Comparison of loss-simulation via PLECS v4.4.4 and TopBench v2.0.0

In this paper a direct comparison of the performance of the software TopBench and Plexim PLECS is performed. For reference a standard B6-inverter has been implemented in Plexim PLECS in version 4.4.4. The control is implemented as a dq-control and a standard 3-phase Triangular-Sinewave-PWM-controller is used to generate the PWM-signals for each IGBT:

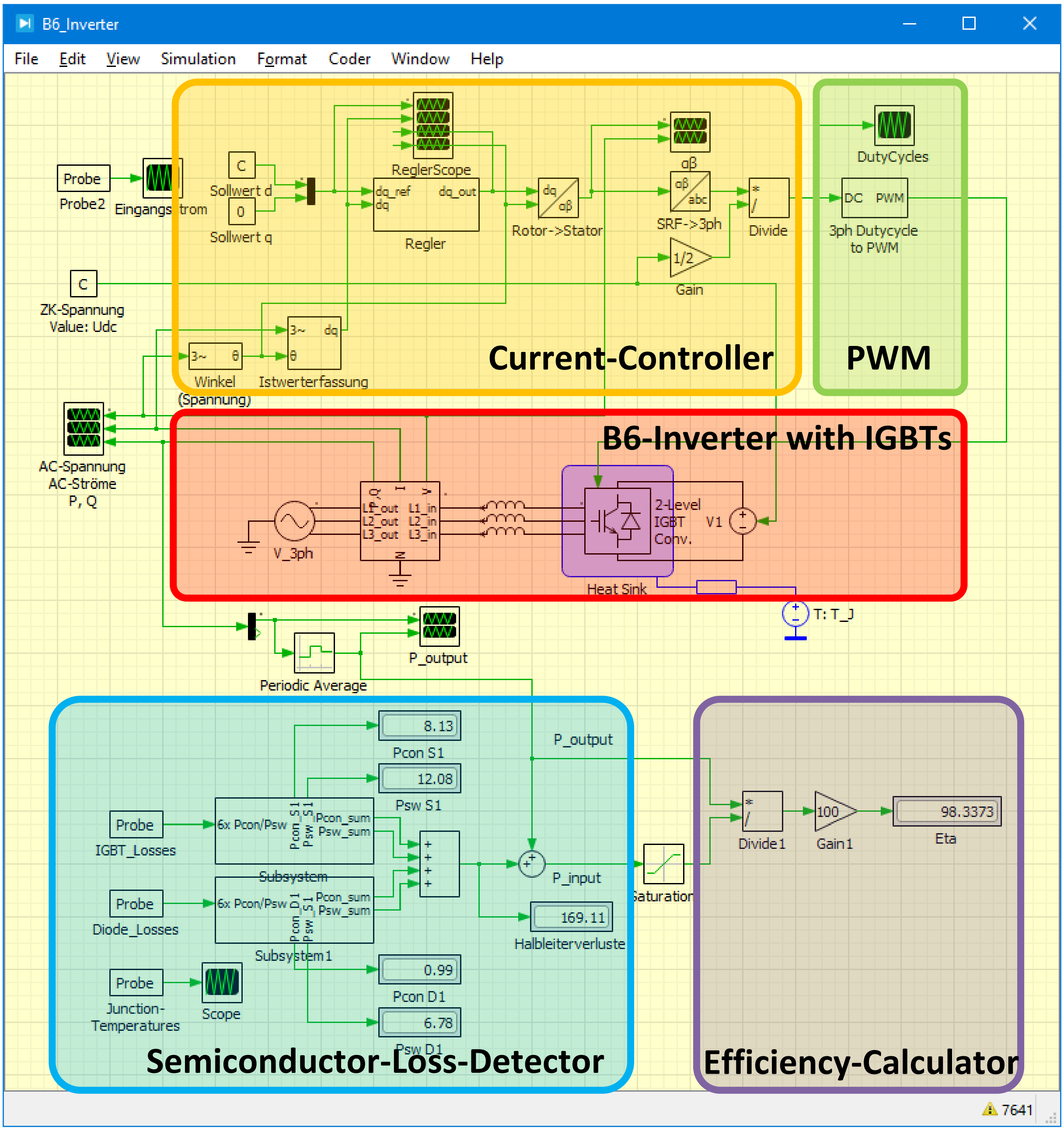

Fig. 1: Simulation in PLECS

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Fig. 1 shows the output-signals of the simulation und der following conditions:

- Output-Power: 10 kW
- Switching-Frequency: 16 kHz
- Grid-Frequency: 50 Hz
- Heatsink-Temperature: 95 °C
- cosphi=1
- Inductance per Phase 1,900 mH
- DC-Link-Voltage: 662V
- AC-Voltage: 230V (Phase2Neutral)

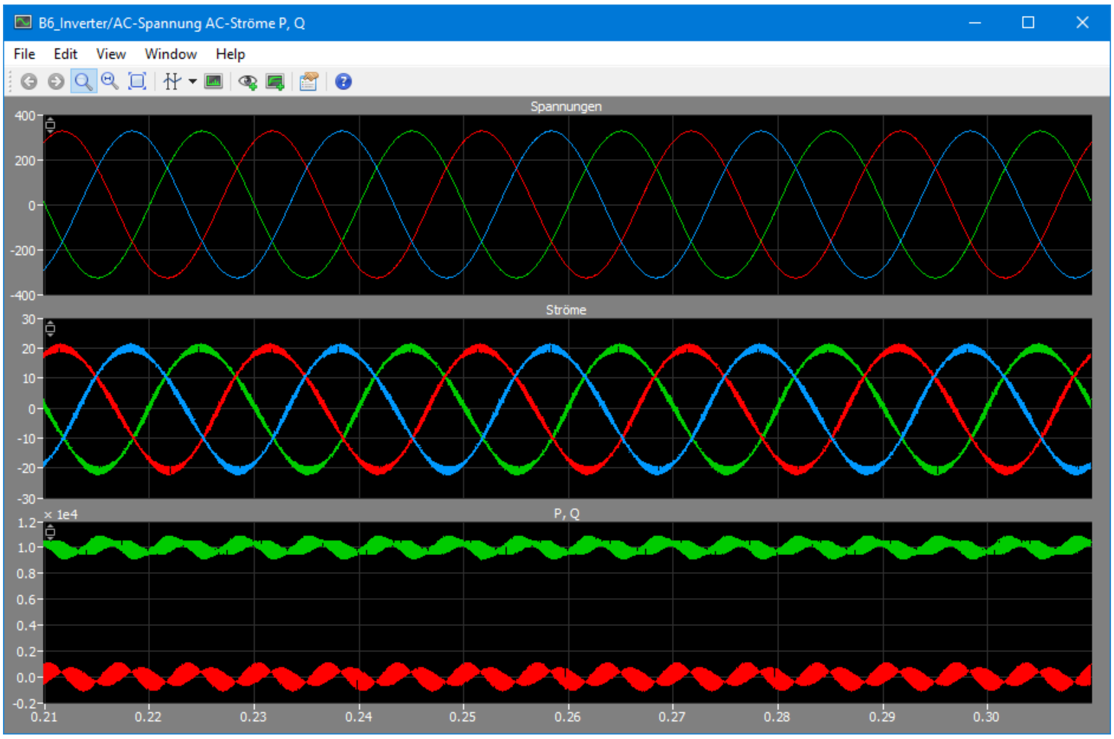

Fig. 2: Output-Signals

To simulate losses with PLECS definitions for conduction- and switching-losses are necessary. These definitions are taken from measurements with a double-pulse-test using the software KDEE-EVS ComCell. The resulting loss-definitions for an IGBT are shown in the following figures Fig. 3 to Fig. 5:

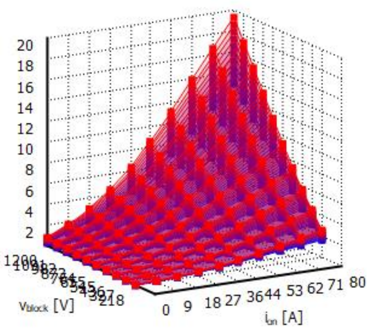

Fig. 3: Turn-On-Losses

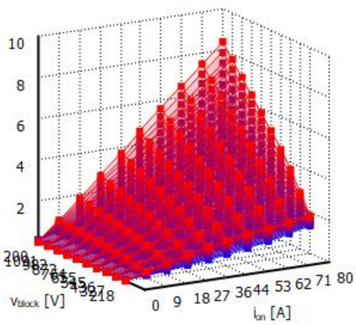

Fig. 4 : Turn-Off-Losses

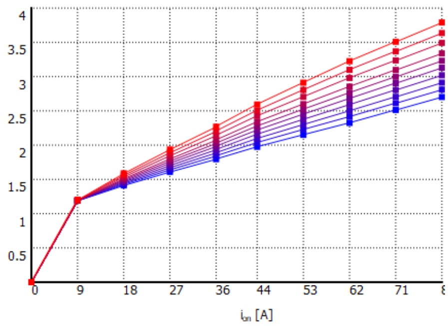

Fig. 5 : Conduction-Losses

Using these definitions PLECS is able to calculate energy-dirac-impulses based on the device-current and -voltage as well as current-based voltage-drop resulting in the conduction-losses. This current through the IGBTs will warm-up the devices during the conduction of 20A in peak, so we will get the following temperature-curves for all six IGBTs:

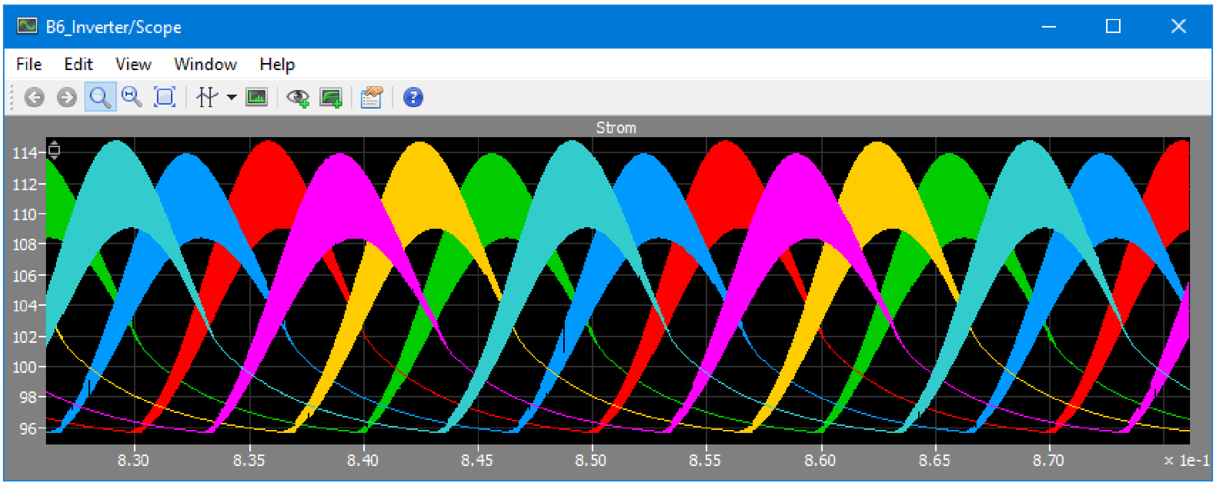

Fig. 6: Temperature-curves for all six IGBTs

During the peak of the current each IGBT will warm up to around 115°C while it will cool down to 95°C during the opposite sine-halfwave with no current. This 20°C difference is directly related to the individual thermal-resistance of 0,31 K/W per IGBT. Fig. 7 shows the conduction-losses over time of IGBT S1 with a peak of 36W of losses. Together with the switching losses of around 14,5W this results in $\Delta T = 0{,}31\frac{K}{W} \cdot (36W + 14{,}5W) = 15{,}6K$. The missing 5K are related to the thermal-capacitance given by a Cauer-Network defined in PLECS.

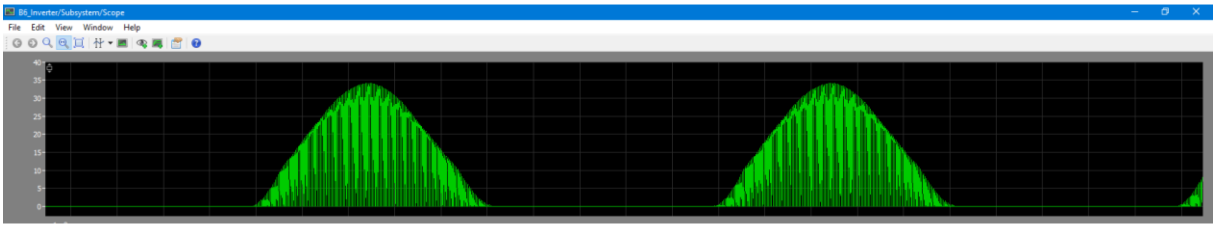

Fig. 7: Conduction-Losses of IGBT S1 in Watt

After about five grid-periods all oscillations and settling processes within the simulations are completed and the loss-values can be taken for $T_{Heatsink}$=95°C and $T_{Junction,Peak}$=115°C:

- $P_{conduction,S1} = 8{,}13W$
- $P_{switching,S1} = 12{,}08W$
- $P_{conduction,D1} = 0{,}99W$
- $P_{switching,D1} = 6{,}78W$
- $P_{loss,Semiconductors} = 169{,}11W$
- $\eta_{@3kW} = 98{,}34\%$

The currents of one single IGBT and Diode are shaped as shown in Fig. 8 and Fig. 9 which will be used in the software TopBench:

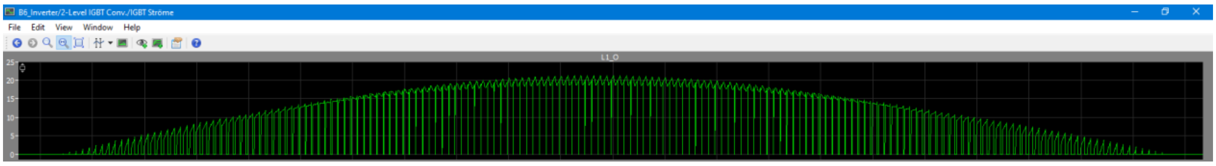

Fig. 8: Current of one single IGBT

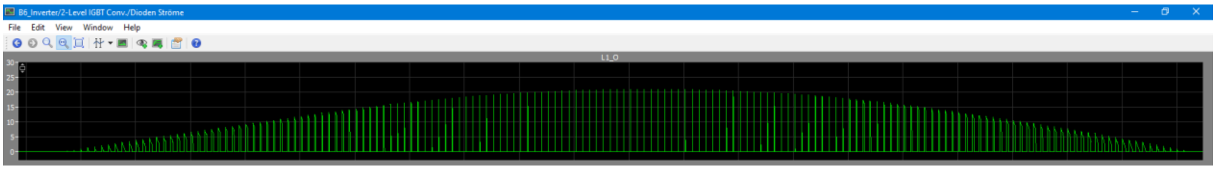

Fig. 9: Current of one single Diode

This is working quite well, but if you want to change parameters like AC-voltage, inductance, ripple, voltages or simply the semiconductors, several parameters must be changed. Most of the time the current-controller has to be adapted and the parameters needs a tuning. TopBench is using a different approach speeding up the calculation while being more robust at the same time. Therefore, TopBench is using the calculated dutycycle over time based on several parameters like AC-voltage, DC-Link-Voltage, etc. The user defines which kind of modulation and what kind of inverter (2-level, 3-level, etc.) is used to calculate the correct dutycycle for each individual switch or diode. *Fig. 10* shows the loss-definition in TopBench based on the modulation-strategy (here standard-modulation) resulting in the dutycycle over time in blue and the individual device-current in red:

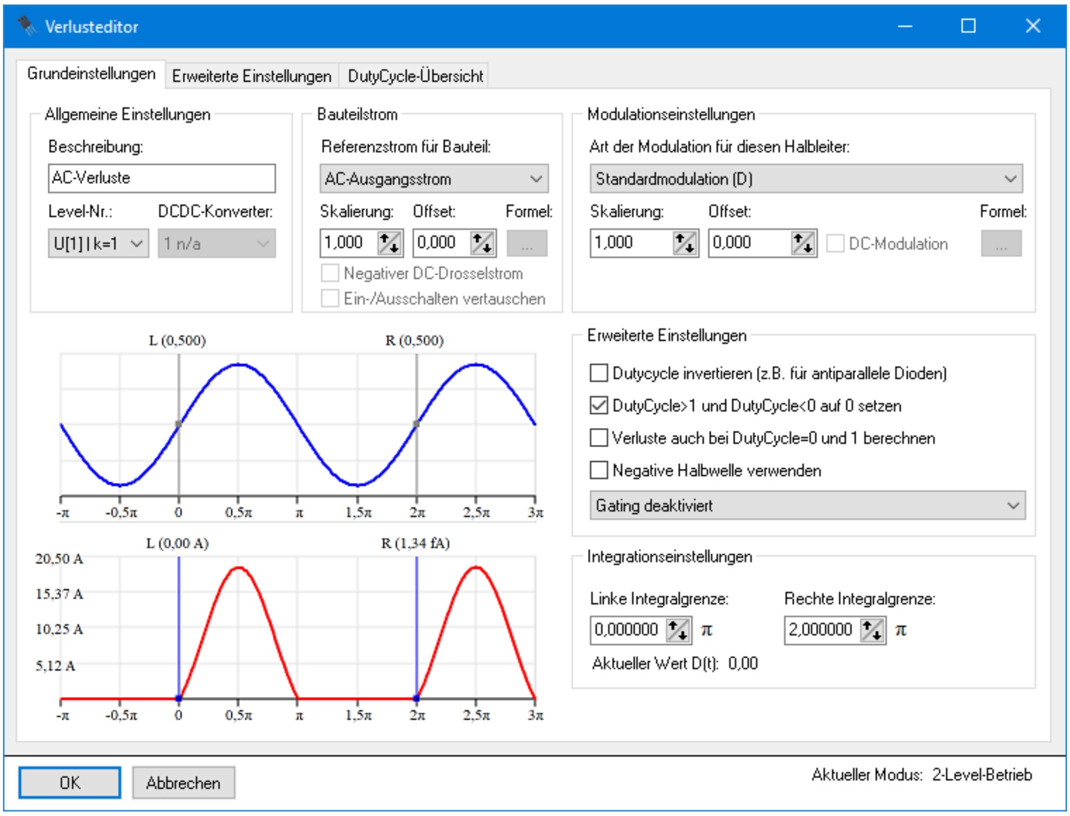

Fig. 10: Current-shaping-definition in TopBench

This device-current is basis for calculating the losses using a loss-definition-database like PLECS, where conduction-losses and switching-energies are stored (Fig. 11):

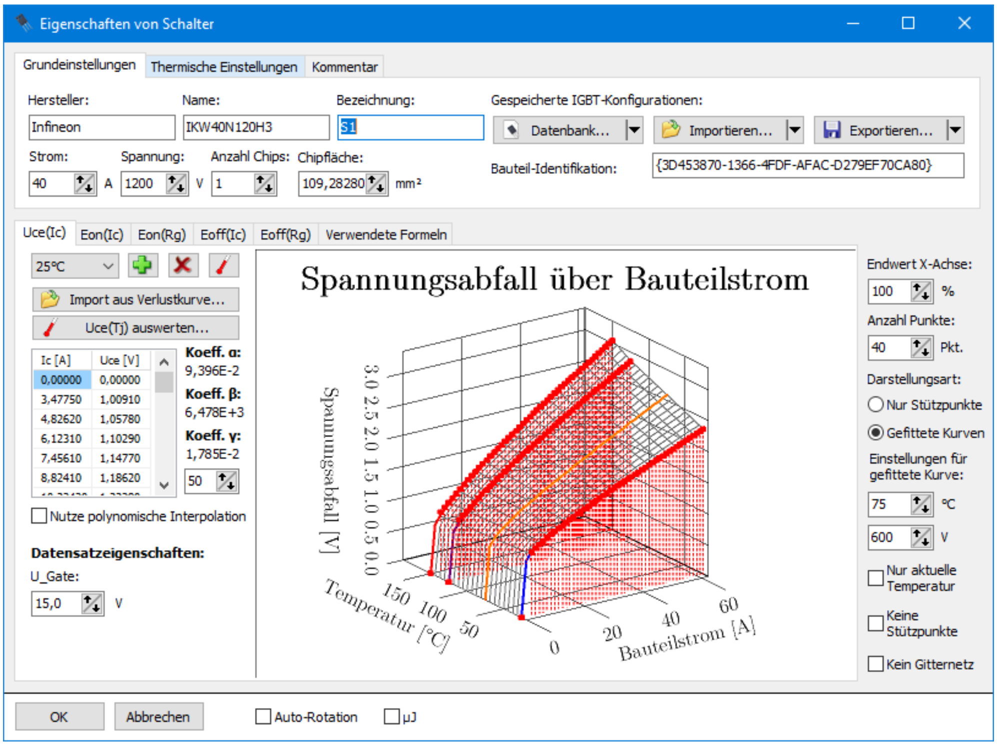

Fig. 11: Loss-definition-database

In the main screen of TopBench (see Fig. 12) all switches and diodes, the associated current-shapes, loss-definitions per device and the general system-definitions (DC-voltage, AC-voltage, power, temperatures, etc.) are set up.

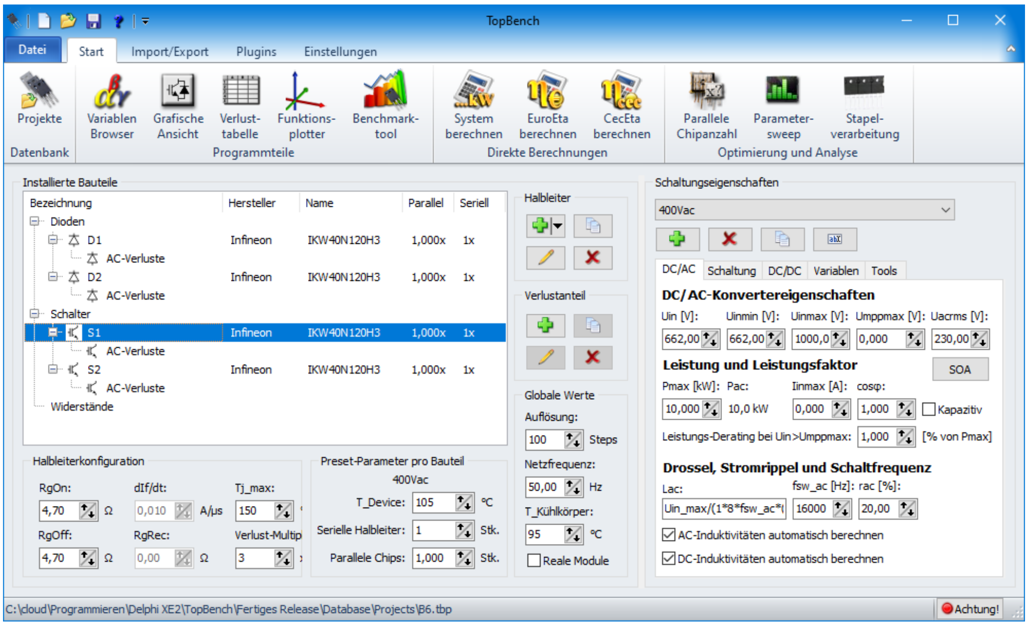

Fig. 12: Main-screen of TopBench

When all parameters are set, the software can calculate the current over time for all devices and thus the losses for each device individually. Based on the given or calculated inductance the current-ripple will be considered, too, as shown in Fig. 13:

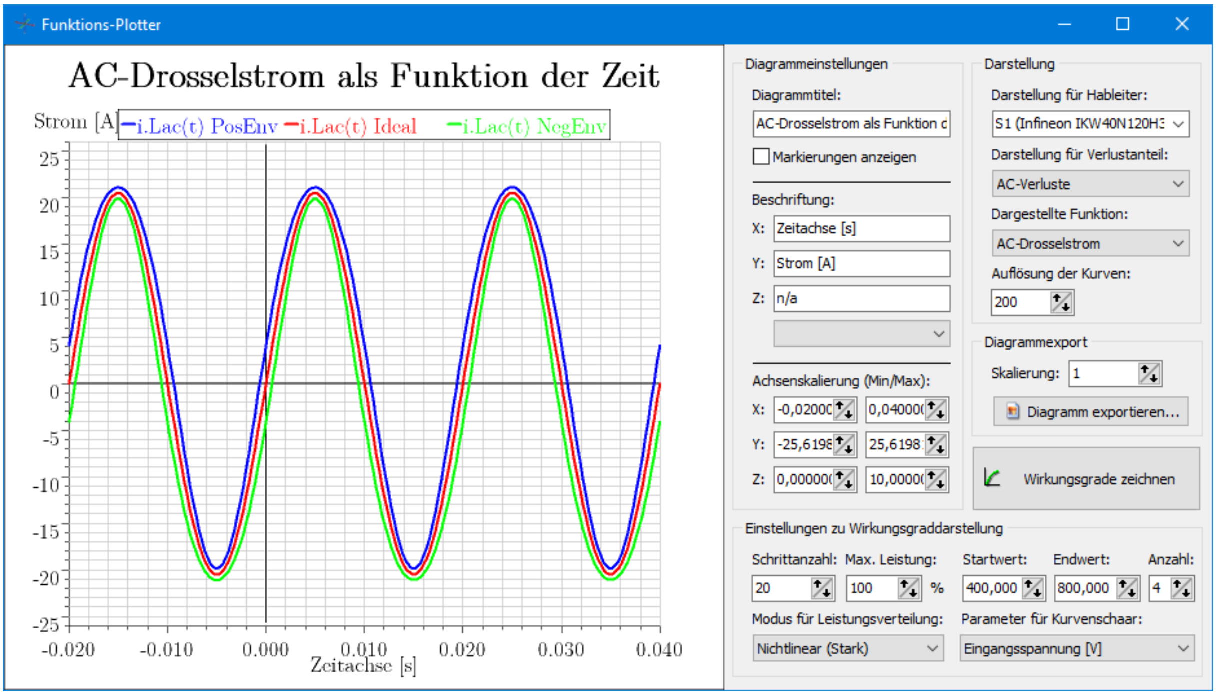

Fig. 13: AC-current with ripple-borders at the output-inductor

Without any further definitions or current-controller the software will output the calculated losses for each individual semiconductor as shown in Fig. 14 and Fig. 15. Due to symmetry only one leg is defined and afterwards multiplied with three:

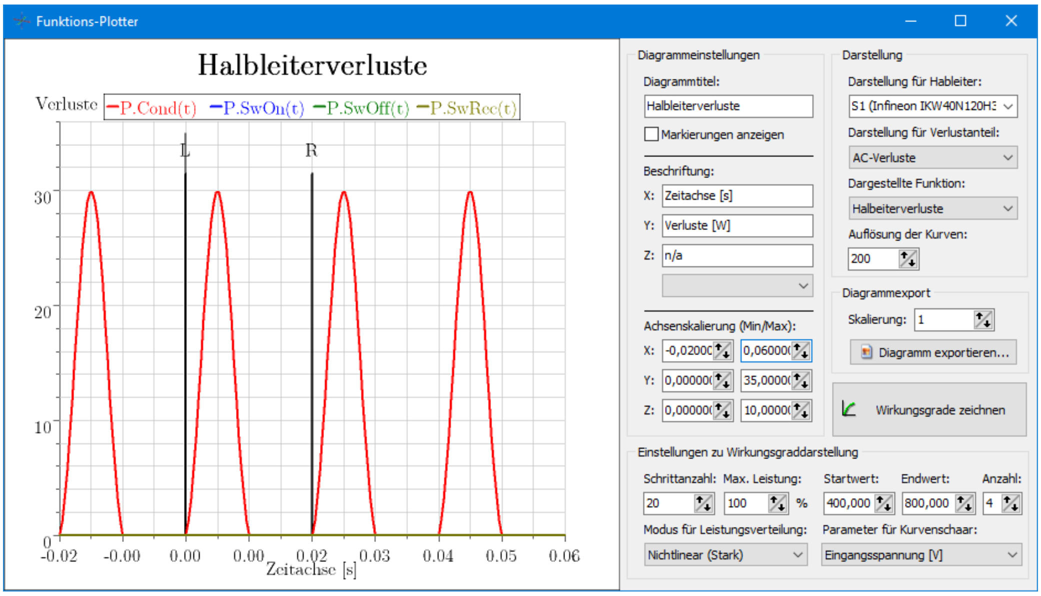

Fig. 14: Calculated conduction-losses for IGBT S1 showing the 30W as seen in PLECS

Verlusttabelle

Bauteil	Verlustanteil	P_cond	P_SwOn	P_SwOff	P_Rec	Summe
Infineon IKW40N120H3 (S1)	AC-Verluste	7,93 W x3	5,62 W x3	6,52 W x3	0,00 W x3	20,07 W x3
Infineon IKW40N120H3 (S2)	AC-Verluste	7,93 W x3	5,62 W x3	6,52 W x3	0,00 W x3	20,07 W x3
Infineon IKW40N120H3 (D1)	AC-Verluste	1,67 W x3	0,00 W x3	0,00 W x3	7,87 W x3	9,54 W x3
Infineon IKW40N120H3 (D2)	AC-Verluste	1,67 W x3	0,00 W x3	0,00 W x3	7,87 W x3	9,54 W x3
Gesamtsumme		57,58 W	33,73 W	39,11 W	47,23 W	177,65 W

Fig. 15: Calculated losses for each semiconductor of the B6-inverter

These 177,65W are 8,54W higher than the simulation-output of PLECS resulting in an efficiency of 98,22%. This is caused by using an approximation of the device-current and not considering the changes of device-temperatures over time but using a user-defined fixed junction-temperature. Implementing a loop-function of the calculated losses and temperatures using the R_{th} could be implemented in further versions of the software but then would result in higher calculation times again.

The real benefit is to calculate these losses and efficiency-curves over several combinations of the possible degrees of freedom like different DC- and AC-voltages, cosphis or powers:

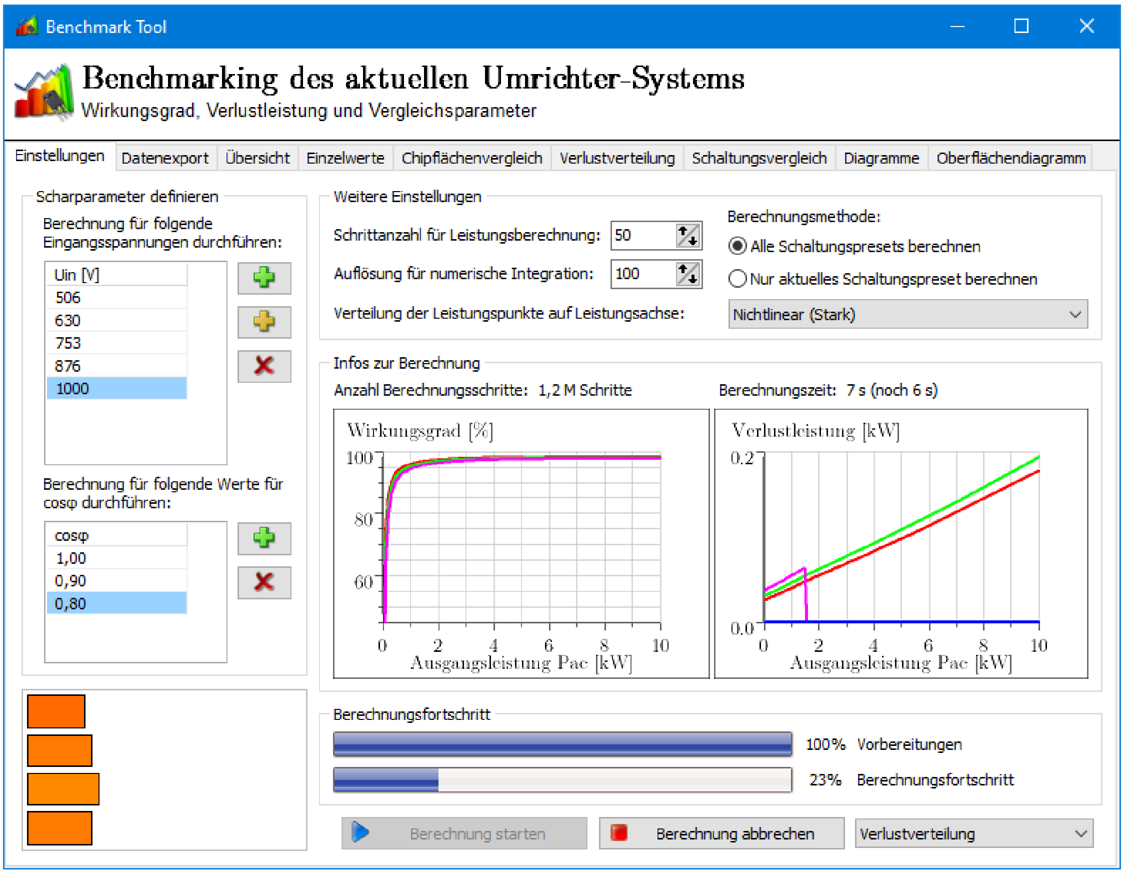

Fig. 16: Benchmark-tool for calculating losses for different parameter-sweeps

After about 8 seconds 1,2 million parameters are calculated that can be explored via sliders and drop-down-boxes to investigate the individual losses for each semiconductor or the sum of all like shown in Fig. 17:

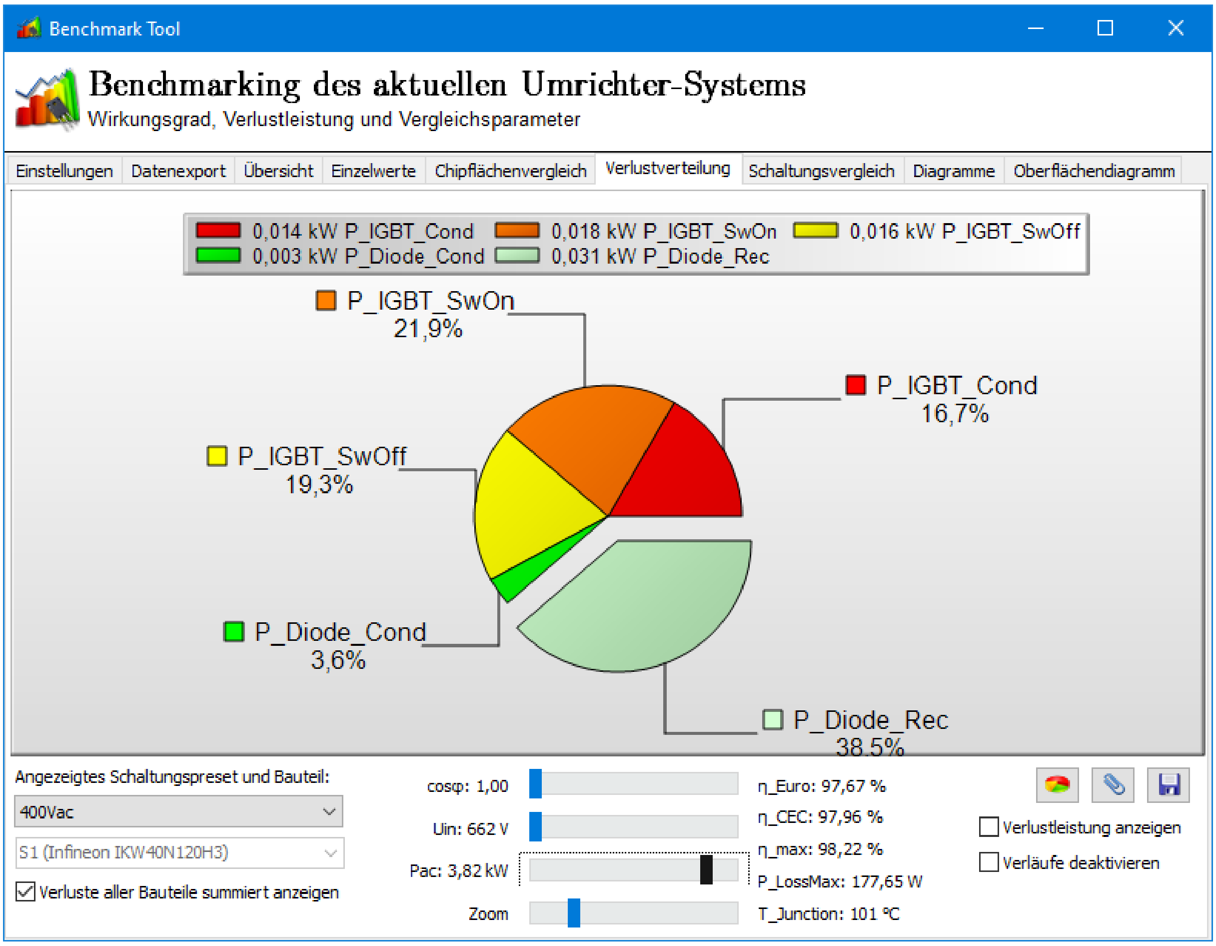

Fig. 17: Interactive loss-distribution-explorer

Different AC-voltages and the impact of the DC-voltage can be investigated using the circuit-comparison-tab:

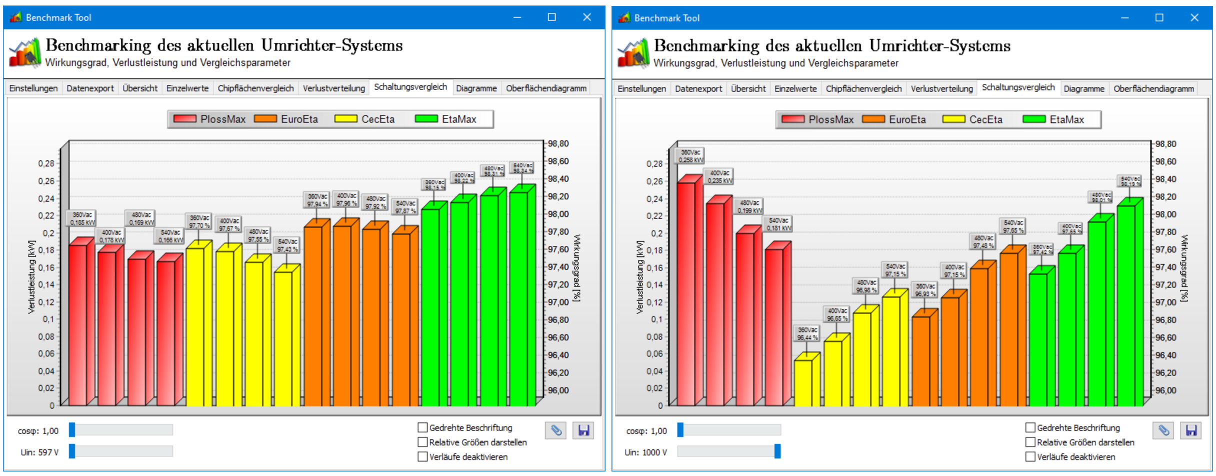

Fig. 18: Circuit-comparison under different conditions like cosphi or DC-voltage

A classical plot of the efficiency-curves or individual semiconductor-losses over the output-power is possible, too:

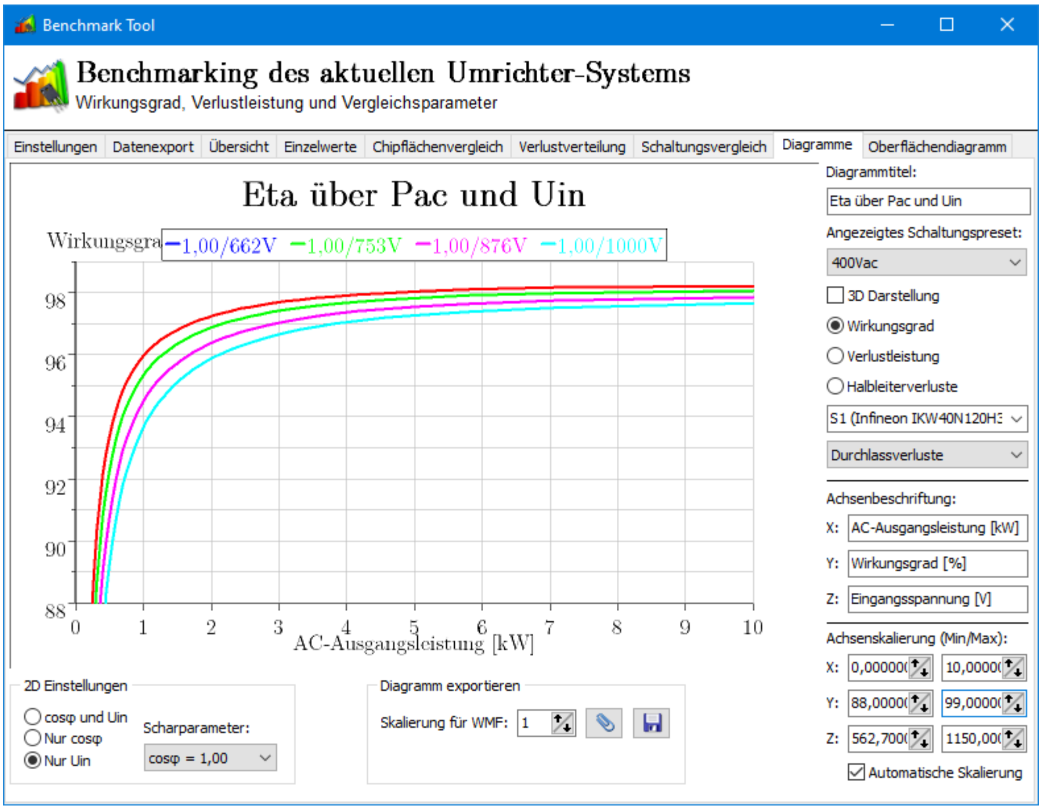

Fig. 19: Plot of classical efficiency-curves

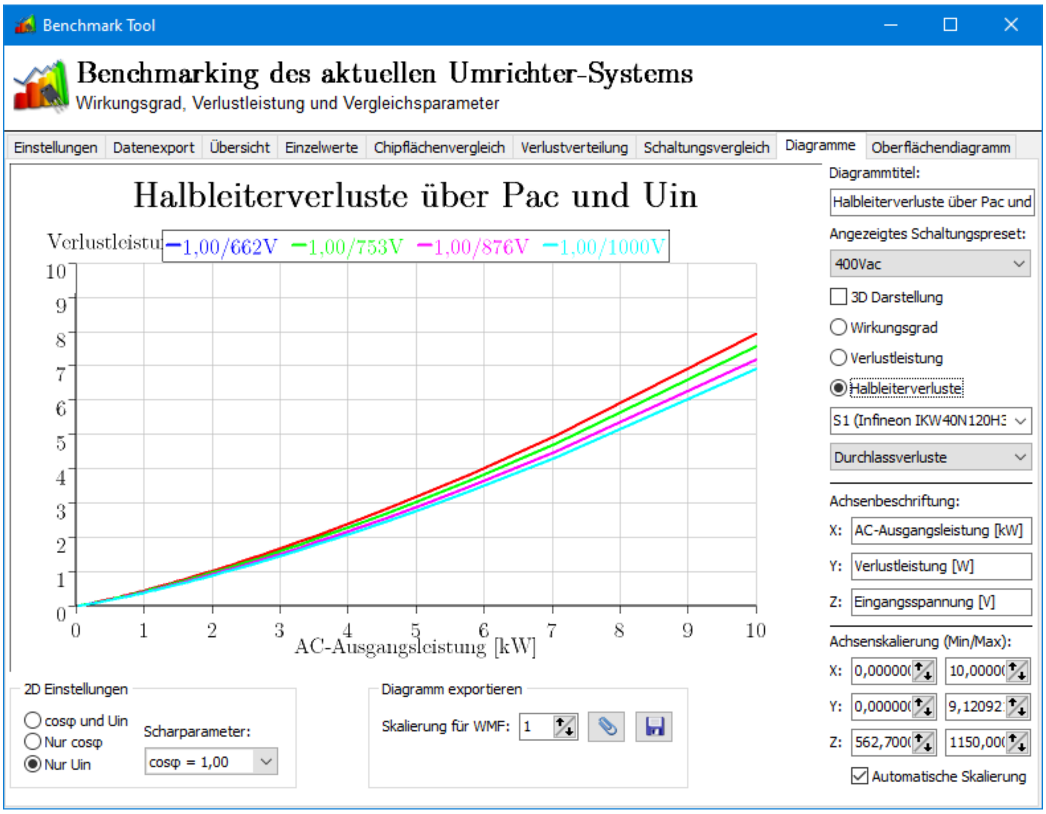

Fig. 20: Plot of individual semiconductor-losses

Finally, the euro- or CEC-eta, eta-max, losses or other parameters can be compared using surface-diagrams like shown in Fig. 21:

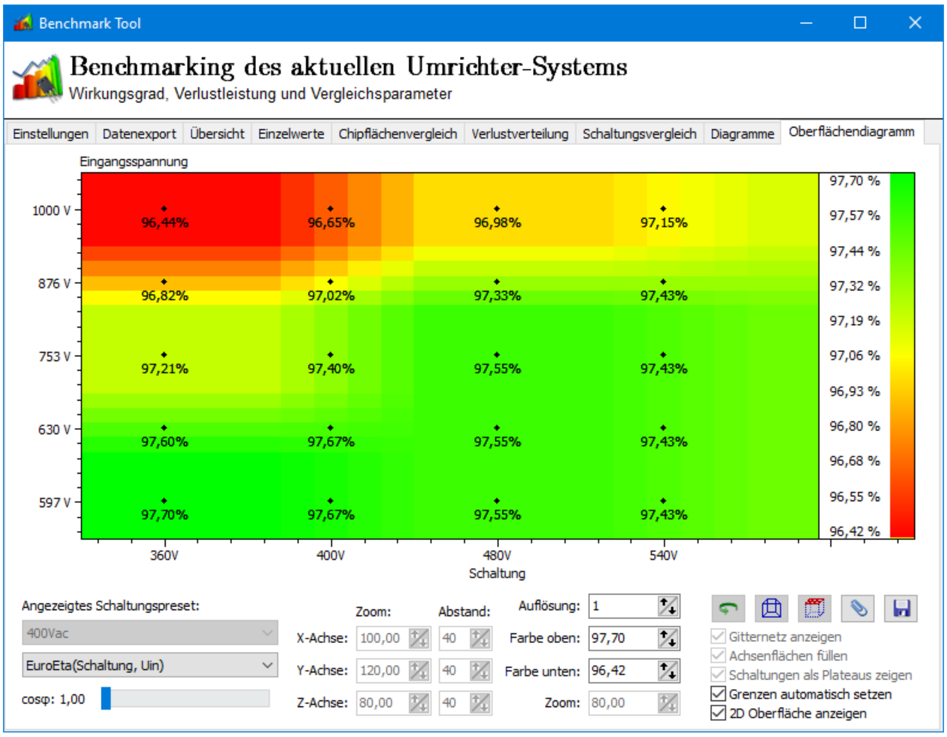

Fig. 21: Surface-diagrams for easy circuit-comparison and evaluation

These functions can be used importing a time-line of parameter-variations using CSV-import-functions or by using the TCP-server. The TCP-server can be used to control individual devices or parameters from an individual software like MatLAB Simulink to use the fast calculation of losses in a more complex simulation:

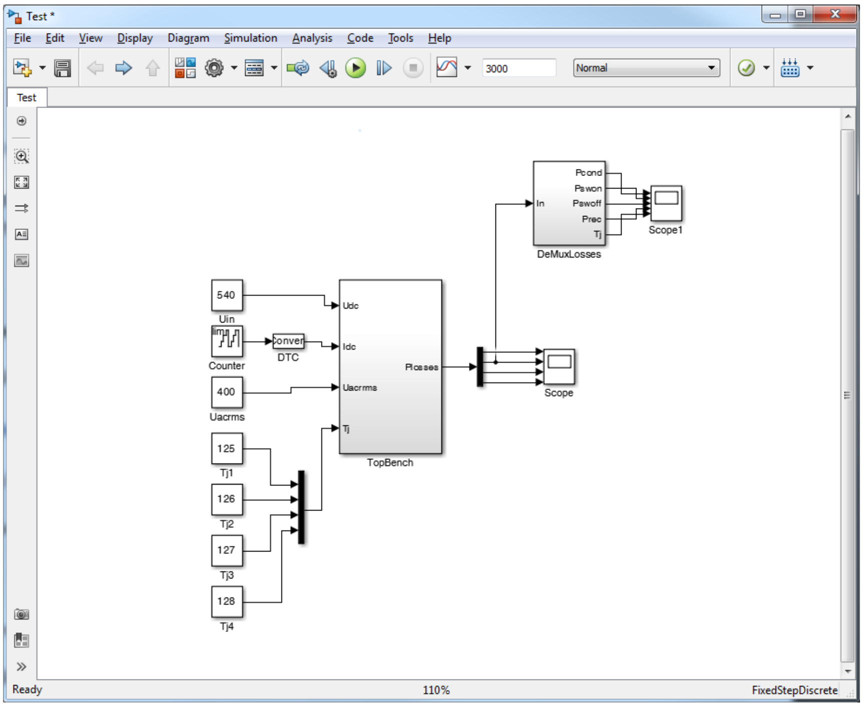

Fig. 22: Using TopBench in MatLAB Simulink via TCP-server