameters, which promotes a closed analytic form. This means that the model is well-suited with the standard parameters of BSIM and SPICE.

A recent work conducted by authors of [8] employed MATLAB/Simulink in the development of a SiC power MOSFET platform model. The authors describe how 1.2KV/350A SiC MOSFET power modules behave electrically. The procedure of extracting the parameters is done in two steps, which are identification and optimisation. Another research, [9], compares both CAD and MATLAB simulation models of power losses for SiC MOSFET. The paper shows that MATLAB /Simulink demonstrates a higher accuracy of the losses analysis compared to CAD tool. SiC MOSFET is also modelled using MATLAB /Simulink in [10]. The model for the high-voltage SiC MOSFET is built based on its static and transient characteristics, then the parameters in the model are extracted.

In paper [11], MATLAB was used to derive the parameters for BSIM MOSFET Model to simulate the model in SPICE. It is found that the results from simulation match the results from experimentation with an error rate of around 1% while for short channels. Next, the author of [12] provides a detailed analysis of temperature effects on the mobility of the MOSFETs. The mobility model depicted by the author is tailored to empirically include a wide range of temperatures. The author succeeds in modelling a MOSFET and extracts its parameters which are simulated using MATLAB.

In this research paper, we will build and simulate the experimentally-validated SiC power MOSFET model proposed by the authors of [13] using MATLAB and Simulink. Their model functions within a wide range of temperatures, and it studies the static and dynamic characteristics of a SiC MOSFET model using temperature-dependent current and voltage sources. Similar to the model proposed by the authors of [7], dynamic characteristics are obtained by introducing parasitic capacitance in the MOSFET equivalent circuit. These authors have implemented a fully functioning Simulink model using a Simulink block of 5 and 2 input and output pins, respectively. Authors of [7] validated their proposed model through experimentation using a 4H-SiC MOSFET consisting of a 5-level cascaded inverter. This verified that the switching

This work is supported by Abu Dhabi University under grants 19300092 and 19300068.

losses and the saturation region estimation were efficient as opposed to the linear region, which was still underestimated.

The remainder of the paper is organised as follows: Section II presents our proposed model, Section III explains the methodologies for simulation in MATLAB, Simulink and LT-Spice as well discusses our results, and Section IV concludes the paper.

II. Proposed Model of SiC MOSFET

Our proposed SiC Power MOSFET modelling includes static and dynamic characteristics modelling, which are implemented in Matlab and verified through LT-Spice and Simulink simulations. Our model deals with long-channel N-type SiC Power MOSFET, where most of the parameters are extracted from the SCT20N120 power MOSFET model data sheet [14]. The nonlinear behaviour of the SiC Power MOSFETs I-V characteristics and its temperature-dependent parameters ensue the complexity in modelling such MOSFET. This section discusses the two types of characteristics modelling, and highlights the parameters taken into consideration at each modelling stage to ensure accurate an efficient modelling of the SiC Power MOSFET.

A. Static Characteristics Modelling

The static parameters under study are Channel Length Modulation parameter denoted by λ as well as temperature.

1) ***Channel Length Modulation Parameter:*** Modelling the I-V characteristics of an electronic device regardless of its type is essential in understanding its modes of operation and acquiring a general understanding of its behaviour. As such, we propose a model that takes into account the channel length modulation parameter while simulating the I-V characteristics of a MOSFET. Although this parameter affects short channel MOSFETS more than it does for long channel ones, it is crucial as it simulates the common non-ideal behaviour of any type of MOSFET.

To confirm our proposed MOSFET model in MATLAB, we develop a spice model using LTSPICE platform. The SCT20N120 silicon carbide power MOSFET, which is classified as a wide bandgap transistor, is used for this purpose. We use the CAD library developed by STMicroelectronics to simulate the I-V characteristics of this MOSFET.

In this model, the drain to source voltage V_{DS} varies from 0 V to 80 V with an increment of 0.01 V as shown in Fig. 1. The gate to source voltage V_{GS} is swept from 10 V to 20 V with a step of 2 V to generate multiple I-V plots in the same graph.

2) ***Temperature Parameter:*** The temperature parameter is used to identify the MOSFET operations at different temperatures ranging from 25°C to 200°C. This static parameter is affected by the threshold voltage, mobility of the carriers, and conduction parameter.

- **Threshold Voltage**:
  The threshold voltage (V_{TH}) is inversely proportional to the temperate; thus, an increase in temperature causes (V_{TH}) to decrease. Moreover, the effect of temperature on the threshold voltage is dominant at lower V_{GS}s.
- **Mobility**:
  The relationship between mobility and temperature follows that, as temperature increases, the mobility decreases given a coefficient of 1.5. Furthermore, at high V_{GS} values, the mobility is highly affected by temperature changes. Consequently, the current decreases with the increase in temperature since the mobility decreases.
- **Conduction parameter**:
  The conduction parameter denoted by (KP_n) is a function of mobility and C_{ox}'. The temperature effect on the transconductance parameter is inversely proportional such that with an increase in temperature, the transconductance parameter decreases; and thus, causing current values to decrease.

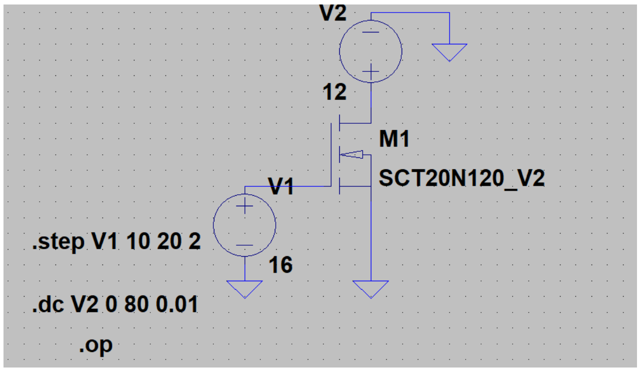


Fig. 1: LTSPICE Simulation Model for I-V Characteristics

Another model for SCT20N120 SiC Power MOSFET is developed using the same CAD library to simulate the effect of temperature on MOSFET's drain current. The temperature is swept from 25°C to 200°C with an increment of 25°C. Two graphs are generated, which represent the drain current versus V_{DS} besides the drain current versus V_{GS} for multiple temperature values as shown in the Simulations section.

B. Dynamic Characteristics Modelling: Switching Processes throughout Different Time Periods

In MOSFET gate equivalent circuit, Gate consists of an internal gate resistance Rg_{in}, and two input capacitors. These parameters and some more are used to define the gate to source value and to get the first time interval value as shown in Equation 1. Equations of the other time intervals are predefined to model the dynamic characteristics for switching processes in the MOSFET. All these equations are implemented in MATLAB to get the characteristics' plots for ON-transient as will be shown in the simulation results.

$$t_1 = RG \times Ciss \times ln(\frac{1}{1 - \frac{VTH}{VGS_{app}}}) \quad (1)$$

The second part which is OFF-transient time intervals of the MOSFET is modelled using Equation 2 and other equations for the fifth and the sixth time intervals. The intervals t_4 and t_6 can be calculated accurately, but the formula for t_5, which is more difficult to solve since during this time period V_{DS} will change, causing C_{gd} to also change. As such, the charge Q_{gd} over voltage is used to get an accurate value.

$$t_4 = RG \times Ciss \times ln(\frac{VGS}{Vgp}) \tag{2}$$

C. Simulink Modelling

Model-Based Design for the I-V characteristics of a MOSFET has an advantage of real-time characteristics plot. Thus, we propose a model that takes into account NMOS parameters to simulate both I-V characteristics and dynamic characteristics of the MOSFET. The models consist of subsystems which consist of many blocks. Modelling using Simulink provides flexibility for the engineers as they would have more control over various parameters and can introduce additional variables for testing purposes.

1) ***I-V characteristics Modelling****:* All subsystems used in modelling the I-V characteristics of the NMOS are connected to form one final model either with multiple V_{GS} inputs by using additional subsystem or with fixed V_{GS} input as shown in the final model Fig. 2. For control over various parameters, knobs and controls are added for this purpose.

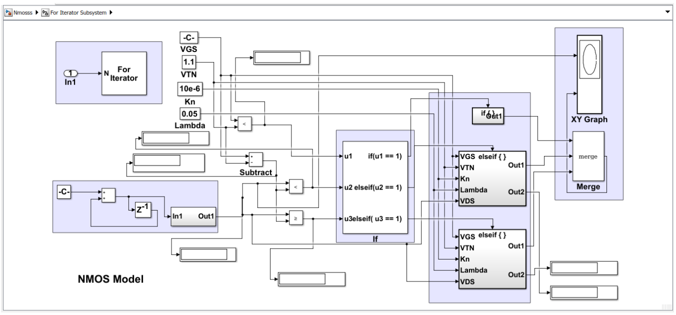


Fig. 2: Simulink MOSFET I-V characteristics Model - Fixed VGS

2) ***Dynamic Characteristics Modelling****:* For testing the dynamic characteristics of the NMOS, we develop a model which consists of two main models one for each transient state. Firstly, ON-transient model, as shown in Fig. 3, is developed for acquiring time intervals, drain current, and drain to source voltages of the MOSFET during this period.

Using the same parameters as in first dynamic modelling, we developed the second part of the model for OFF-transient. Both models then are merged to form the Dynamic characteristics NMOS Model as shown in Fig. 4.

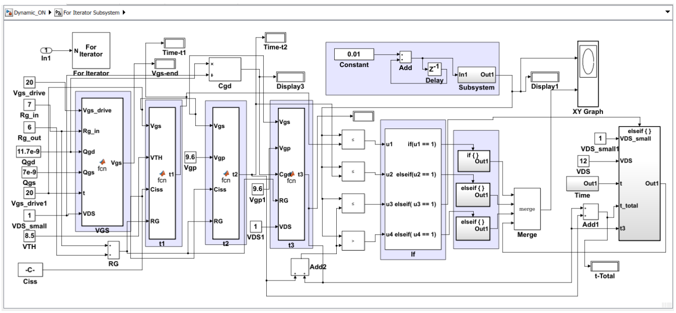


Fig. 3: Simulink ON-Transient Model

III. Simulation Results of SiC Power MOSFET Model

A. Static Parameters Simulation Results

1) ***MATLAB****:* The I-V characteristics graph shown in Fig. 5, takes into account λ effect. The long-channel NMOS parameters used theoretically have a smaller Conduction Parameter KP_n and a smaller V_{THN}. However, our utilised parameters show a significant increase in KP_n, which is directly proportional to the Drain to Source Current (I_{DS}). This modification is done to account for the huge current ranges the Power MOSFETs can handle, unlike the regular NMOSFET.

In Fig. 5, the intersection point acquired from poly-fitting the I-V curves resides at -20 V. This means that λ value is

$$\lambda = -\frac{1}{-20} = 0.05$$

This value matches with our λ parameter used in generating the graph, which verifies the accuracy of this method. The closer the intersection point of the linear poly-fits, the steeper the saturation region curve becomes, and the greater the λ effect would be.

Similarly, Fig. 6 demonstrates the I-V characteristic curves for an SiC Power MOSFET simulated using the SCT20N120 Model Data sheet parameters [14].

It can be noticed that the lambda value is very small, and as such an approximately ideal behaviour would ensue in the saturation region. In the ideal case of having λ equal to zero, the intersection point would be at $-\infty$.

Fig. 7 shows the I-V characteristics graphs for multiple gate to source voltages at two different temperatures being at 25°C & 250°C. It can be noticed that the current increases with the increase in temperature for a given V_{GS} value. This increase is due to the V_{THN} dependency on temperature. As previously mentioned, as the temperature increases, the threshold voltage decreases, which increases the drain to source current. Therefore, Fig. 7b shows higher current ranges than Fig. 7a. This proves the efficiency of our proposed model that takes into utmost consideration the effect of the temperature on the threshold voltage.

2) ***LTSPICE****:* Our proposed model for the SCT20N120 MOSFET is simulated using LTSPICE platform to generate I-V characteristics for the MOSFET. We obtain six coloured lines representing the different V_{GS} values for a drain to source voltage sweep as shown in Fig. 8a. If the Gate to Source Voltage V_{GS} is less than V_{THN} of the MOSFET, the drain current is said to be zero amps as the MOSFET is switched off. It is noticeable that, the saturation region starts at different V_{DS} with a positive proportional relation to V_{GS} values.

As the temperature varies from 25°C to 200°C in our proposed LTSPICE model for the temperature dependency, the

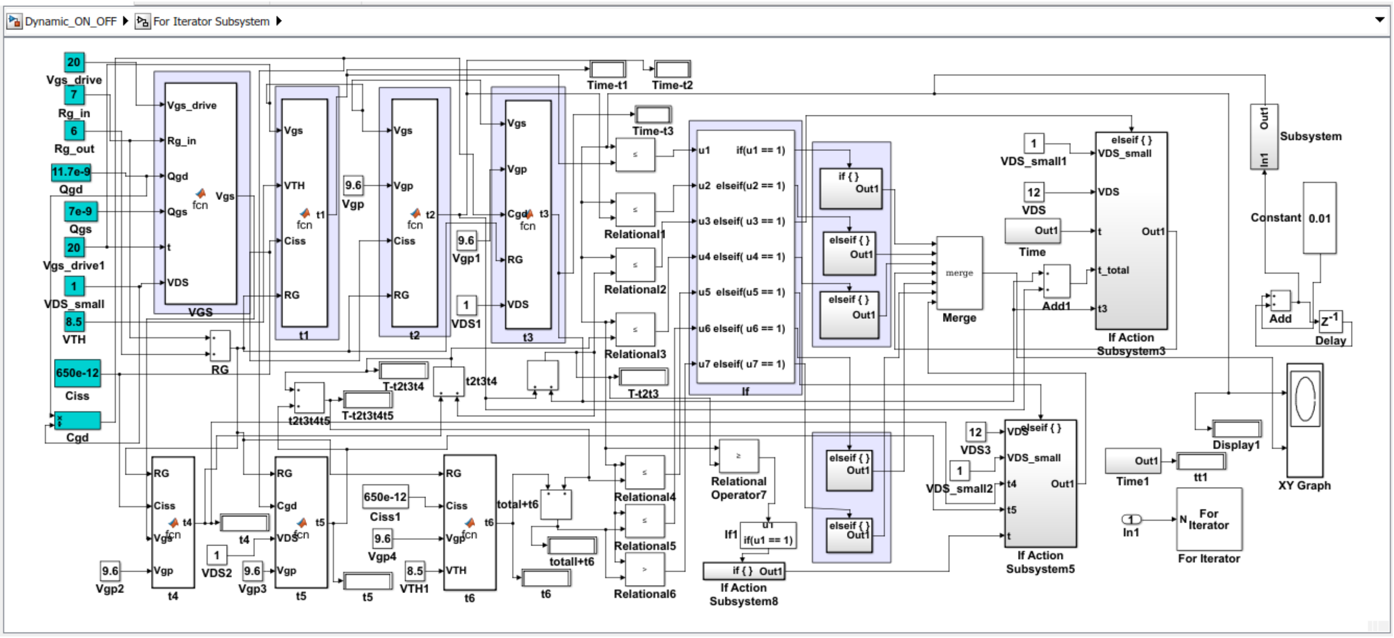


Fig. 4: Simulink Dynamic characteristics Model

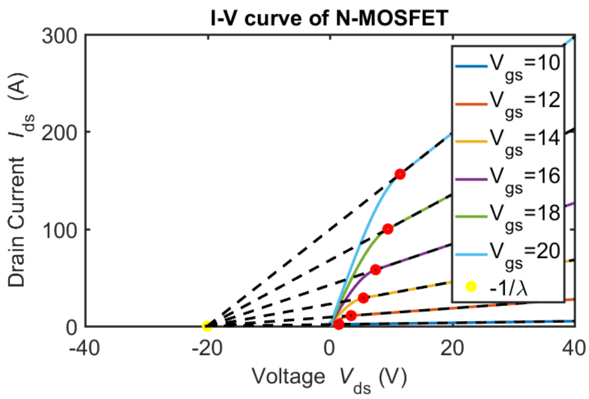


Fig. 5: Channel Length Modulation Parameter Extraction from an I-V Characteristics Curve for NMOS

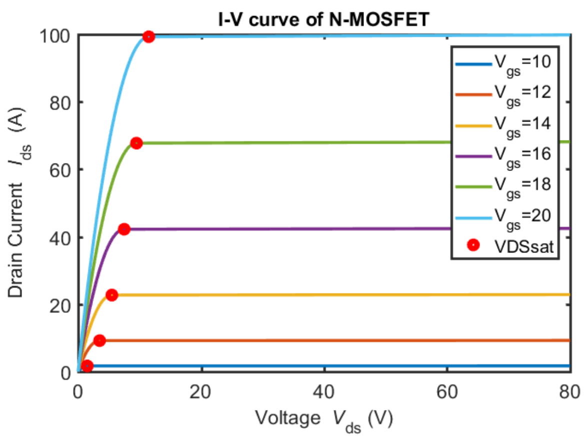
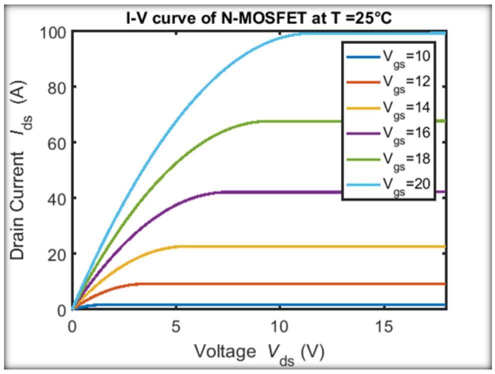
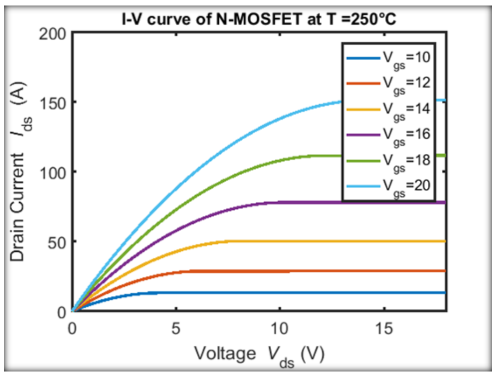


Fig. 6: I-V Characteristics for Multiple Gate to Source Voltages for SiC Power MOSFET

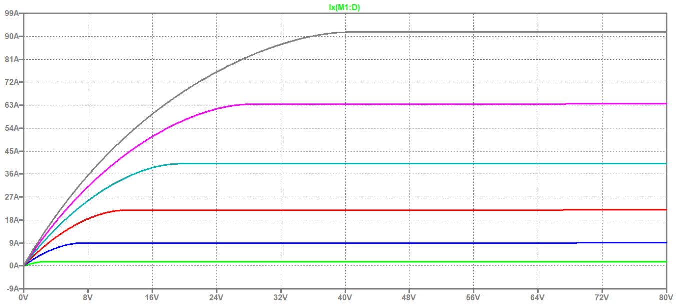


(a) I-V Characteristics at 25°C

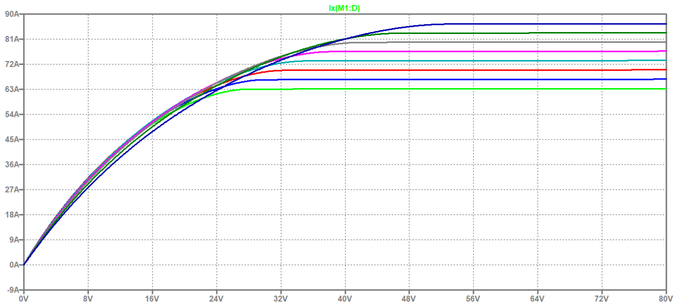


(b) I-V Characteristics at 250°C

Fig. 7: Output Characteristic Curves for Gate Voltages of 10-20V & temperatures at 25°C & 250°C

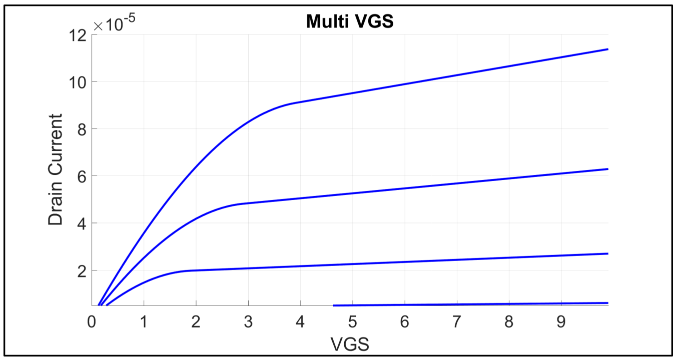


(a) LTSPICE I-V Characteristics Simulation

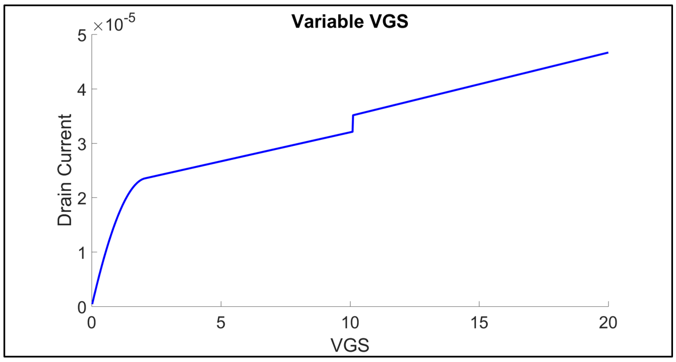


(b) LTSPICE Temperature Dependency Simulation

Fig. 8: LTSPICE Simulations



(a) Simulink MOSFET I-V characteristics Plot - Multi VGS inputs



(b) Simulink MOSFET I-V characteristics Plot - Variable VGS

Fig. 9: Simulink MOSFET I-V characteristics

drain current versus V_{DS} varies with a positive proportional relation. Fig. 8b shows that as the temperature increases, the drain current values show an incremental behaviour.

Another simulation shows the drain current of the MOSFET versus its gate to source V_{GS} swept values with a variation in temperature. It is obvious that at low V_{GS} values, the drain current increase with temperature increment since the threshold voltage in this region dominates the current which has a positive proportional relation with it and a negative proportional relation with temperature. Whereas as the gate to source voltage increases, the drain current decreases with temperature increment since the mobility in this region dominates the current which has a negative proportional relation with drain current and with temperature.

*3) **Simulink**:* Our proposed Simulink model is simulated for observing the I-V characteristics of the MOSFET. The output for the drain current subsystem and the output of V_{DS} sweep are merged to get an I-V characteristics plot. For multiple V_{GS} plots in one graph, we use the multi-input subsystem to generate the I-V characteristics shown in Fig. 9a. In these previous two figures, the parameters are fixed while in Fig. 9b it is noticeable that, there are sudden increments at specific points. That occurs due to changing V_{GS} parameter value during the simulation process which is essential in understanding MOSFET modes of operation and real-time changes due to varying some parameters.

B. Dynamic Characteristics Simulation Results

*1) **Matlab**:* Simulations for the On and Off transient period intervals are made possible through their respective equations to achieve the best simulated models.

As such, the three On-transient time periods denoted by t_1, t_2, and t_3 are simulated as 16.031 ns, 27.200 ns, and 380.250 ns. Whereas, the three Off-transient time periods denoted by t_4, t_5, and t_6 are simulated as 344.950 ns, 158.440 ns, and 102.830 ns.

After acquiring the 6 different time periods, we simulate the I_{DS}, V_{GS}, and V_{DS} curvatures through each time period. Fig. 10 illustrates the dynamic switching performance of the SiC Power MOSFET in the On transient period. V_{DS} is represented in blue, while I_{DS} is represented in black and V_{GS} is represented in red.

In the turn-on transient periods shown in Fig. 10, the SiC Power MOSFET is turned off during t_1, which corresponds to the Sub threshold interval. At this time period, the Gate to Source Voltage is less than the threshold voltage, which means that no current passes from the drain to the source, hence the zero I_{DS}. In time, the current starts flowing during the second time period until it reaches its maximum value and stabilises through the third time period. The third time period, t_3, is often referred to as Miller transient period, where V_{GS} plateaus at a constant voltage known as Gate Plateau Voltage (V_{GP}). During this period, V_{DS} begins to decrease until it reaches its minimum value. Upon exceeding the third time period, the SiC Power MOSFET is said to be conducting.

Similarly, the turn-off dynamic performance is modelled during three time intervals. During the first time period in this switching performance, V_{GS} decreases until it plateaus at V_{GP}

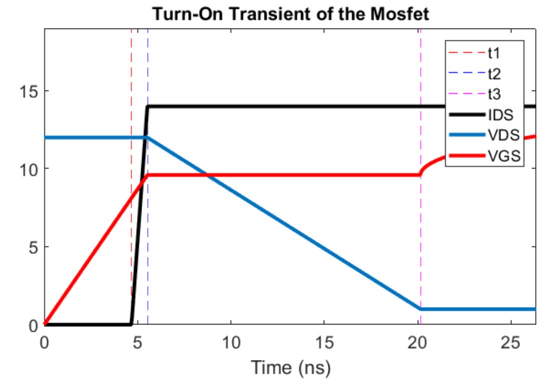


Fig. 10: ON-Transient Switching Behaviour of the SiC Power MOSFET

in the second time period denoted by the range $t_4 - t_5$. During that Miller Plateau time period, V_{DS} rises till it reaches its off-value. Moreover, in the last transient period ranging from $t_5 - t_6$, the switching performance of the Power MOSFET demonstrates an exponential decrease in the Drain-to-Source current till it hits zero. At this point, the SiC Power MOSFET completes its conduction process.

2) ***Simulink****:* For testing ON-transient characteristics, the first part of the dynamic model is simulated to observe the drain to source voltage vs time in the ON state of the MOSFET. Fig. 11 shows V_{DS} in V vs time in ns. To get accurate readings for intervals and V_{DS} values, we use display blocks which are connected to the subsystems outputs. For ON-transient, the time intervals are found to be 4.67 ns, 5.52 ns, and 14.6 ns, for t1, t2, and t3 sequentially. Both ON and OFF transient model are then merged and simulated to get the dynamic characteristics of the MOSFET. Both V_{DS} versus time characteristics are merged for ON and OFF transient in the final model.

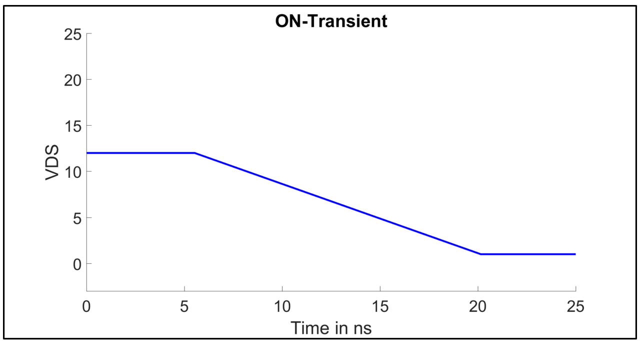


Fig. 11: Simulink ON-Transient Plot

IV. Conclusion

In conclusion, this paper models the SCT201N120 SiC Power MOSFET using MATLAB, LTSpice, and Simulink. It delves into the realm of static modelling whereby the channel length modulation and temperature parameters are simulated followed by dynamic characteristic for switching processes throughout different time periods and defining time interval equations on MATLAB. The paper provides a comprehensive mathematical formulation of the MOSFET model that is used for MATLAB. Simulation plots for channel length parameter (λ), and IDS vs. VDS values for different temperatures are obtained and presented. Simulation plots for switching performances i.e. Turn-On and Turn-Off transient periods are also shown for the dynamic characteristics modelling. These plots are then ascertained using LTSpice as similar graphs are attained. Furthermore, in order to create an interactive graphical user interface for MOSFET modelling, Simulink is used. The results thus obtained conform to the previous simulation results; hence, fulfilling our aim to model a SiC Power MOSFET using MATLAB, LTSpice, and Simulink.

References

[1] 2017. [Online]. Available: http://www.st.com/en/power-transistors/sic-mosfets.html?querycriteria=productId=SC1704

[2] R. Keim, "Exploring the pros and cons of silicon carbide (sic) fets: A new mosfet from cree," 2017. [Online]. Available: https://www.allaboutcircuits.com/technical-articles/pros-cons-silicon-carbide-sic-fets-c3m0075120K-MOSFET-Cree/

[3] J. Wang, T. Zhao, J. Li, A. Q. Huang, R. Callanan, F. Husna, and A. Agarwal, "Characterization, modeling, and application of 10-kv sic mosfet," *IEEE Transactions on Electron Devices*, vol. 55, no. 8, pp. 1798–1806, Aug 2008.

[4] K. Sun, H. Wu, J. Lu, Y. Xing, and L. Huang, "Improved modeling of medium voltage sic mosfet within wide temperature range," *IEEE Transactions on Power Electronics*, vol. 29, no. 5, pp. 2229–2237, 2014.

[5] M. Mudholkar, S. Ahmed, M. N. Ericson, S. S. Frank, C. L. Britton, and H. A. Mantooth, "Datasheet driven silicon carbide power mosfet model," *IEEE Transactions on Power Electronics*, vol. 29, no. 5, pp. 2220–2228, 2014.

[6] G. I. Zebrev, V. V. Orlov, A. S. Bakerenkov, and V. A. Felitsyn, "Compact modeling of mosfet i-v characteristics and simulation of dose-dependent drain currents," *IEEE Transactions on Nuclear Science*, pp. 1–1, 2017.

[7] P. Giammatteo, C. Buccella, and C. Cecati, "Matlab/simulink modeling of sic power mosfets," *International Review of Electrical Engineering (IREE)*, vol. 9, no. 4, p. 671, 2014.

[8] G. Tsolaridis, K. Ilves, P. D. Reigosa, M. Nawaz, and F. Iannuzzo, "Development of simulink-based sic mosfet modeling platform for series connected devices," *2016 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2016.

[9] H.-J. Chen, G. L. Kusic, and G. F. Reed, "Comparative pscad and matlab/simulink simulation models of power losses for sic mosfet and si igbt devices," *2012 IEEE Power and Energy Conference at Illinois*, 2012.

[10] Y. Cao, L. Yuan, K. Chen, Z. Zhao, T. Lu, and F. He, "Modeling of sic mosfet in matlab/simulink," *2014 IEEE Conference and Expo Transportation Electrification Asia-Pacific (ITEC Asia-Pacific)*, 2014.

[11] S. Yener and H. Kuntman, "Algorithms on the extraction of bsim mosfet model parameters via measurement data," in *Electrical and Electronics Engineering, 2009. ELECO 2009. International Conference on*. IEEE, 2009, pp. II–237.

[12] J. Singh and G. Wadhwa, "Mosfet mobility model at nanoscale including temperature effects," in *Computer Research and Development (ICCRD), 2011 3rd International Conference on*, vol. 3. IEEEE, 2011, pp. 325–330.

[13] G. Li, Q. Gao, M. Jin, J. Kou, X. Li, and D. Xu, "An improved matlab/simulink model of sic power mosfets," *2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia)*, 2016.

[14] [Online]. Available: http://www.st.com/en/power-transistors/sct20n120.html