

Statistical Modelling Method for Active Power Components Based on Datasheet Information

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Abstract

This paper presents a methodology to derive mathematical models of active power components based on statistical theory and datasheet parameter extraction. The models have the objective of providing reliable data of gate-to-drain voltage (V_{GD}), gate-to-source voltage (V_{GS}) and direct current (I_D) for nominal operating temperature range using only datasheet points. For achieving that, statistical learning theory is used to fit models in a reliable and systematic way. Besides predicting accurately static operation points, the proposed model can be used to estimate dynamics and switching losses in power switches. The model is validated using static and dynamic data available in a datasheet. The model is used to analyze a MOSFET behavior in typical power electronics applications. Finally, it is discussed the data availability in datasheets in order to easily create accurate models.

1. Introduction

Designing power converters requires detailed information about active power components. While component datasheets provide important data for the converter design process, this data are often incomplete for more complex analysis. The evolution in optimization routines and simulation software can constitute powerful tools to access more detailed data to the power electronic engineer [1].

A current solution is to use SPICE models from the component manufacturer for support in simulations. However, these models are not always open information and the designers are still attached to time domain simulation tool that limit their capacities to run optimization routines.

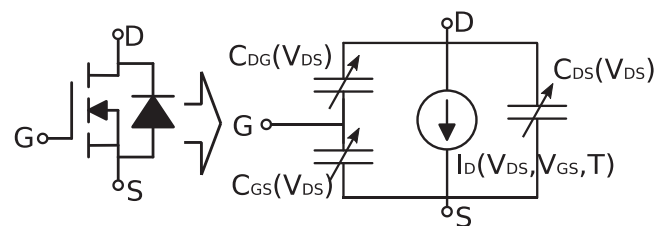


Fig. 1. Proposed model in this work: representing a MOSFET by statistical functions that represents variable capacitors and a voltage controlled current source.

To answer this simulation issue, this work proposes to use statistical tools to create simulation-ready mathematical models based only on the data available in the datasheet of the component of interest. This model can be used, in turn, to predict the behavior of the given component under conditions that are not given by the original dataset. A similar idea is used for photovoltaic models based on datasheet [2] and battery models [3].

Once data is extracted from the charts of a datasheet, through for instance manual methods [4], it can then be used to create a reliable model as in a traditional regression problem. There are several different techniques to create a regression model, mainly parametric techniques, and non-parametric techniques [5]. This paper focuses on applying non-parametric Gaussian process regression on several sets of data obtained from the charts of a IRF740 MOSFET datasheet and create a model as shown in figure 1. The validity of the models is tested by predicting charts and data given by the same datasheet that have not been used to create the models.

The model is then implemented in a time domain simulation. Several simulations are made, for different operation points in terms of temperature, gate resistor (R_g), and in different circuits: resistive charge, inductive charge + diode. The results of the switching energy (E_s), turn ON and turn OFF

times are acquired and new mathematical models are created, offering to the final user a way to obtain dynamical results without realizing time domain simulations. Finally, the work presents several possible predictions that the model is capable of performing.

2. Statement of the problem

In order to simulate power device dynamics and to calculate switching losses in a MOSFET using traditional methods, many approximations are usually made [6].:

- The value of Miller's plateau is presented only in one given operating condition;
- The non-linearity of capacitances C_{iss} , C_{oss} and C_{rss} is not accurately depicted
- Temperature variations are hardly considered.

This subject is widely discussed in many works [7-10]. In practice, the calculation of switching losses requires a lot of time and effort from the power electronics engineer. This would be a straightforward task if an accurate model could be built from the combination of a simple function that represents the static behaviour of a MOSFET and a simple simulation setup. This work proposes and automated methodology to achieve this end.

The static behaviour function of the MOSFET yields (I_D) as a function of ($V_{GS} \times V_{DS} \times$ Temperature). The simple simulation then consists of a current source driven by this static function combined with three capacitors (C_{GS} , C_{DS} , C_{DG}) whose capacitance variance is modelled by its charges integral over time, as shown in figure 1.

Based on these models, the user can extract important data to better analyses a converter operation and obtain data that would be impossible obtaining with the more traditional methods.

3. Model Extraction

Two types of active device models are needed for analysing its behaviour in a power electronics converter. One model considers the static behaviour of the power device and the other model represents its dynamic behaviour. Their combination is used to predict component behaviour under any operating conditions.

A) Static model estimation

For static analysis of a power switch, the component datasheet presents two important graphs:

- 1) Drain-to-Source voltage (V_{DS}) versus Drain to source current (I_D) for different Gate-to-Source voltages (V_{GS}) at a fixed temperature;
- 2) Temperature versus Drain to Source ON resistance (R_{ON}), for a fixed I_D and V_{DS} .

These graphs can be used to provide an estimation of the transistor static characteristics for some specific operating conditions. But for accurate analysis and optimization of multiple operating conditions, reliable data is not available especially with respect to variations in temperature [6]. This data is essential for the accurate representation of the Millers' plateau with respect to V_{GS} and V_{DS} . In some charts, this is not available.

For properly modelling dynamic behaviour, the static model derived from the graphs above must be combined with an accurate static model which predicts the relation between the gate to source voltage (V_{GS}), the gate to drain voltage (V_{GD}) and the voltage-controlled current source (I_D). This is critical in the case where this dynamic model is used to precisely estimate switching losses in fast switching applications, where the gate to source current needed to turn OFF the switch is very large, and the MOSFET channel may be switched OFF early in the commutation.

In this scenario, statistical techniques can be used as a tool in order to extract models from the available data. Based in a representative set of points, several different techniques can be used to make a regression model. Statistical methods, such as linear regression or polynomial regression are able to fit wide ranges of data with a pre-determined acceptable error. Statistical techniques are easy to use, do not require long statistical training effort from the user and their resulting model is interpretable. Statistical methods can also be applied to non-linear problems, such as the $V_{DS} \times I_D$ behaviour of the MOSFET.

In this work, Gaussian Process Regression (GPR) method is used to predict values of I_D for various V_{GS} and V_{DS} . GPR is a non-parametrical technique that consist in using the data set to build a predictive distribution, capable of averaging the effect of all possible mathematical functions that can describe the phenomenon to estimate the missing data points without prohibitive

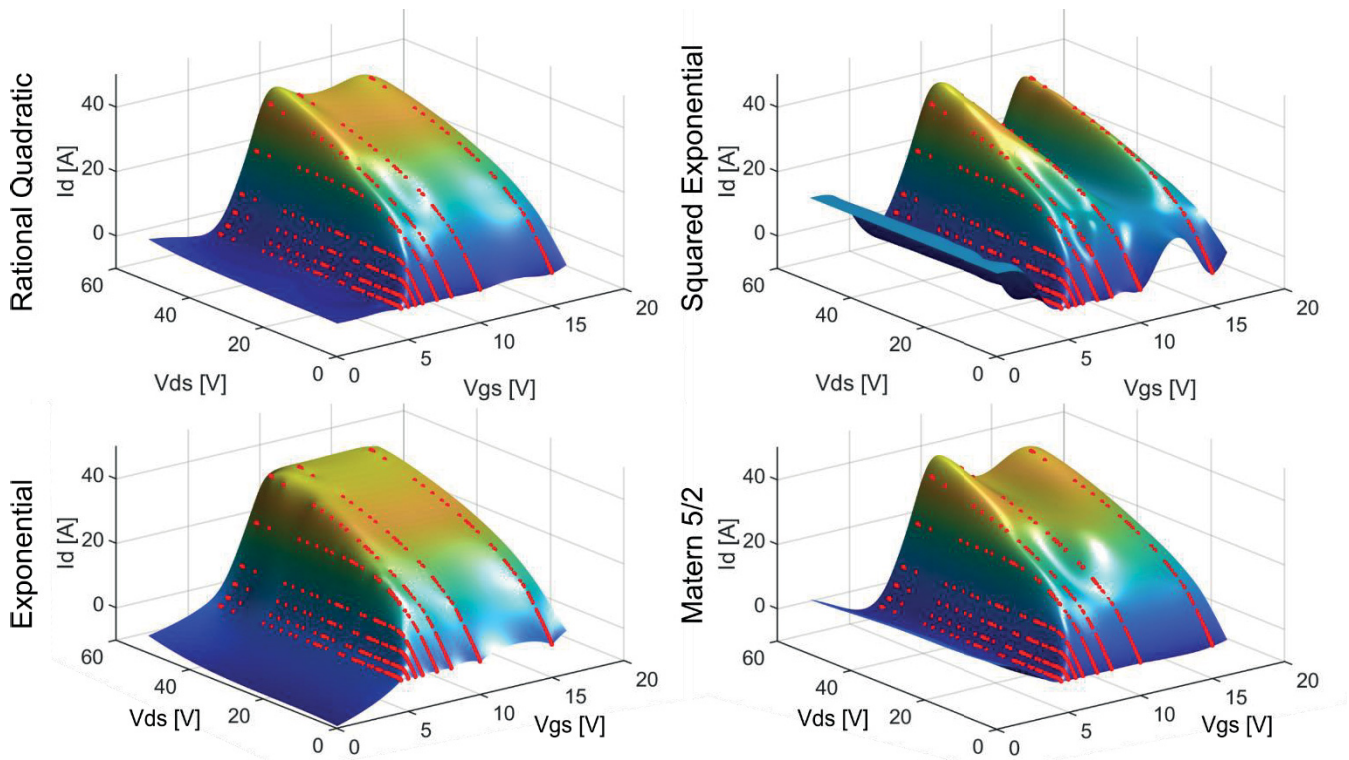


Fig. 2. Four different kernel functions tested to create a Gaussian Regression Process. The red dots are the data acquired from the IRF740 datasheet.

computational cost [11]. It requires a covariance distribution, or ‘kernel function’, which extracts the information from the input data to generate accurate predictions. Kernel functions have *hyperparameters* which must be set according to characteristics of the input data set. GPR is a flexible type of statistical learning model for fitting non-linear problems such as the $V_{GD} \times V_{GS} \times I_D$ data, as it requires only calculating its kernel function to yield highly accurate predictions [12].

In this work the MOSFET IRF740 was chosen to be modelled due to its very detailed datasheet and its data easily exploitable. It is important to note that, any MOSFET with well detailed datasheet could be used. In figure 2 it can be seen four different kernel functions tested to fit the $V_{GD} \times V_{GS} \times I_D$ curves. The data used (red points in the figure) were exported from the IRF740 datasheet using the tool available in [4]. The input data is made of 1 value of I_D for each 2 V variation of V_{DS} for all available V_{GS} , resulting in 240 input data points.

It is evident in figure 2 that the definition of kernel function is fundamental to create a reliable model. Just by trusting the basic knowledge one should have about a MOSFET, it seems obvious that the more flexible functions such as squared exponential, created completely incorrect models.

The task to define the best function to use is very tricky, once the mainly common used parameters to measure the quality of the model cannot be trusted to define the model that fits best the real characteristics of a MOSFET. For example, table 1 presents the Root Mean Squared Error (RMSE) for each one of the models presented in figure 1.

Method	Rational Quadratic	Squared Exp.	Exp.	Matern 5/2
RMSE	0.046	0.137	0.131	0.028

Despite the fact that the Matern 5/2 obtained the minor value, it is visible in figure 1 that its wiggly form does not represent the behaviour of a MOSFET. The exponential function, which is a much more ‘rigid’ function, was chosen to create the model. This type of kernel is infinitely differentiable, meaning it is very smooth [12], which is very adapted for the case of a physical behaviour of a switching MOSFET. Some adjustments were made in the function before creating the definitive model: All values of I_D below 0 are considered 0. Values of I_D at $V_{DS}=0$ are considered 0.

The final model is presented in figure 3. This model represents the $V_{GD} \times V_{GS} \times I_D$ at 25 °C. The same

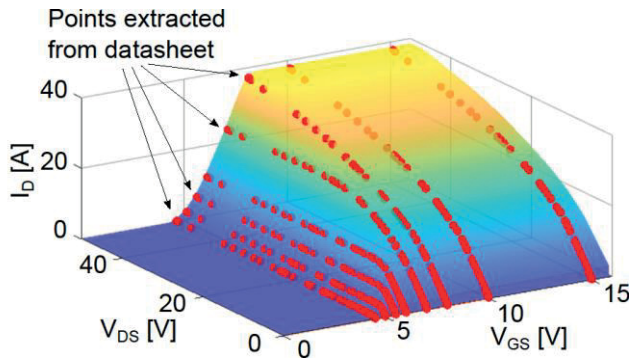


Fig. 3. IRF740 $V_{GD} \times V_{GS} \times I_D$ data (red points); Fitted Gaussian process model (plane)

procedure was made to represent the MOSFET behaviour at 150 °C. However, it is possible to compute the predictions needed to build intermediary temperature planes to cover all temperature operating range of the MOSFET. For achieving that, it was used the graph Temperature versus R_{ON} available in the datasheet. This relationship can be easily represented by a 2-order polynomial as presented in figure 4. Using this polynomial model, the 25 °C and the 150 °C temperature planes, the intermediary planes between -60 °C and 150 °C were interpolated.

B) Dynamic model estimation

During the switching transitions, the capacitances C_{DG} , C_{GS} and G_{DS} vary according to their voltage/charge ratio. These variations impact directly the dynamics of the rise time and fall time of a switch, as well as the value of the Miller's plateau and interfere directly on switching losses. In order to have an accurate image of the switching transitions, this work proposes to derive mathematical models to represents the three capacitors aiming to run a simulation capable of reproduce accurately the switching process.

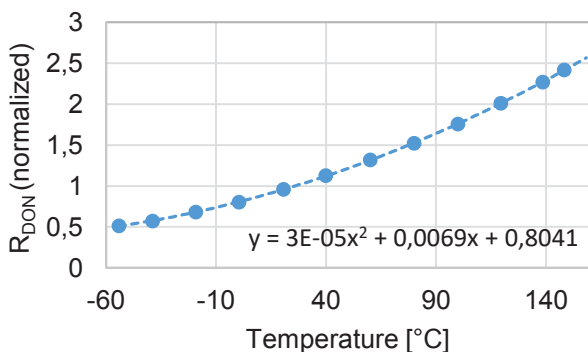


Fig. 4. R_{DON} versus temperature chart. Points extracted from datasheet. Line: 2nd degree polynomial used to describe the behavior

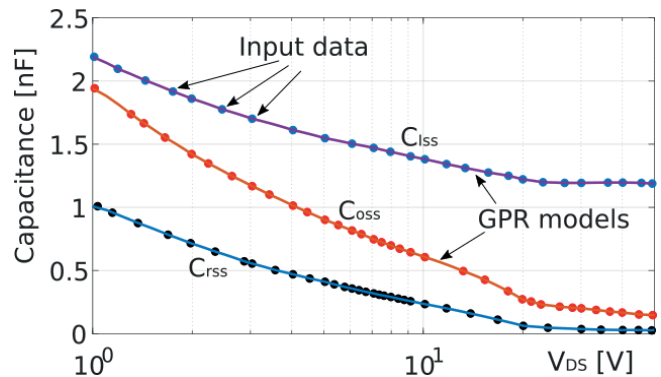


Fig. 4. Typical capacitance vs. V_{DS} chart. Points: Data extracted from IRF740 datasheet. Lines: GPR fitted models.

As the three capacitors have a non-linear behaviour, GPR was also used to model their comportment. An exponential Kernel function was used for fitting the GPR. The derived models that represent C_{ISS} , C_{OSS} and C_{RSS} are presented in figure 5 together with the data obtained from the datasheet charts that were used to fit them.

4. Model Validation

To test and validate the proposed MOSFET static model, a comparison between the variation of I_D with respect to V_{GS} given by the statistical model was plotted against the data given by this same chart presented in the datasheet. It is important to notice that this chart was not used to create the model. Results are presented in figure 6, which shows a very accurate result of the obtained models.

The validation of the dynamic model composed by the capacitor models together with the voltage controlled current source static model was done in Matlab Simulink. A simulation was made following the exact values of the test circuit presented in IRF740 datasheet: A 200 V DC source connected

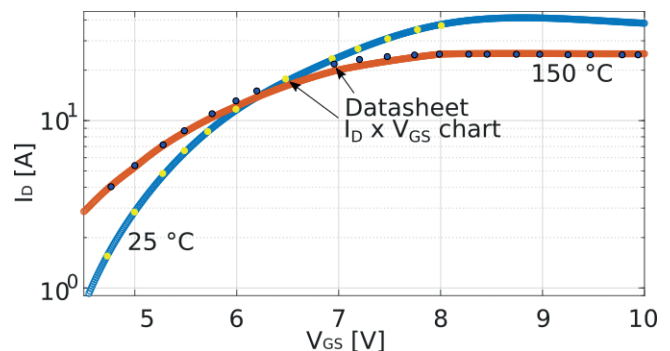


Fig. 5. Comparison of I_D vs. V_{GS} points extracted from the datasheet. Lines plotted by the GPR models.

to a 10 Ω resistor and the MOSFET model in series. Figure 5 presents the simulation results. The fall time (t_f) was estimated 25 ns and the rise time (t_r) 22 ns. The datasheet provides values of 27 ns and 24 ns respectively. The errors of 7,4% and 8% encourage the validity of the model.

Once the proposed models perform accurate results in the ‘resistor-switch’ circuit, more complex circuits can be simulated, like the commutation process of a MOSFET with a diode as commonly found in power converters.

5. Application of the model

This work presents a utilization of the mathematical models for providing information of a more complex situation existent in power converters. However, several other models can be created with respect of variations in temperature, voltages V_{DS} and V_{GS} , variations in gate resistances R_G and a mix of this variables can be made for multi-dimensional models able to provide data that are too complex for traditional mathematical solutions and models that can be inserted in optimization routines.

5.1. Analysis of switching in different temperature conditions

One interesting application is to analyse the switching energy in the MOSFET during a

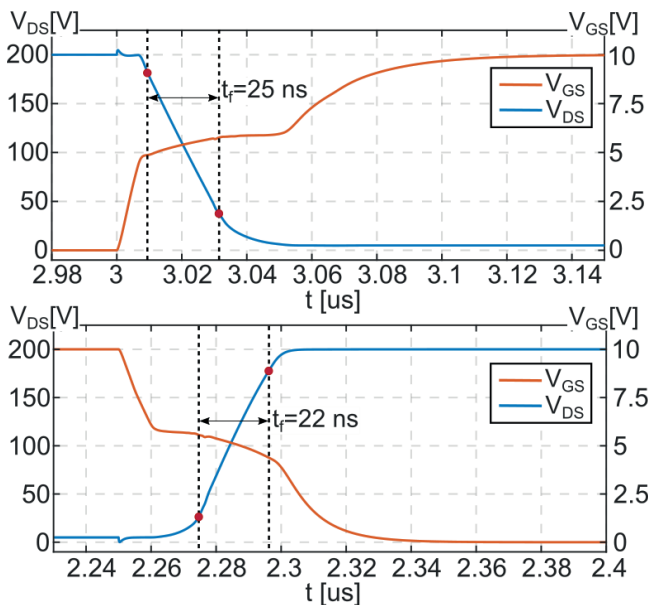


Fig. 7. Dynamical model validation. Simulation results of a turn ON and turn OFF switching processes. Fall time t_f and rise time t_r (10% - 90%) highlighted.

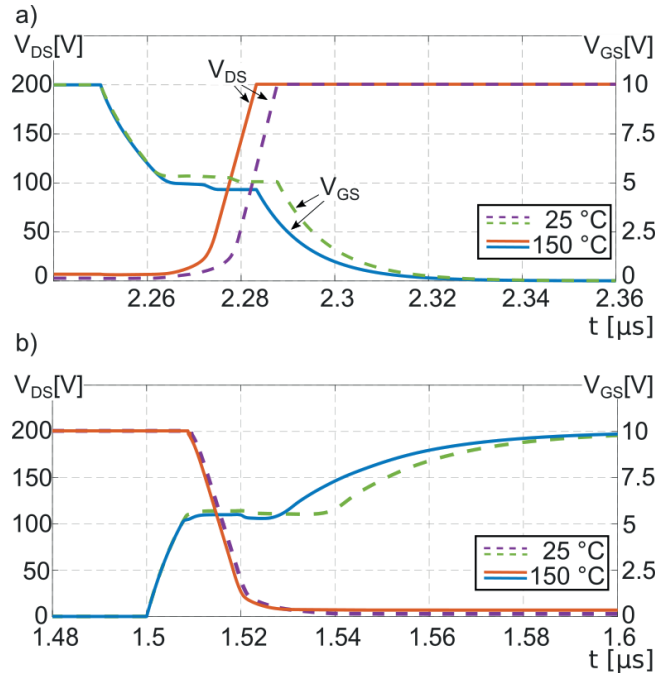


Fig. 9. Turn OFF and turn ON process of the MOSFET in different temperatures. Dashed line at 25 °C, solid line at 150 °C. Switching process to a diode-inductive charge at 6 A, 200 V.

MOSFET-to-diode switching with respect to the temperature. For this analysis, a simulation circuit of a voltage source connected to a MOSFET and an inductance with a free-wheel diode was implemented.

In figure 7 is presented the MOSFET turn ON at 25 °C and at 150 °C. Although they have similar shapes, it is visible that while operating in higher temperature the MOSFET presents a different behavior during the driving process. Especially, the voltage and current switching are delayed by about 5nsec. The modeling technic can be used to investigate the optimization of the dead time inverter harm with respect to temperature.

These time domain simulations can also be used to estimate switching losses. By integrating the power consumed by the MOSFET during the switching it is possible to find the switching energy. Simulations at 25 °C and 150 °C resulted in 26.66 μJ and 29.80 μJ of energy respectively for a blocking + driving switching.

Supported by these simulation results, it is possible to forecast the losses for various operating points, just by changing the operating conditions. Based on several simulations results a multidimensional map representing the switching cell behavior with respect to numerous parameters such as: component junction temperatures, switched voltage and current, gate driver characteristics (R_G and $V_{GSmin\&max}$) and switching

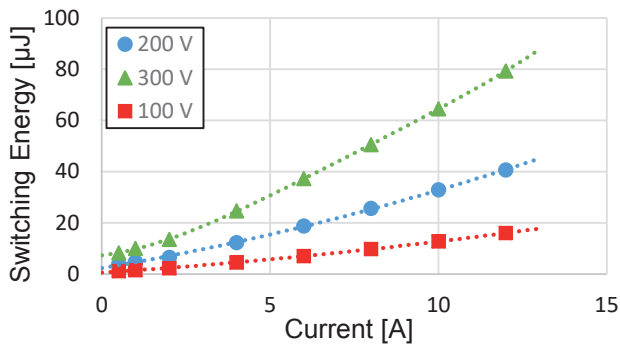


Fig. 10. Comparison of I_D vs. V_{GS} points extracted from the datasheet. Lines plotted by the GPR models.

cell inductance. Based on the time domain simulation results, a math model can be derived and implemented in an optimization routine, giving the opportunity to avoid time domain simulations in optimization loop. The math model outputs can be related to voltage and current switching speed, commutation energy losses, ON state losses with respect to switching frequency and duty cycle. Depending of accuracy and data availability, OFF state losses can also be computed. From that model, the designer can extract quickly and accurately many results and optimizations. The next paragraph provides an illustration on a basic case with one parameter variation.

5.2. Switching losses in switching-sinusoidal waveform

Several applications of power electronics converters have sinusoidal current waveforms, such as inverters or rectifiers with power factor correction. In this typical situation, the switching losses are complicated to calculate accurately in time domain simulation since the time constants are too different between the switching time and the sinus period. Besides, since every switching event considers a different operating point, it is difficult to derive the losses accurately over a line period. A simple design of experiment can be set to illustrate how a simple math model can be used here to solve the issues.

Several simulations were performed to analyze the switching process with different current levels. Figure 8 presents this time domain simulation results considering the turn ON and OFF switching losses with respect to the switched current. A second order polynomial equation represents this behavior. Supported by this relation between current and switching losses energy, a designer is able to calculate the switching losses of a

MOSFET + freewheeling diode for any current periodic shape or mission profile.

This work presents how math models are used to provide information of a more complex situation existent in power converters. However, several other models can be created with respect of variations in temperature, voltages V_{DS} and V_{GS} , variations in gate resistances R_G and a mix of this variables can be made for multi-dimension models able to provide data that are too complex for traditional mathematical solutions and models that can be inserted in optimization routines.

6. Conclusion

This work presented an innovative method to create detailed static and dynamic models of a MOSFET. The method can determine the electro-thermal behaviour of a MOSFET for any V_{DS} , V_{GS} and I_D based only in the charts presented in its datasheet. It was used to calculate precise conduction and switching losses for any operating point of $(I_D, V_{DS}, V_{GS}, I_g, T)$ in any switching condition (hard switching, partial soft switching ZVS/ZCS). One important result is that the models can be operated in math format, to enable usage in optimization routines.

The use of Gaussian process regression to create a model to represent the MOSFET is an interesting and powerful technique. This work achieved satisfactory results using an exponential kernel function to create the model. The compromise between flexibility and accuracy of the model is something to be better evaluated. More complex kernel functions might create models that achieve more precise representability of the true behaviour of the MOSFET.

The proposed model can be used for studying several different situations in power electronics converters, as analysis of switching losses, optimization of dead time for MOSFET-MOSFET switching transitions, etc. All taking in account the temperature variation and behaviour of the intrinsic capacitances in a MOSFET.

7. References

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