Electro-thermal modelling of three phase inverter

Hui Huang, A.T. Bryant, P.A. Mawby
PEATER group
School of Engineering, University of Warwick
Coventry, UK
Email: h.huang.1@warwick.ac.uk

Keywords

<<IGBT>>, <<Modelling>>, <<Voltage source inverter>>.

Abstract

This paper introduces an electro-thermal model of an inverter implemented in PLECS. This model is able to calculate IGBT junction temperature with a mission profile. Look up tables (LUT) of switching power loss are generated by running physics-based IGBT and diode models under different operating conditions. The inverter model interpolates power dissipation from the LUTs to speed up the simulation rather than running the physics-based device model, which is relatively slow. The thermal network is extracted from the heating curves of IGBT junction and case temperature which are measured on a power cycling rig. Junction temperature under operating condition is obtained with the power dissipation and thermal network. Although the work presented here is general applicable to any converter applications, our particular emphasis in this paper is on renewable energy system such as wind power applications. This model extends the current available inverter model[1] which is fixed frequency and voltage to various frequency and voltage which is more closely aligned with the operation of wind turbine.

Introduction

According to a recent survey[2], the converter is one of the most unreliable parts of an electrical system when operating in a harsh environment, such as wind turbine. The cost of converter failure and maintenance is high, especially in the case of off-shore operation. Therefore the reliability of inverter is critical.

The chip temperature goes up and down as the IGBT turns on and off during converter operations. A cyclic strain is developed in the solder because of junction temperature cycling and thermal expansion coefficient (CTE) mismatch between silicon and copper, which leads to solder fatigue[3]. Therefore junction temperature is the key parameter for further investigation on device reliability.

An inverter model build in PLECS is presented in this paper to obtain junction temperature profiles from a typical vehicle mission profile. Fig.1 shows the framework of the inverter model. The inverter is controlled by a Pulse Width Modulation (PWM) signal generator whose amplitude modulation ratio is calculated from the mission profile. The switching and conduction power loss is integrated from the LUTs generated by device switching model and forward V-I characteristics respectively. Junction temperature can therefore be calculated with the power dissipation and thermal network model. This model extends the current available inverter model[1] which is fixed frequency and voltage to various frequency and voltage which is more closely aligned with the operation of wind turbine.

Inverter electro-thermal simulation

Build Look-Up-Tables for IGBT and diode power losses

An important reason for circuit simulation in a power electronic system is to estimate the power loss under different operating conditions. IGBT instantaneous switching power loss is far higher than the instantaneous conduction power loss. Although the switching period is quite short, it cannot be ignored under high frequency operation. Therefore power loss cannot be simply calculated as P = VI. Furthermore, some device parameters are temperature dependent, thus accessing switching loss requires an accurate physics-based device model and a practical way to extract the parameters needed in the model

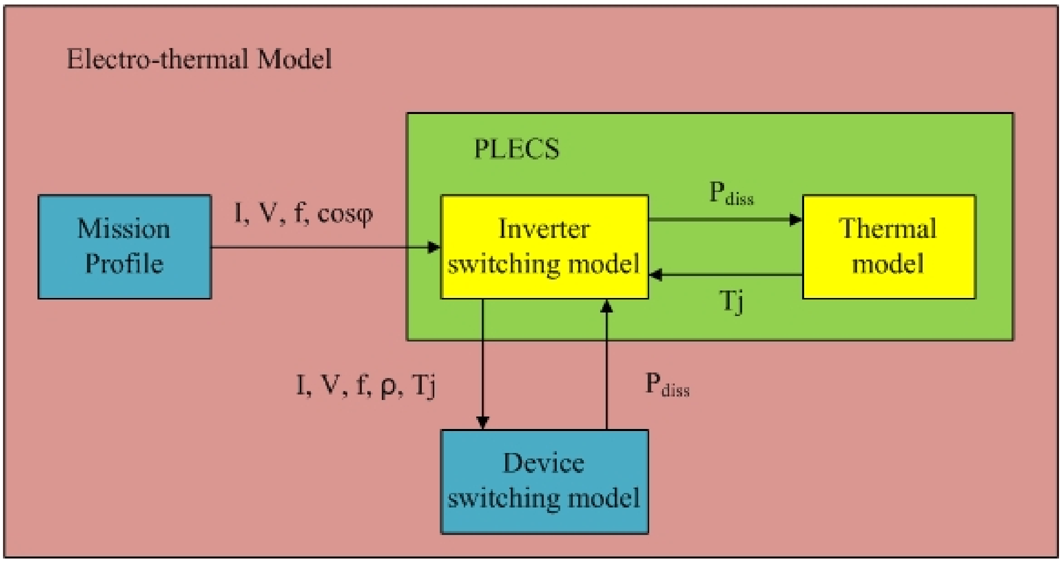


Figure 1: Framework of inverter electro-thermal model

to ensure the simulation is accurate under different operating conditions. A realistic mission profile normally includes millions of switching events. Therefore traditional compact device models[4][5] cannot be used directly in the inverter electro-thermal model, because, although they are accurate, they are very slow.

The models used in this paper are Fourier-based-solution physics-based IGBT and power diode models[6] [7]. This model is more accurate when compared with behavioral models and runs much faster when compared with Finite Element Method (FEM) models.In order to tailor the model to a specific module, careful parameter extraction needs to be performed with a wide range of temperatures. Current literature[8] describes a simple and accurate two step parameter extraction method. Only one simple clamped inductive load switching test is needed for the extraction. The first step is initial parameter extraction based on the device datasheet and inductive switching test. The second step is the optimization procedure to refine the parameters. The aim is to fit simulation waveforms to the experimental waveforms specifically Vak, Vce and Ic because they are used to calculate power loss.

Switching energy loss LUTs similar to those used in[**?**] are generated by running the device switching model under different load currents, DC voltages and device junction temperatures, and recording the energy dissipated during the switching period. Conduction power loss LUTs are created from the device forward V-I characteristics at different temperatures. Seperating switching energy loss and conduction power loss could enable greater flexibility since it allows the model to run at various DC voltages or output frequencies such as converter operation in wind power applications.

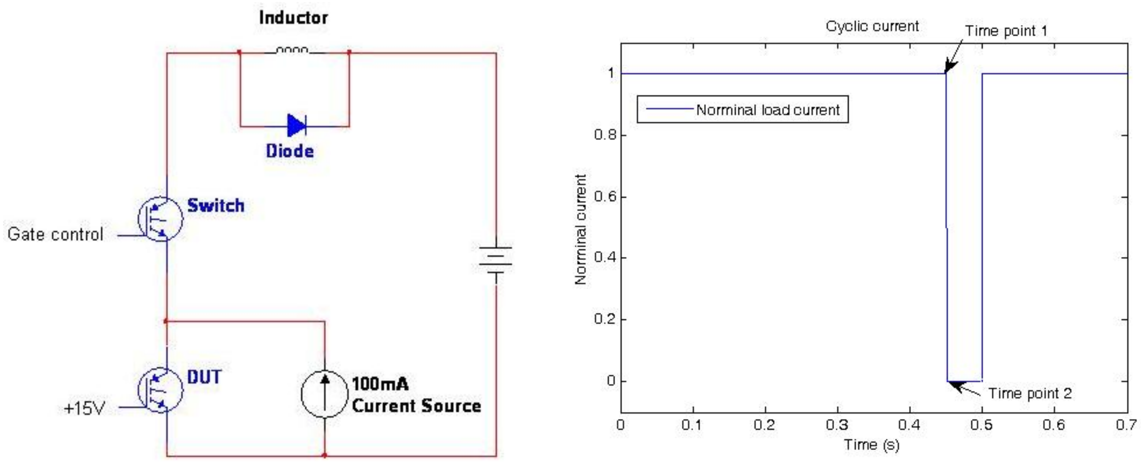
Thermal impedance extraction

A simple test is designed to extract thermal impedance, its circuit diagram is shown in Fig.2(a). IGBT forward voltage drop at 100mA is selected as a temperature sensitive parameter to sense IGBT junction temperature since it decreases linearly as temperature goes up[9]. A cyclic load current is supplied by turning off the switch every 0.5s so that Vce at 100mA can be measured. Vce at 100mA, case temperature and water temperature are measured and recorded at time point 2, Fig.2(b), of each load cycle and takes 0.05s, therefore the duty ratio (D) is 0.9. Vce at load current is measured and recorded at time point 1 of each load cycle, Fig.2(b). The warming phase stops when junction temperature reaches a stable state (normally 150s). Thermal network can be extracted from the warming curves of the junction (T_j) and case (T_c) temperature by the equation (1) and (2). All thermal power generated by the IGBT chip is assumed to transfer from chip to case.

$$(T_j(t) - T_c(t))/P(t) = \sum R_i \cdot (1 - exp(-t/R_i \cdot C_i) \quad (1)$$

$$P(t) = V_{ce}(t) \cdot I \cdot D \quad (2)$$

The thermal network extracted from the above formula is a Foster network which doesnt have any physical meaning. It can only correctly describe the thermal behavior at the input and output terminals of the network. A foster network can be converted to Cauer network, which is an electrical transmission line equivalent network. The parameters of this topology can be derived from the structure of the elements since they are closely related with physical reality.



(a) Thermal network extraction test circuit

(b) Cyclic load current

Figure 2: Thermal network extraction

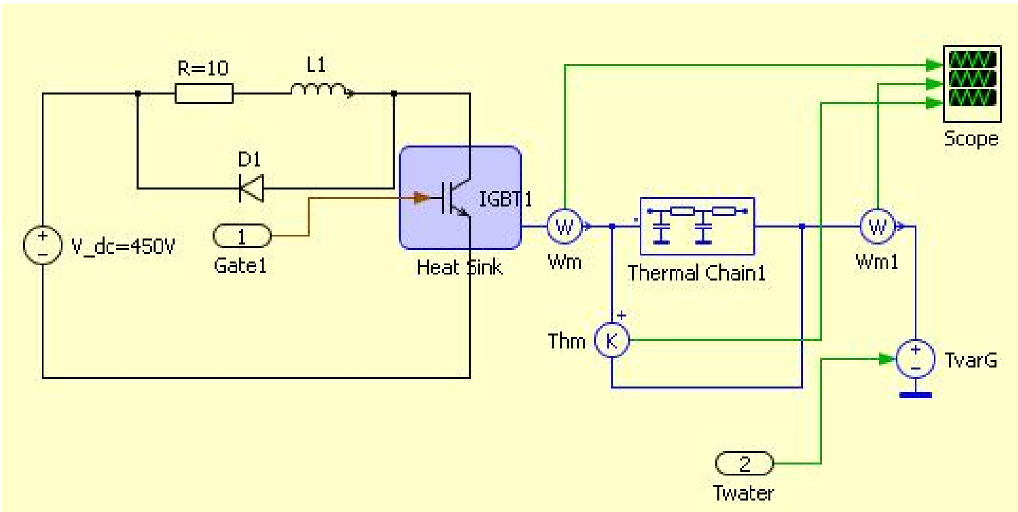


Figure 3: Simulation of thermal impedance extraction test

The thermal network can also be extracted from cooling curves. The power dissipation is assumed to be the same as the power carried away by the water and can be calculated by equation (3). However, it is not as accurate as the former method. This is mainly because either temperature difference between junction and case or input and output water is very close during the cooling phase thus the calculated thermal impedance can be strongly affected by measurement noise.

$$P_{jc} \approx P_{water} = C_{water} \cdot m_{water} \cdot T = C_{water} \cdot \rho_{water} \cdot V_{water} \cdot (T_{wout} - T_{win}) \tag{3}$$

Both methods introduced above would induce errors from assumptions, measurements, filtering and curve fitting. An optimization process is needed to obtain a more accurate simulation . A simple model, which simulates the thermal impedance extraction test, built in PLECS shown in Fig.3 is used for this purpose. The power loss LUTs and thermal networks obtained previously are used to describe the electrical and thermal behavior of the devices respectively. Thermal Chain 1 is used to simulate the thermal behavior of the heatsink. TvarG is the water temperature. The optimization process is simular to that described in, change each value of the thermal network until the error between simulation results and experiment waveforms is minimized.

Implement inverter model in PLECS

PLECS is a Simulink toolbox for the fast simulation of electrical and power electronic circuits. It uses ideal component models where possible to simplify switching transitions and to allow for larger simulation time steps. At the circuit and system levels, this results in a fast and efficient simulation because only those details that affect the circuit response are modeled. [10]

A three phase inverter model is built in PLECS with the electrical and thermal models developed before to obtain IGBT junction temperature profiles for a particular mission profile. Fig.4 shows the main electrical circuit of the inverter model. A constant voltage source of 300V is used to supply DC voltage and a constant inductive load (R=1Ω, L=0.01H) is connected to the output of the inverter. Each IGBT and free-wheel diode shares a heatsink since they are physically located close to each other, and it is assumed that there is no heat flow between each heatsink. Water temperature is assumed to be constant and is set to be the initial temperature of the system.

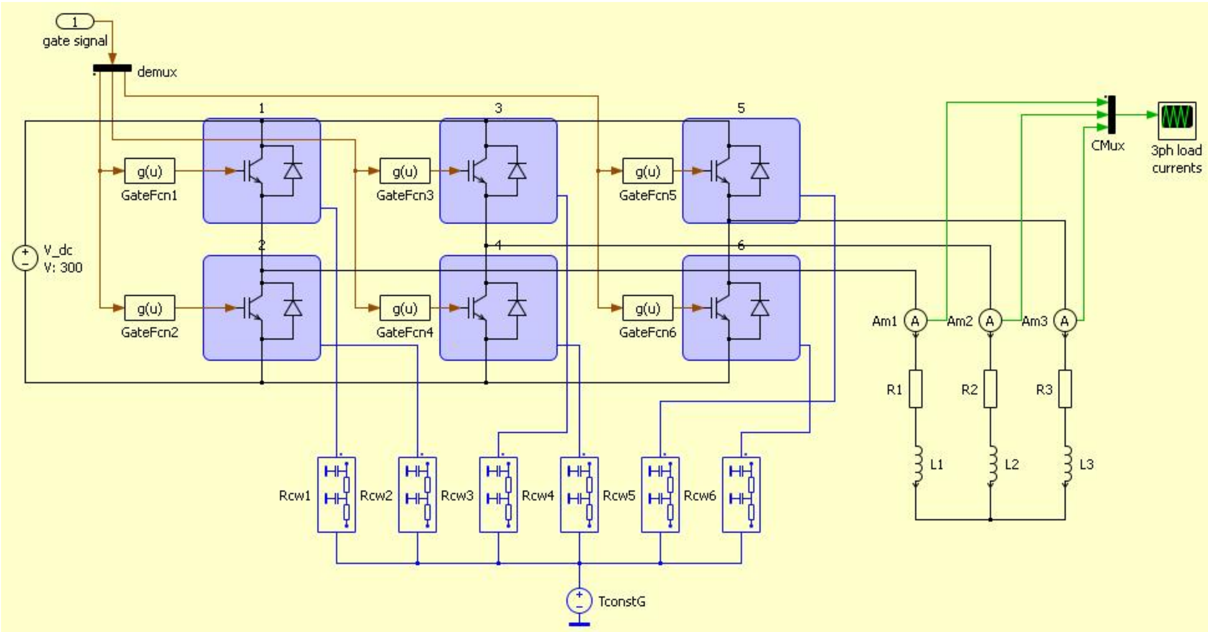


Figure 4: Electro-thermal model of a 3 phase inverter

The inverter model is controlled by a PWM signal generator whose amplitude modulation ratio (m) is tuned by the mission profile (inverter output voltage) according to equation (4). The control signal for the PWM is a 50Hz three phase sinusoidal waveform whose amplitude is tunable from 0.005 to 1 while the carrier signal is a 150Hz triangular waveform whose amplitude is 1.

$$m = 2V_{out}/300 \tag{4}$$

Results and discussion

The parameters of the device switching model are extracted to fit the switching waveforms measured from the inductive switching test. Fig.5 shows the simulation results (solid line) compared with the experimental waveforms (dashed line) at both 30°Cand 130°C. It is obvious that the simulation fits the experimental data well even at different temperatures, therefore the switching energy losses calculated from the voltage and current waveform can be considered relatively accurate.

LUTs of IGBT and diode switching energy losses shown in Fig.6 are then generated by running the device switching model at different voltages, currents and temperatures. Switching energy loss increases while load current, voltage or temperature increases. The inverter model interpolates switching energy loss from the LUTs according to different operating conditions. The power dissipation during operation can then be calculated by equation (5) together with the forward V-I characteristics at different temperatures. Power loss due to leakage current during off state is neglected.

$$P_{diss}(V,I,T) = E_{on}(V,I,T) + E_{off}(V,I,T) + V \cdot I \cdot t_{on} \tag{5}$$

The thermal network is extracted and then optimized to fit the warming curves measured from the experiment in order to obtain a more accurate inverter model. Fig.7 shows the results before and after optimization. Table I shows the parameters of the thermal network before and after optimization. The results clearly show a better fit after optimization.

A mission profile is used to control the inverter operation and a constant 3 phase inductive load is connected to the inverter output. The same heatsink thermal network is used in the inverter model. However, these can be changed according to different applications. Fig.8 shows the input (mission profile) and output (temperature profile) of the inverter model.

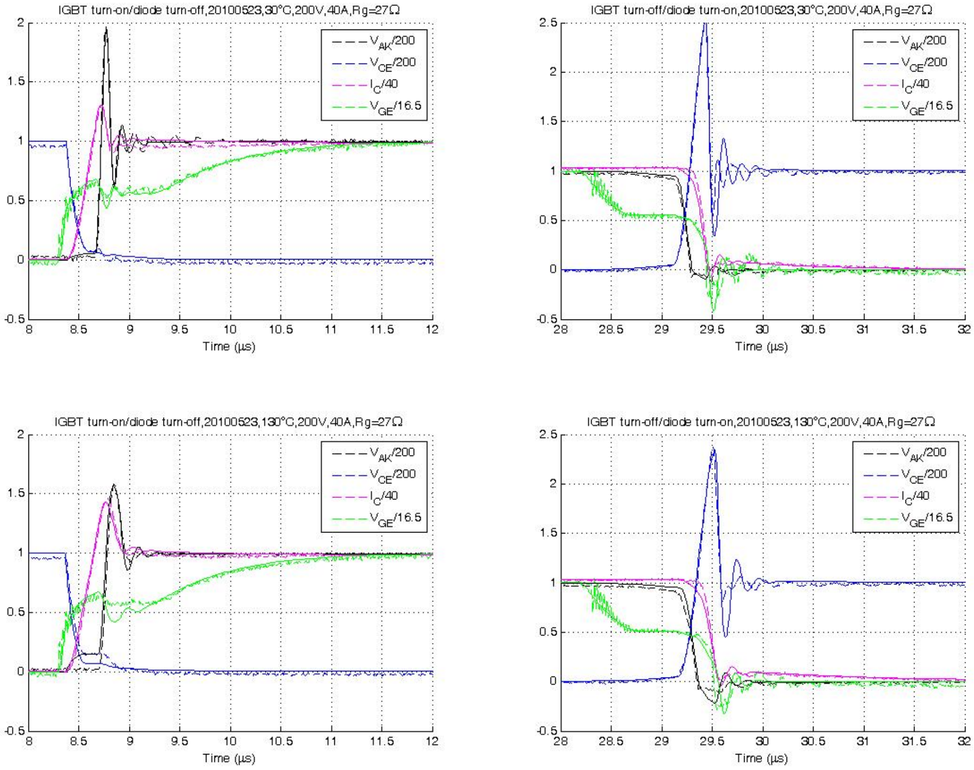


Figure 5: Comparison of simulation and experimental switching waveforms at different temperatures

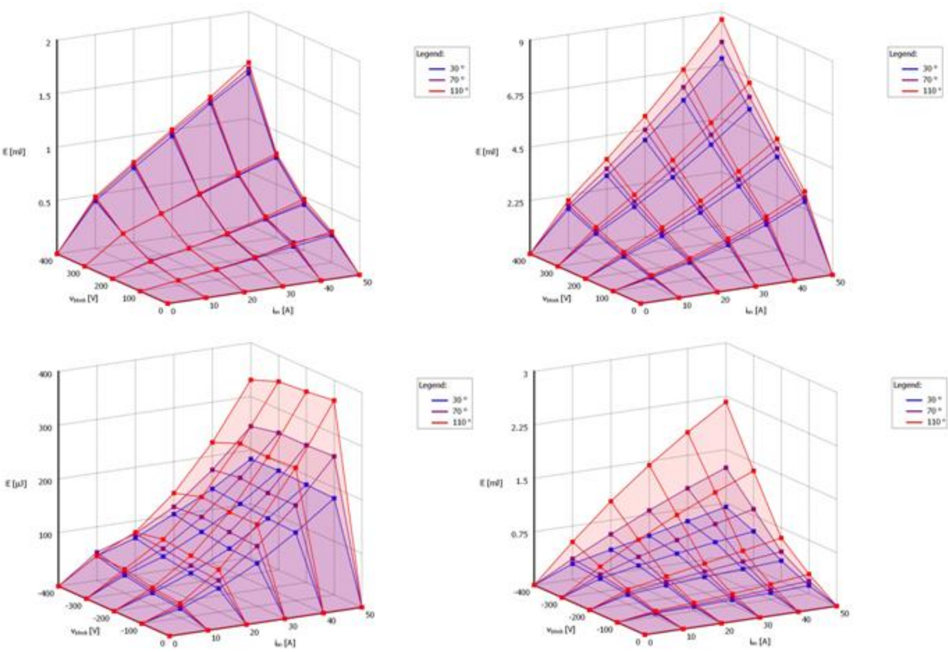
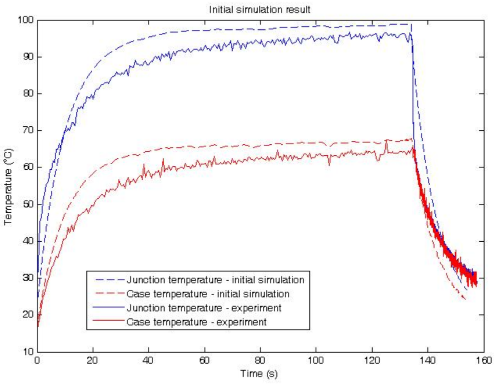
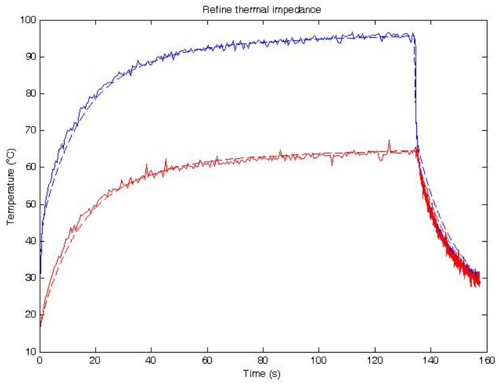


Figure 6: Top-left:IGBT turn on loss; Top-right: IGBT turn off loss; Bottom left: diode turn on loss; Bottom right: diode turn off loss

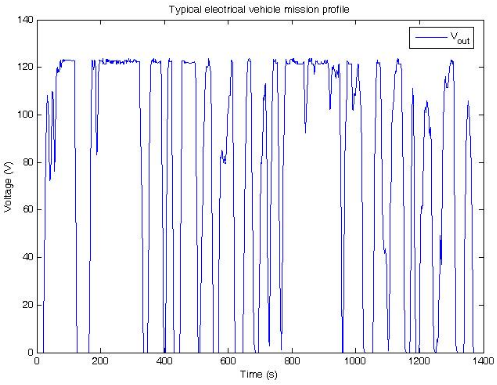


(a) Simulation results before optimization

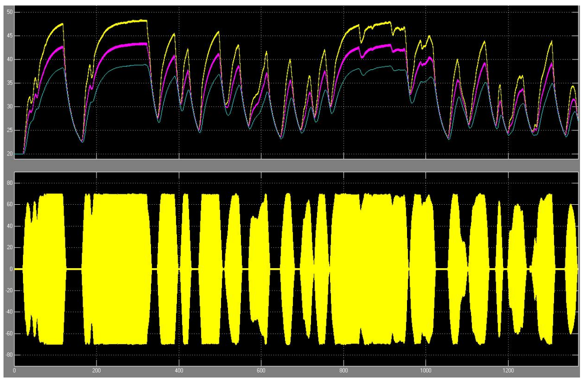


(b) Simulation results after optimization

Figure 7: simulation outputs



(a) Mission profile: inverter leg mid point voltage



(b) Temperature profiles (T_{jI}:yellow; T_{jD}: purple; T_c: cyan) and inverter output current

Figure 8: Simulation input and output

Table I: Thermal network extraction (Cauer)

	R1 (K/W)	C1 (J/K)	R2 (K/W)	C2 (J/K)
Initial junction to case	0.04733	2.136	0.1965	12.88
Optimized Junction to case	0.22	1.8	0.02	36
Initial case to water	0.2964	0.2063	0.05873	3.195
Optimized case to water	0.32	0.2	0.02	800

Conclusion

This paper introduces an inverter electro-thermal model developed in PLECS. This model converts an electrical mission profile to a temperature profile which is needed for fatigue investigation. It is relatively fast and the parameters needed are easy to extract compared with the FEM models. Physical based IGBT and diode switching models are used to ensure the accuracy of the power dissipation simulation under different operating conditions. The parameter extraction for this model is simple, only an inductive switching test and an IGBT heating curve are needed. Simulation speed increases a lot by using LUT technology. By seperating the switching energy loss and conduction power loss, this model is suitable to simulate applications such as converters used in wind power where AC frequency is variable.

References

[1] A. T. Bryant, P. A. Mawby, and P. R. Palmer, “Exploration of power device reliability using compact device models and fast electrothermal simulation,” *IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS*, vol. 44, no. 3, pp. 894–903, MAY/JUNE 2008.

[2] S. Yang, A. T. Bryant, P. A. Mawby, D. Xiang, L. Ran, and P. Tavner, “An industry-based survey of reliability in power electronic converters,” in *ECCE*, San Jose, USA, 2009.

[3] W. W. Lee, L. T. Nguyen, and G. S. Selvaduray, “Solder joint fatigue models: review and applicability to chip scale packages,” *Microelectronics Reliability*, vol. 40, pp. 231–244, 2000.

[4] T. Kojima, Y. Yamada, M. Ciappa, M. Chiavarini, and W. Fichtner, “A novel electro-thermal simulation approach of power igbt modules for automotive traction applications,” in *in Proc. ISPSD*, Kitakyushu, Japan, 2004, pp. 289–292.

[5] A. R. Hefner, “A dynamic electro-thermal model for the igbt,” *IEEE Trans. Ind. Appl.*, vol. 30, no. 2, p. 394405, Mar./Apr. 1994.

[6] P. R. Palmer, E. Santi, J. L. Hudgins, X. Kang, J. C. Joyce, and P. Y. Eng, “Circuit simulator models for the diode and igbt with full temperature dependent features,” *IEEE Trans. Power Electron.*, vol. 18, no. 5, pp. 1220–1229, Sep. 2003.

[7] X. Kang, A. Caiafa, E. Santi, J. L. Hudgins, and P. R. Palmer, “Characterization and modeling of high-voltage field-stop igbts,” *IEEE Trans. Ind. Appl.*, vol. 39, no. 4, pp. 922–928, Jul./Aug 2003.

[8] A. T. Bryant, X. Kang, E. Santi, P. R. Palmer, and J. L. Hudgins, “Two-step parameter extraction procedure with formal optimization for physics-based circuit simulator igbt and p-i-n diode models,” *IEEE transactions on power electronics*, vol. 21, no. 2, pp. 295–309, Mar. 2006.

[9] P. Cova and F. Fantini, “On the effect of power cycling stress on igbt modules,” *Microelectronics Reliability*, vol. 38, pp. 1347–1352, 1998.

[10] *PLECS user mamual*.