

FlowSIM – new innovative electrical and thermal simulation method for power modules in inverter applications.

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Abstract

The goal of the flowSIM simulation project is to run electrical and thermal simulations of power modules simultaneously. An electrical simulation part yields excitation current and voltage time waveforms for the specific power module components taking part in the power conversion process.

Basic topologies and parameters of the application can be defined by the user. The electrical simulator part works on ideal components, where excitation waveforms are numerically calculated. The result of the electrical simulation section is fed into a loss calculation part that gives the excitation for a thermal simulation part. The components are characterized prior to the thermal simulation. Main properties of the components are described by the static and thermal characteristics and by the switching characteristics for devices that are working in switching mode.

The thermal simulation uses the dynamic thermal characteristics to predict the semiconductor component temperature as a function of time during a period of excitation.

Introduction

The electrical and thermal simulation of the semiconductors is a powerful tool for optimized component selection. However the limitation of desktop computing capacity still requires a compromise to be made between accuracy and speed of a joint electro-thermal simulation process. Modern semiconductor switching devices switch in tens of nanoseconds while thermal time constants of the system can reach hours.

Universal electrical circuit simulators need plenty of calculation to reach acceptable accuracy on both end of the timescale.

Furthermore due to numerous nonlinearities in the switching process of the semiconductors precise loss calculation can not be done on linear small signal models of the used components.

Averaging is done for each period of the switching process (T_{sw}). It is assumed that the state-variables in the system do not significantly change during one switching period.

On the other hand to avoid long calculation with high thermal time constants only steady state solution is given. For thermal calculation a fix thermal reference point as heat sink temperature is selected.

There is a finite number of building blocks for selecting one or three phase AC input and one or 3 phase AC output for a frequency converter. The input block is connected with the output block through a DC link capacitor. In case of single phase input an optional PFC stage can be selected. (see Fig 1)

Description of operation

For cutting computational needs for signals on the low timescale flowSIM uses the state-space averaging model for pulse width modulated (PWM) switching converters [1].

$$D(t) = \int_{x=t}^{x=t+T_{sw}} PWM(x) dx$$

Where $PWM(x)$ is the device duty cycle function taking values of 0 and 1 for switching device off and on states while $D(t)$ is the averaged duty cycle taking values $0 \leq D(t) \leq 1$ through the modulation process.

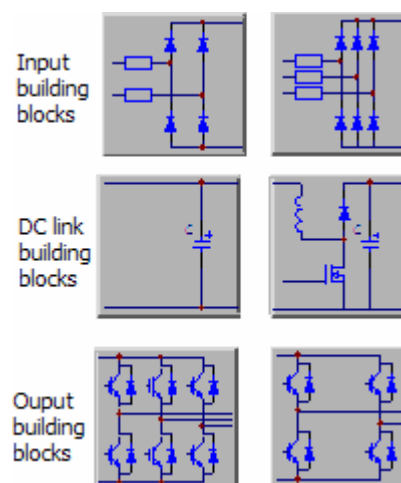


Fig. 1 Electrical building blocks

Electrical Simulation

Each building block is described by a mathematical model that is used for excitation current calculations. For example the following equations are solved in case of a single phase input and a three phase output.

$$U_{in}(t) = U_{in_{RMS}} * \sqrt{2} * \sin(2 * \pi * f_{in} * t)$$

$$U_{dc}(t) = \left(\int (abs(I_{in}(t)) - P_{dc} / U_{dc}(t)) dt \right) / C_{dc}$$

$$abs(I_{in}(t)) = (abs(U_{in}(t)) - U_{dc}(t)) / R_{in} \text{ if } abs(U_{in}(t)) > U_{dc}(t)$$

$$I_{in}(t) = 0 \text{ if } abs(U_{in}(t)) \leq U_{dc}(t)$$

$$I_r(t) = (I_{in}(t) + abs(I_{in}(t))) / 2$$

$$U_{out_U}(t) = U_{out_{RMS}} * \sqrt{2} * \sin(2 * \pi * f_{out} * t)$$

$$I_{out_U}(t) = I_{out_{RMS}} * \sqrt{2} * \sin(2 * \pi * f_{out} * t + \phi_i)$$

$$I_{sw_{U low}}(t) = I_{out_U}(t) * (D_u(t) - 1)$$

$$I_{igt}(t) = (I_{sw_{U low}}(t) + abs(I_{sw_{U low}}(t))) / 2$$

$$D_u(t) = 1 / 2 + U_{out_{RMS}} * \sqrt{2} / U_{dc}(t) * (\sin(2 * \pi * f_{out} * t) + 0.167 * \sin(3 * 2 * \pi * f_{out} * t))$$

where U_{in} , f_{in} , C , R_{in} , U_{out} , f_{out} , I_{out} and ϕ_i are scalar variables while input voltage, input frequency, DC link capacitor, input line resistance, output voltage, output frequency, output current, output load phase shift are defined by the application.

I_r is the current of a single rectifier on the input. I_{igt} is the current of the low side IGBT of the U phase in the three phase output inverter. The D duty cycle modulation type for the output can be selected as standard SPWM or 3th harmonic modulation for higher output voltage. The modulation index is compensated with the DC link ripple voltage to get an undistorted sine wave on the output. (see Fig 2)

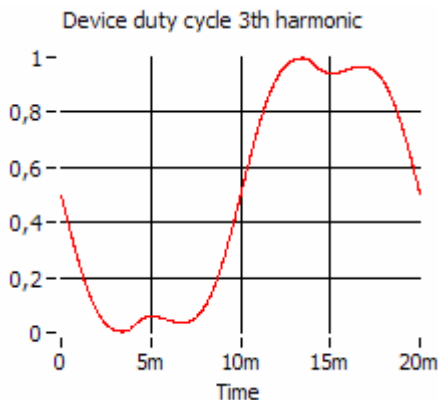


Fig. 2 Duty cycle in the low side switch of the U output phase

Time dependent electrical variables are calculated by numeric iteration from the input excitation. For the convergence of the iteration process f_{out}/f_{in} is allowed to be an integer power of the number 2 only.

The time-step for the calculations is defined as $\Delta t = 1/f_{in}/N$ where N is the number of data points during one input cycle. N is selected as a compromise between speed and accuracy of simulation. Iteration cycles are running until one period of the result signal reaches a certain error level relative to the previous result. (see Fig 3)

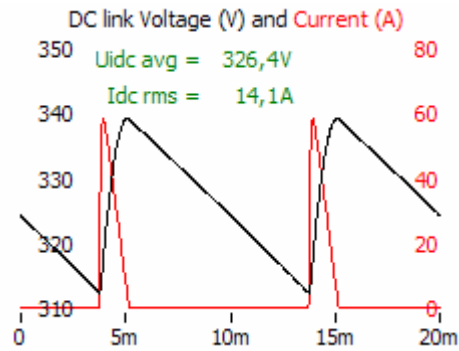


Fig. 3 DC link voltage and current result

The iteration process is speed up by the proper selection of the initial condition for the U_{dc} state-variable. In case of a peak rectifier the selection of input peak voltage as the initial parameter for the DC link capacitor voltage will result in a small number of cycles.

For the PWM switched current signals the envelop curves are displayed for later use in the loss and thermal calculation section as both static and switching losses are dependent on the actual peak current level during the cycle. (see Fig 4)

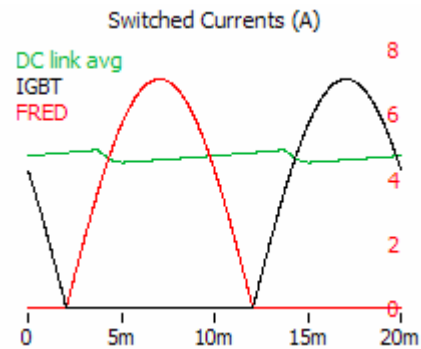


Fig. 4 PWM switched currents

The real shape of DC link current to the inverter is different for given types of modulation but the averaged current is following the output power.

$$I_{dcavg}(t) = P_{dc} / U_{dc}(t)$$

Loss and thermal simulation

The loss and thermal calculation section calculates the electrical power loss and temperature of a selected component in the power conversion process. These components are rectifier of the input building block, PFC switching transistor and PFC FRED of the optional PFC stage and inverter IGBT and inverter FRED of the output building block.

These calculation are running synchronously in an iterative mode to be able to include the cross dependency of component loss and component temperature. The consecutive runs of the iteration process are using the loss and thermal results of the previous run.

The junction temperature waveform of the selected component is displayed when a given error level is reached between the runs. (see Fig 5)

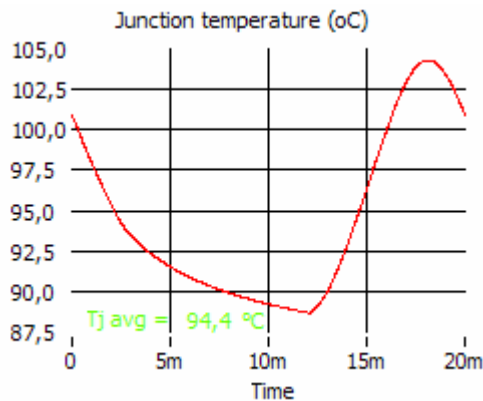


Fig. 5 Component junction temperature result

The error level is a preset parameter, which is set to give acceptable accuracy with the smallest possible number of iteration cycles. If the given error level is not reached after a certain number of iteration cycles a warning message is generated.

The number of iteration cycles can be drastically reduced by initializing the state variables with the steady state estimated average values.

(see Fig 6)

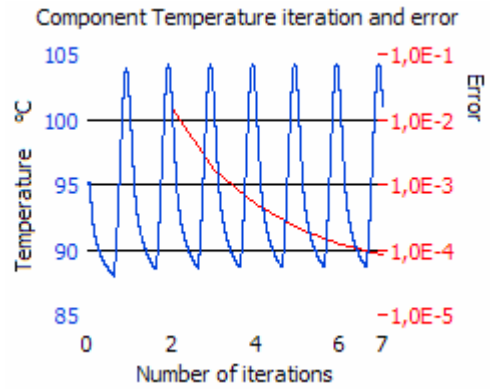


Fig. 6 Temperature and error as a function of iteration cycles

The state variables of the temperature calculation are the thermal capacitances in the thermal model of the component.

The loss calculation is based on the measured electrical characteristics of the components.

There are two kinds of losses considered. Both static and switching losses are calculated as a function of time.

Static losses of components that are not operating in the switching mode are calculated from the excitation current using the static characteristics only.

$$P_{st}(t) = U(T, I(t)) * I(t)$$

Where T is the junction temperature while U(I) is the static voltage current characteristics of the component.

The static voltage characteristic values are given in two dimensional arrays as a function of temperature and current. At the end of the iteration both the result voltage and excitation current time functions can be seen. (see Fig 7)

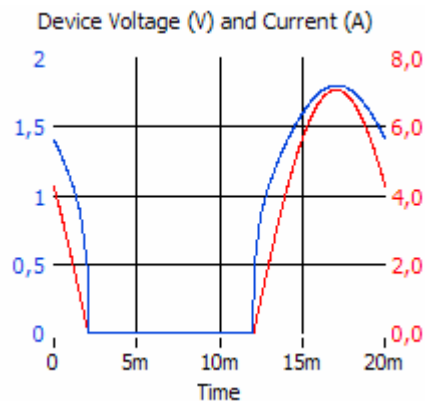


Fig. 7 Component voltage result

Static losses of components that are operating in the switching mode are calculated from the excitation current dependent on the static character-

istics and from the $D(t)$ averaged duty cycle function of the component.

$$P_{st}(t) = U(T, I(t)) * I(t) * D(t)$$

The switching losses are calculated as following

$$P_{sw}(t) = (E_{off}(T, R_g, I(t)) + E_{on}(T, R_g, I(t))) \cdot f$$

$E_{off}(t)$ and $E_{on}(t)$ are the turn off and turn on energy losses of the switching type component. Both quantities are stored as three dimensional arrays as a function of temperature current and gate resistance. A linear interpolation method is used in all three dimensions to get the exact value of loss for different values of R_{goff} turn off resistance, (R_{gon} turn on resistance), and for instantaneous current and temperature values.

As a fourth dimension for each point of the loss curve the switching losses are interpolated from two nominal voltage switching measurement points with the actual value of the DC link voltage.

$$P(t) = P_{st}(t) + P_{sw}(DC(t), t)$$

The static, the switching and the total losses are all available at the end of the iteration. (see Fig 8)

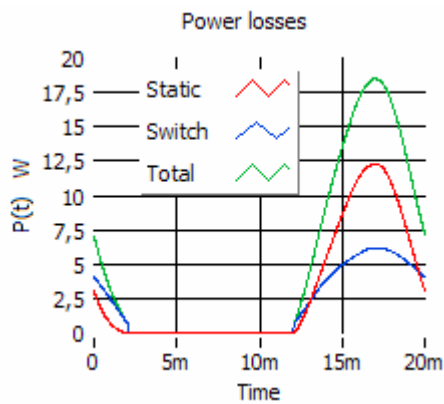


Fig. 8 Component loss result

The thermal simulation is based on a Foster type thermal model of the component.

The total power loss $P(t)$ is the excitation for the thermal calculation. (see Fig 9)

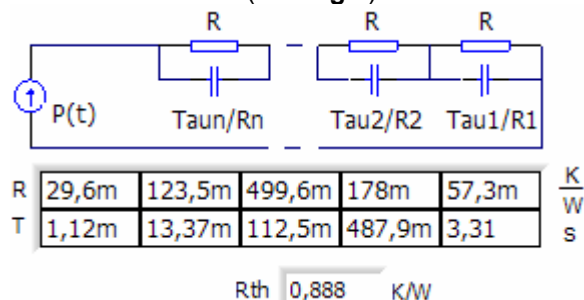


Fig. 9 Component thermal model

At the base of the component mounting a selectable constant heat sink temperature is assumed.

Dependent on the (n) total number of (R_i) thermal resistance and (τ_{ai}) thermal time constant pairs describing the thermal model, the following equations are used for the temperature difference in degrees.

$$\frac{d\Delta T_i(t)}{dt} = \frac{P(t) \cdot R_i - \Delta T_i(t)}{\tau_i}$$

The equations are solved by Euler method. So the temperature time function of the component is

$$T(t) = T_h + \sum_{i=1}^n \Delta T_i(t)$$

where T_h is the heat sink temperature.

It is important to give the right T_i initial values for the τ_{ai}/R_i thermal capacitances to have a fast iteration. The initial values are calculated from the average dissipation of the first run with an initial junction temperature of 125°C.

Characteristical data

The component data that contains the static, switching and thermal characteristics of the components is organized in a different file, which can be continuously extended with new components. The data base is constructed in a way that components taking part in the power conversion process are linked through physical appearance in specific power modules. (see Fig 10)

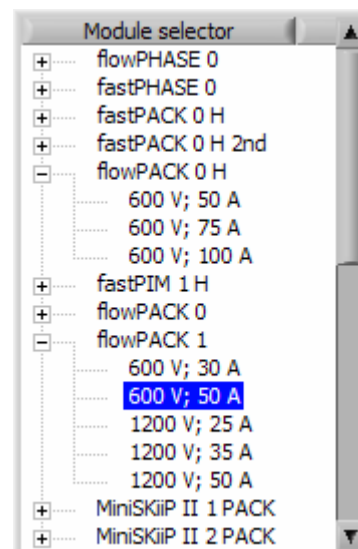


Fig. 10 Module selector

However it is possible to select components from different power modules for the components of the different building blocks used in the simulation.

To decrease the size of the database file the measured characteristics of the devices are re-sampled when composing the database file. A high (125°C) and a low (25°C) temperature characteristics of each component are stored. The temperature dependency is supposed to be linear between the measured values in the whole temperature range.

Only static characteristics of typical gate voltage e.g. 15V are subtracted and equidistantly sampled in current. (see Fig 11)

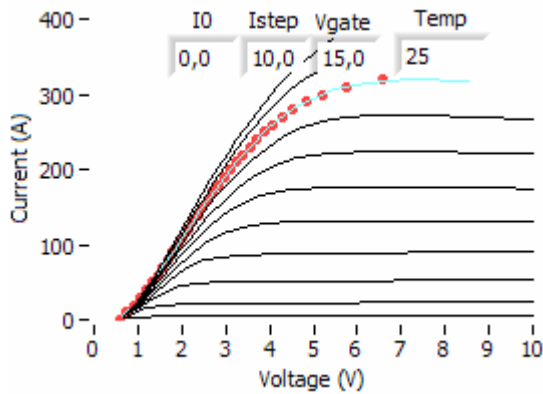


Fig. 11 Re-sampling of static characteristics

The dimension of the switching characteristics data is dependent on number of available measurements.

Current level, gate resistance and temperature variables can be handled as full dimensions for piecewise linear interpolation, while measurement at two different values of supply voltage allows a linear interpolation and extrapolation for supply voltage dependency of switching energy losses.

The diagrams below show the measured turn off switched current and voltage waveforms for 5 different current levels and each with 5 different gate resistor values. The calculated turn off energy losses can be also seen. (see Fig 12)

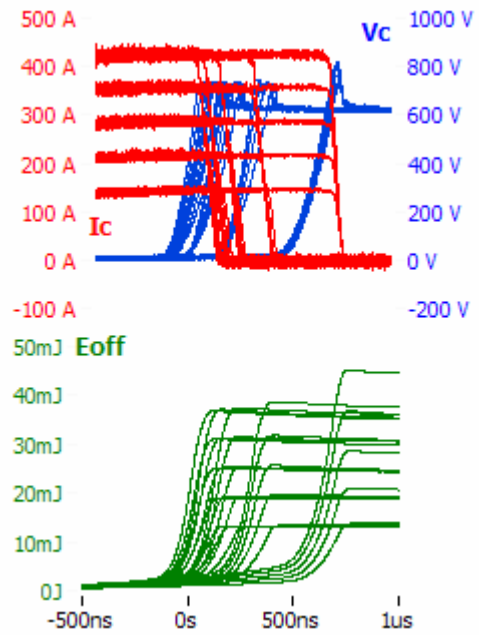


Fig. 12 5*5 set of curves for Eoff calculation

During loading measurement data the current level is always re-sampled for predefined step resolution for good accuracy and speed. In most cases only 25°C and 125°C measurement curves are used for composing the switching loss description database. (see Fig 13)

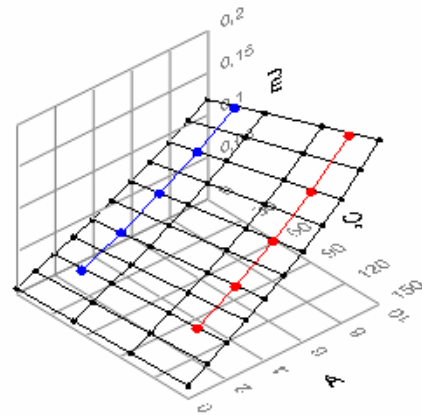


Fig. 13 Re-sampling of switching energy loss measurement results for current and temperature

Thermal characteristics are given with the Ri thermal resistance and Taui time constant pairs. The values are derived from thermal characterization of each component.

After heating up the component with a known power to a steady state temperature the heating power is suddenly removed and the cooling curve of the component is recorded. (see Fig 14)

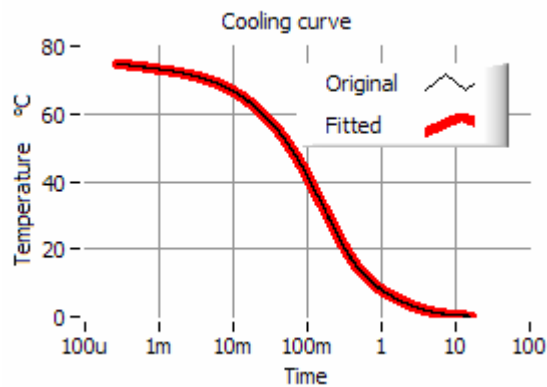


Fig. 14 Original measured and fitted cooling curves of a component

The cooling curve is estimated as a sum of independent exponentially decaying curves.

$$\Delta T_{off}(t) = P \cdot \sum_{i=1}^N R_i \cdot e^{-\frac{t}{\tau_i}}$$

As a result of fitting the R_i and τ_i pairs are available for storing into the database.

Summary

The effectiveness of a joint electro-thermal simulation is mainly dependent on the selection of simulation model that is both accurate and fast enough for practical usage.

The flowSIM tool uses a limited number of electric circuits for simulation and works on idealized components to get fast results of the circuit simulation section.

The characteristic parameters of the components used for the loss and thermal calculation are compressed in a predefined data base format for fast easy and access by the loss and thermal simulation section.

These simplifications allow displaying a quasi real time response of the chip temperature in time function for the changes in electrical circuit, power module and component type and for all programmed application specific parameters.

Literature

- [1] R.D. Middlebrook and S. Cuk, "A General Unified Approach to Modeling Switching Power Converter Stages" IEEE PESC 1976,pp.18-34.