# Experiences with Simulation Software for the Analysis of Inverter Power Sources in Arc Welding Applications

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*Abstract* - **Nowadays various simulation tools are widely used for the design and the analysis of power electronic converters. From the engineering point of view it is rather difficult to parameterize power semiconductor device models without the knowledge of basic physical parameters. In recent years some data sheet driven behavioral models or so called „wizard“ tools have been introduced to solve this problem. In this contribution some experiences with some user-friendly power semiconductor models will be discussed. Using special simulation test circuits it is possible to get information on the static and dynamic behavior of the parameterized models before they are applied in more complex schemes. These results can be compared with data sheets or with measurements. The application of these models for power loss analysis of inverter type arc welding power sources will be described.**

*Keywords* - **Simulation, power semiconductor behavioral model, welding power source, inverter**

## I. INTRODUCTION

Today about 70 % of modern welding equipment are inverter type power sources. Arc welding inverters are very complex power electronic systems characterized by a small volume and a low weight, high switching frequencies up to 150 kHz, integrated power factor correction, a wide range of output power, a high dynamic response and an increasing implementation of digital control [1]. Fortunately it is possible to reduce costs on the project level by using simulation software, which can help to eliminate errors appearing during the design and optimization process.

Simulation software allows in an easy way to test the behavior of inverter power sources under different, even extreme, operating conditions. It is possible to find out a proper inverter topology and control for a given application in a very short time, without building and testing several expensive prototypes. Besides this, some direct measurements are not possible in practice, or are very complicated. Some of those problems are for example:

- the measurement of switching and total power losses of semiconductor devices,
- the measurement of currents in paralleled semiconductors,
- the specification of the influence of snubber networks and parasitics on operating conditions,
- a proper driver configuration,
- and an optimal design of control loops.

However, it is possible to get a theoretical solution of most of these problems by using simulation software.

SABER and SIMPLORER are two of many simulation software packages existing on the international simulation software market [2], [3]. Both of them are equipped with an integrated simulation environment, including a graphic user interface design tool module, a compiler which translates the graphic models into a code the simulator can understand, a simulator as the heart of the simulation system and a postprocessor allowing to view and to analyze the results. Apart from that, both of them have ready-to-use data bases of models, and they allow to create new models of elements and subsystems. Models can be created in the simulator language or in other programming languages as well.

Talking about parameterization of power semiconductor models the following types of models can be distinguished:

- physical,
- behavioral,
- ready-to-use component models (provided by manufacturers or software, mostly encrypted).

Physical models are difficult to parameterize without a detailed knowledge of the physical data of the modeled object. These models are unsuitable for daily engineering use, but are very good if the modeling of internal phenomena in the semiconductor structure are of special interest. The development of special parameterization tools which will combine the exactness of physical models with the available behavioral data is one of the goals of simulation software development in the next years [4].

Behavioral models are good in circuit applications if the semiconductor structure and internal phenomena are not the point of interest, but if the device is treated as a "black box" and described by external parameters which are directly measurable or which are given in the data sheets. Very often, if semiconductors are used in special applications, it is necessary to verify the data by own measurements. But anyway, these measurements are not so complicated as the measurements needed for parameterization of a physical model.

Often in ready-to-use models, provided by manufacturers, the documentation is not sufficient to use these models directly in the practical applications. These models are provided precompiled, so we don't know how these models are built and how they will work under different conditions. It is advisable to check up these models precisely before using them in specified applications.

Before a simulation runs, some conditions have to be performed. So it is necessary to define the simulation aim and following from this the expected character of phenomena. For some applications, static semiconductor models supply sufficient simulation data. If turn-on and turn-off losses, transient voltages, thermal analysis are the aims of simulation, dynamic elements have to be used. Than it is possible to simplify the whole circuit and to concentrate only on selected phenomena. In this case proper models of elements and devices - static or dynamic - have to be chosen, because the circuit complexity is one of the most important factors influencing the simulation time. The second one is the integration step size. The smaller the integration step size the more correct results will be achieved, but the simulation time will also be longer. Therefore, the specification of the minimum and maximum integration step size involves a compromise. It should be chosen appropriately to achieve necessary accuracy and to speed up simulation time without numerical errors. With today's computational power and capacity of hard disks of workstations, the problems of computing time and file size have lost importance. These simulation programs are very mighty tools, because they allow to build models on different complication levels and also provide a wide spectrum of analysis methods.

This paper will present some of the experiences with simulation and modeling of inverter power sources used in arc welding applications. Especially it will be shown how to use data sheet driven behavioral models of one of the most advanced simulation software on the market and how to realize the parameterization and the test of these models. An application example will be given to demonstrate the capabilities of modern simulation tools in the field of power electronics.

## II. DATA SHEET BASED DYNAMIC DIODE BEHAVIORAL MODEL

The SABER *dp1a* template is a diode model including reverse recovery, forward recovery and voltage-dependent junction capacitance. Forward recovery and junction capacitance are modeled on a physics-based approach [5]. The static characteristic is determined by a piecewise linear model with a constant resistance $r_{on}$, which is independent from current, and a constant resistance $r_{off}$ in the reverse direction. Table I shows the argument description. Most of the required arguments are provided by data sheets. Some arguments are not given explicitly, but they can be determined easily. The quality, the extent and the accuracy of data sheets are very different. So the dependency of junction capacitance on reverse voltage is often not given and has to be measured. In some cases the parameters used as a model argument are different from the data sheet parameter description. For the analysis of welding power sources three types of diodes were of special interest:

- body diodes of MOSFET inverters,
- inverter-side free-wheeling diodes for IGBT inverters,
- secondary-side rectifying diodes for higher frequencies.

Table I shows as examples of the parameterized diode models the values for two types of diodes. The first diode BYT261PIV400 (STmicroelectronics) is used in a 100kHz/5kW arc welding inverter as a secondary rectifier. The rectifier consists of several diodes in parallel. The data sheet was sufficient for extracting all parameters. The second diode is a 11kA/200 V high-current disc-type diode, used in inverter power sources for resistance welding applications. In this case no information was available concerning the dynamic characteristics, because this diode was originally dedicated for line frequency applications. With own measurements under real working conditions we have obtained the turn-off parameters for reverse current and capacitance. The turn-on is not relevant in this application.

TABLE I
PARAMETERS OF SABER DIODE MODEL *dp1a*
PARAMETERIZED DIODES

| **Parameter** | **Available from data sheet** | **BYT261PIV400 (ST)** | **5SDD120 C0200 (ABB)** |
|---|---|---|---|
| ***static (pwl)*** | | | |
| ron | (x) | 4.5 mΩ | 20 μΩ |
| roff | (x) | 67 kΩ | 67 kΩ |
| von | x | 1.1 V | 0.75 V |
| ***turn-off*** | | | |
| ifo | x | 60 A | 10 kA |
| dir/dt | x | 240 A/μs | 424 A/μs |
| irrm | x | 18 A | 719 A |
| trr | x | 100 ns | 2700 ns |
| qrr | x | not required | not required |
| c1 | ((x)) | 200 pF | 40 nF |
| v1 | ((x)) | 1 V | 1 V |
| c2 | ((x)) | 130 pF | 10 nF |
| v2 | ((x)) | 200 V | 200 V |
| ***turn-on*** | | | |
| dif/dt | x | 300 A/μs | (300 A/μs) |
| vfp | x | 20 V | (20 V) |
| tfp | (x) | 200 ns | (200 ns) |

x directly available from data sheet
(x) indirectly available ((x)) mostly not available

After parameterization of the dynamic diode model one cannot be sure, that the expected electrical properties of the model correspond to real circuit behavior, because all models have certain limitations, the diodes are used under different conditions and data sheet values or measurement results could be incorrectly or contradictorily. Dynamic models require a certain accuracy of simulation which is higher than in case of simulation with static models. Simulation results can even be wrong or simulation fails if the simulation parameters as time increments, truncation error and integration type are not adjusted adequately. For these reasons it is recommended to test and validate all parameterized behavioral models before using them in complex topologies. For this purpose a number of special simulation test circuits has been developed for diodes, MOSFETs and IGBTs as well as for magnetic components. Fig. 1 shows one of these simulation test circuits for the dynamic turn-on of diodes. Reverse voltage and current slope can be adjusted separately as indicated in the test conditions of the data sheet.

From data sheet diagrams for this type of diode a dynamic maximum forward voltage of 20 V for a di/dt of 300 A/μs can be extracted. The time $t_{fp}$ corresponds to the voltage maximum and is not given in the data sheet. An input $t_{fp}$ value of 200 ns results in a simulated $t_{fp}$ value of only 125 ns. The data sheet time $t_{fr}$ is given as 250 ns and has a different definition. Consequently, the three parameters are not sufficient to characterize the turn-on behavior. It is recommended to use measurement results to adjust the model.

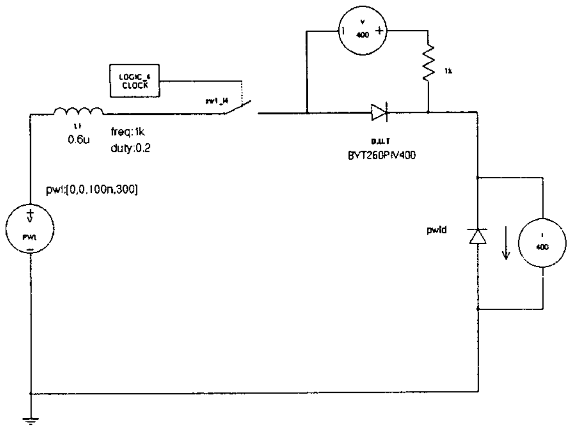

Fig. 1: Simulation test circuit, turn-on behavior of diodes

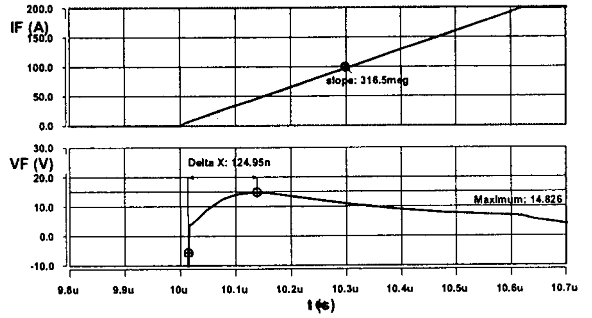

Fig. 2: Simulation test results, turn-on behavior of diode BYT261PIV400

The suggested simulation test circuit for diode turn-off behavior is a buck converter with constant output current and adjustable di/dt at turn-off, reverse voltage and ideal switch. This circuit is used by the diode manufacturers to specify reverse recovery. Usually data sheets content all measuring conditions.

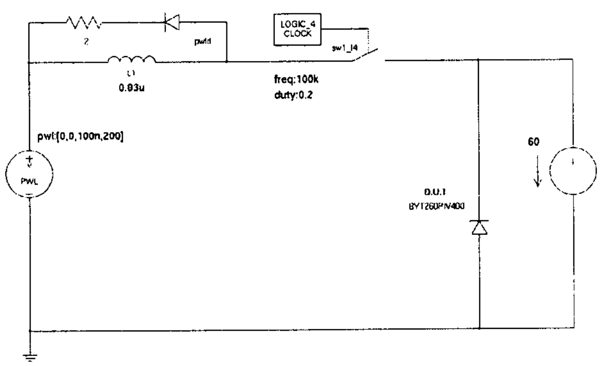

Fig. 3: Simulation test circuit, turn-off behavior of diodes

Test results have shown that maximum reverse recovery current can precisely be simulated for different di/dt. The smoothness of the current waveform is mostly not indicated in data sheets. It can be modeled by choosing the amount of charge and/or the reverse recovery time $t_{rr}$. This parameter has to be greater than the time of maximum reverse current $t_{IRM}$. If not the diode will turn-off very hardly. Another way to influence turn-off behavior is to consider the voltage dependent junction capacitance. The influence of both parameters is shown in Fig. 4 and Fig. 5. The capacitance value $C_2$ at reverse voltage $V_2$ leads to a two step current decrease with a different di/dt. The second step can be adjusted using the parameter $t_{rr}$. With the described parameters the so called soft-factor can be modeled as well.

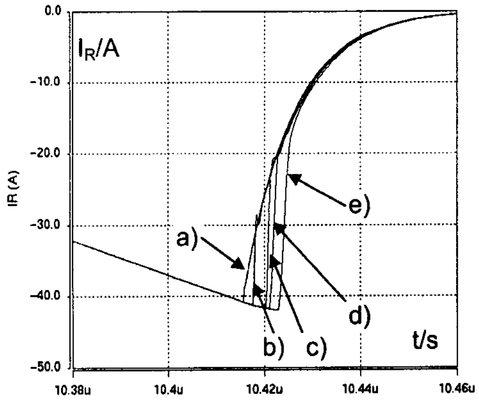

Fig. 4: Simulation test results, turn-off behavior of diode BYT261PIV400, parameter influence of Cj (0V/-25V) from left: a) 0pF/0pF b) 90pF/45pF and 300pF/45pF c) 300pF/200pF d) 300pF/300pF e) 500pF/500pF $I_{RM}$: 40A; dir/dt: 240 A/µs; $t_{irm}$: 167 µs; $t_{rr}$: 190 µs

The softness of diode turn-off behavior is mostly not sufficient documented in data sheets. Some manufacturers give special parameters extracted from non-standardized measurement configurations. The simulation test gave a high degree of conformity with the data sheet parameter C, Fig. 5. With the characteristics given in data sheets it is rather difficult to validate the dynamic behavior of diodes. Even more complicated is the parameterization if no dynamic parameters are given as in the following case.

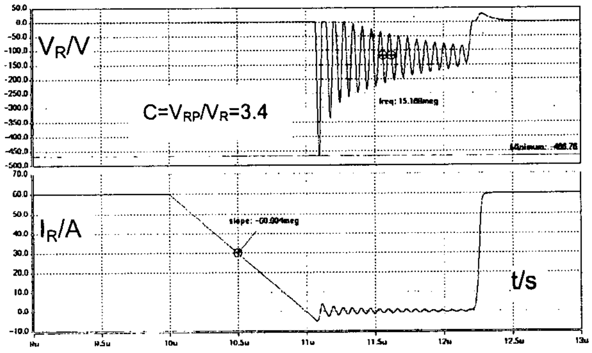

Fig. 5: Simulation test results, turn-off behavior BYT261PIV400, test circuit from data sheet; 800 nH series inductance

The only way out is to measure turn-off behavior, to extract parameters and to validate the parameterized model in a simulation test circuit close to the measurement configuration. We solved this successfully for a high-current diode used in resistance welding applications [6]. The experimental and simulation results are shown in Fig. 6 and Fig. 7.

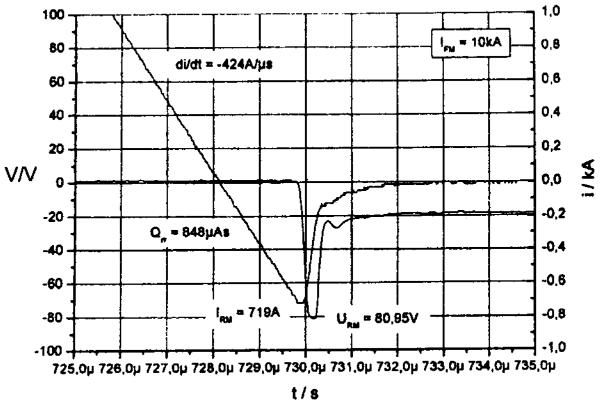

Fig. 6: Measured turn-off behavior, high-current diode 5SDD120 C0200

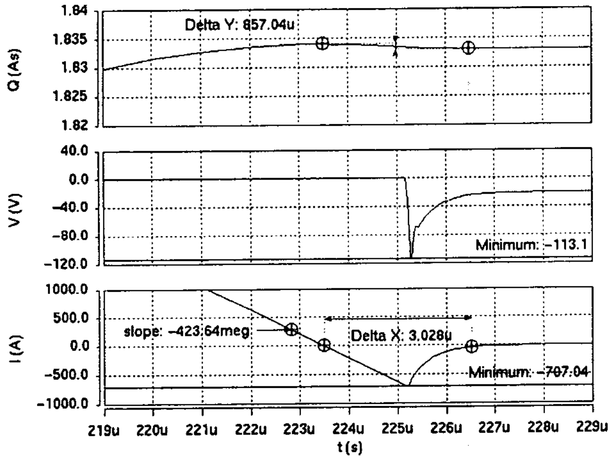

Fig. 7: Simulated turn-off behavior, high-current diode 5SDD120 C0200

The characteristics $I_{RM}$, $Q_{RR}$, $t_{IRM}$, $V_{RM}$ coincide, but the waveform of the decreasing reverse current is more angular in reality.

## III. DATA SHEET BASED DYNAMIC MOSFET AND IGBT BEHAVIORAL MODELS

### A. *MOSFET model*

The SABER *mp1* template is a behavioral power MOSFET model with DC characteristics and non-linear interelectrode capacitances [2]. Most of the 24 parameters as indicated in Tab. II and Tab. III are given in the data sheet either as characteristic values or as diagrams. 10 parameters describe the static behavior, as output and transfer characteristics and the other 14 determine dynamics with nonlinear capacitances and gate charge. There are some limits of the model. The temperature influence has not been considered. The parasitic body diode is not a part of the model and has to be inserted and parameterized separately. This model was tested for the 26A/900V MOSFET type STE26NA90 (STmicroelectronics). The static behavior can be described by three points of the static output characteristic. Two of them have to be taken from the boundary line between saturated and quasi-linear region, the third point is in the quasi-linear region and determines $R_{DSon}$. The channel threshold voltage $V_t$ can be taken from the transfer characteristic. This parameter is a very sensitive one. The data sheet value led to instabilities. A higher value resulting from a linearization of the transfer characteristic solved this problem. To validate the static behavior two simulation test circuits have been used. The results correspond to data sheet, Fig. 8.

The dynamic parameterization of the MOSFET model is a relatively extensive, iterative process because all 14 input parameters have an effect on the switching performance.

TABLE II
STATIC PARAMETERS OF SABER MOSFET MODEL *mp1*

| Parameter | Description | data sheet | STE26 NA90 |
|---|---|---|---|
| vds1 | vds at P1 (between quasi-linear and saturated area) | x | 27 V |
| vgs1 | vgs at P1 | x | 5 V |
| id1 | id at P1 | x | 63 A |
| vds2 | vds at P2 (between quasi-linear and saturated area) | x | 2 V |
| vgs2 | vgs at P2 | x | 4 V |
| id2 | id at P2 | x | 4 A |
| vds3 | vds at P3 (in quasi-linear area) | x | 18 V |
| vgs3 | vgs at P3 | x | 10 V |
| id3 | id at P3 | x | 56 A |
| vt | Channel threshold voltage | (x) | 3.9 V |

x directly available from data sheet
(x) indirectly available, to be adjusted

Some problems that have to be solved are that data sheet characteristics, which are given as values in a certain min/max range, have been measured under specified conditions. Additionally, some parameters for fine tuning are even unknown. The only way to validate the model is to test it in an environment close to the measurement conditions. Unfortunately, the definition of switching characteristics is very different in the data sheets of various manufacturers.

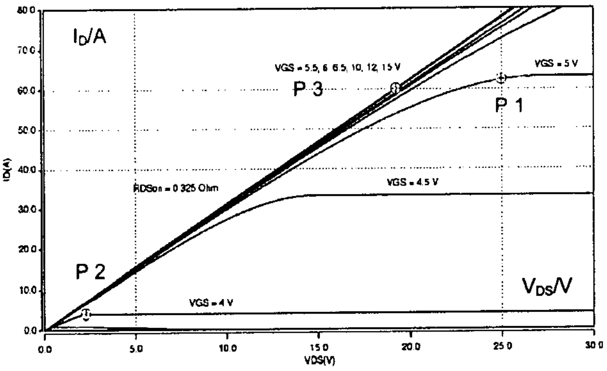

Fig. 8: Simulated output characteristic, MOSFET STE26NA90

And usually, there are no current or voltage waveforms given in the data sheets. Because a comprehensive test would be too extensive, some basic test simulations are recommended. These are for example the simulation of the nonlinear voltage dependent interelectrode capacitances, Fig. 9, and the gate charge plot. Both diagrams can be extracted from the simulation results.

TABLE III
DYNAMIC PARAMETERS OF SABER MOSFET MODEL *mp1*
Data sheet and parameterized STE26NA90

| Parameter | Description | data sheet | STE26 NA90 |
|---|---|---|---|
| crss1 | reverse transfer cap. vds=vgs=0 | 3 nF | 3 nF* |
| crss2 | rev. transf. cap. vds= vds4, vgs=0 | 270 pF | 252 pF* |
| coss1 | output cap. vds=vgs=0 | 7 nF | 7 nF* |
| coss2 | output cap. vds= vds4, vgs=0 | 1.13 nF | 0.81 nF* |
| vds4 | vds on crss curve | 25 V | 25 V |
| q1 | Qg at beginning of Miller-plat. | 43 nC | 25 nC* |
| q2 | Qg at end of Miller-plat. | 270 nC | 125 nC* |
| q3 | total on-state charge | 470 nC | 350 nC* |
| vgs4 | vgs at Miller-plateau | 4.2 V | 4.2 V |
| vgs5 | on-state gate voltage (vgs5>vgs4) | 10 V | 10 V |
| vds5 | on-state vds | 7 V | 7 V |
| vds6 | off-state vds | 720 V | 720 V |
| rg | internal rg | - | 1.2 Ω* |
| m | Miller capac. coeff. | - | 0.6 |

* measured

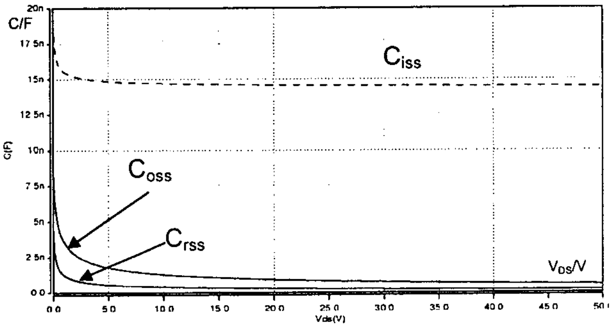

Fig. 9: Simulated nonlinear interelectrode capacitances, MOSFET STE26NA90

If the simulation results confirm that the model has the expected characteristics concerning the capacitances and gate charge, we can go on to the next step. Switching performance is characterized by switching times and in some cases by switching losses or energy. With a simulation test circuit as shown in Fig. 10, it is possible to test the switching behavior very easily.

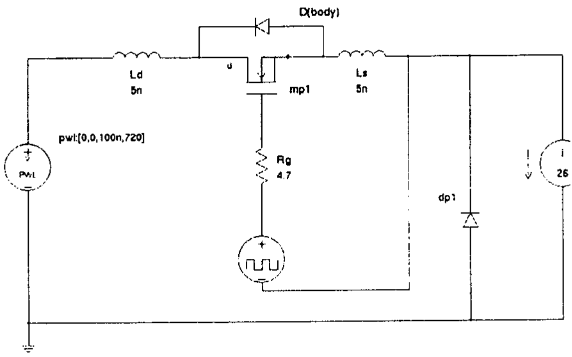

Fig. 10: Simulation test circuit, switching behavior of MOSFET models, hard switching

The circuit elements can be taken from the measuring conditions of the data sheet. Fig. 11 shows the simulated switching waveforms at hard turn-off of the MOSFET STE26NA90 considering an internal series inductance.

Tab. IV gives a comparison of simulated to data sheet characteristics for resistive turn-on and inductive turn-off.

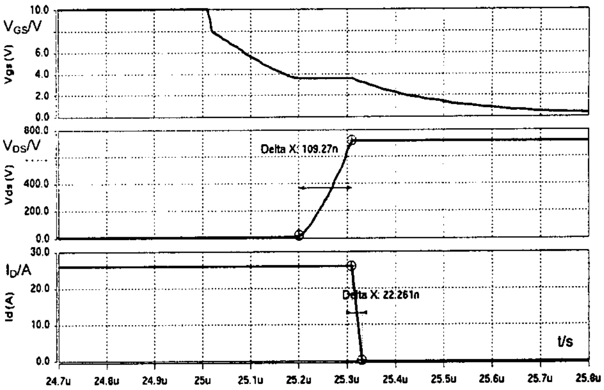

Fig. 11: Simulation test results, switching behavior of MOSFET STE26NA90, hard turn-off

TABLE IV
COMPARISON OF SWITCHING TIMES MOSFET STE26NA90

| Parameter | Description | data sheet | simulation |
|---|---|---|---|
| tr(Voff) | off-voltage rise time | 108...152 ns | 109,3 ns |
| tf | fall time | 25...35 ns | 22.3 ns |
| tc | cross-over time | 145...203 ns | 184,8 ns |
| td(on) | on-time delay (resistive) | 40...56 ns | 21.1 ns |
| tr | rise-time (resistive) | 52...73 ns | 91.6 ns |

### B. *IGBT model*

The *igbt1* template is an IGBT model featuring the static characteristics, the non-linear interelectrode capacitances and the tail current in turn-off switching [2]. The parameters correspond to the *mp1* model. Additionally, three parameters describe the tail effect. Unfortunately these parameters are not given in data sheets and have to be measured. For a validation of the parameterized model it is recommended to simulate the switching losses in a test circuit close to the data sheet. From the $V_{CE}/I_C$ waveforms the switching energy can be extracted easily. The switching loss diagrams delivered from most of the IGBT manufacturers give the only possibility to validate the influence of the tail effect. As an example we parameterized the IGBT SKM200GAL124D (Semikron) which is often used in inverters for resistance welding or high power arc welding. As Tab. V clearly shows, the results of simulation and data sheet diagrams coincide very good.

TABLE V
COMPARISON OF SWITCHING PARAMETERS
IGBT SKM200GB124D

| Parameter | Description | data sheet | simulation |
|---|---|---|---|
| td(on) | turn-on delay | 75 ns | 84.2 ns |
| tr | rise time collector current | 50 ns | 55.3 ns |
| Eon | turn-on energy | 21 mWs | 22 mWs |
| td(off) | turn-off delay | 520 ns | 771 ns |
| tf | fall time collector current | 50 ns | 47.4 ns |
| Eoff | turn-off energy | 19 mWs | 18.3 mWs |

## V. ANALYSIS OF ARC WELDING INVERTER POWER SOURCES

Based on the described models a detailed power loss analysis has been carried out for inverter arc welding power supplies [7]. Comparing the simulation results of an inverter model based on ideal switches with an inverter model based on dynamic models makes the differences clear. The full model consists of 4 MOSFETs STE26NA90 with body diodes and parasitics, paralleled secondary rectifier diodes BYT261PIV400 with RC snubbers, bipolar driving circuits with gate resistors and a transformer model with leakage inductance and constant ohmic winding resistance, Fig. 12.

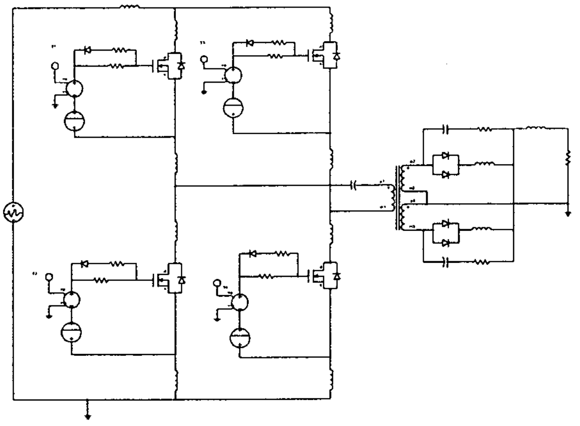

Fig. 12: Full-bridge phase-shifted arc welding inverter, simulation model with dynamic semiconductor models and parasitics

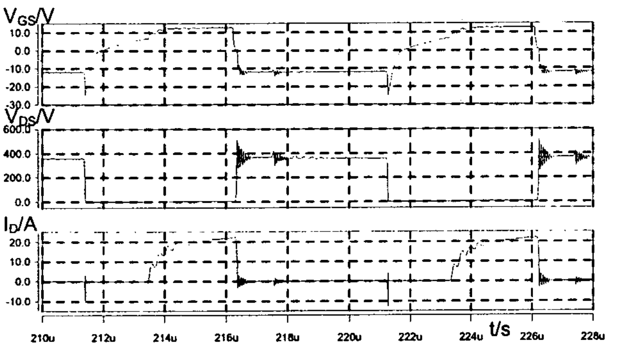

Fig. 13: Simulated MOSFET current and voltage waveforms

TABLE VI
SIMULATION RESULTS: POWER LOSS ANALYSIS @ 100 KHZ

| Element | Power Losses |
|---|---|
| MOSFET (4) | 157 W |
| Rectifier diodes (4) | 175.8 W |
| Transformer | 81 W |
| Snubber (2) | 4.2 W |
| Bodydiode (4) | 9.6 W |
| **Total** | **427.6 W** |
| Pin | 4631.9 W |
| Pout | 4189.3 W |
| **Pin - Pout** | **442.6 W** |

As an example of the simulation results Fig. 13 shows the MOSFET switching waveforms. Precise results concerning ringing effects, voltage transients and switching losses can only be achieved with these dynamic models. As another result a power loss analysis of the inverter is given in Tab. VI.

The computing time for all toplevel parameters and a simulation time of 200 µs was 2 min for the ideal model and 7 min for the full model both on a Solaris SunUltra workstation 143 MHz/ 256 MB RAM. On a WinNT platform and using a 1.3 GHz Athlon processor and 512 MB RAM the computing time for the full model has been extremely decreased to about 7.8 sec for the same simulation time, truncation error and output file.

## VI. CONCLUSION

With the presented experiences a contribution should be given to the ongoing application of modern simulation tools in power electronics. Data sheet based semiconductor behavioral models are a good alternative to physical models especially in the design process of switched mode power sources. The parameterization of data sheet based models requires some experience and practical understanding of power semiconductor behavior, but is much easier than a parameterization of physical models. These tools give a higher flexibility introducing new power semiconductors, which have better characteristics but mostly the same structure and basic behavior. All models reviewed in this paper contain some non-data-sheet parameters which require own measure-ments or which have to be adjusted. The parameterized models should be validated with simulation test circuits close to the real test circuits described by manufacturers. One of the problems to be solved is the demand for high quality and more detailed data sheets. Furthermore, the number of simulation software products which have already implemented these models is still too low. And last but not least, the documentation of the capabilities of these models is not yet very user-friendly. But, the application engineer should notice that former arguments such as limitations in computing time, file size and a too high circuit complexity have lost their importance due to the recent years computer hard- and software development.

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