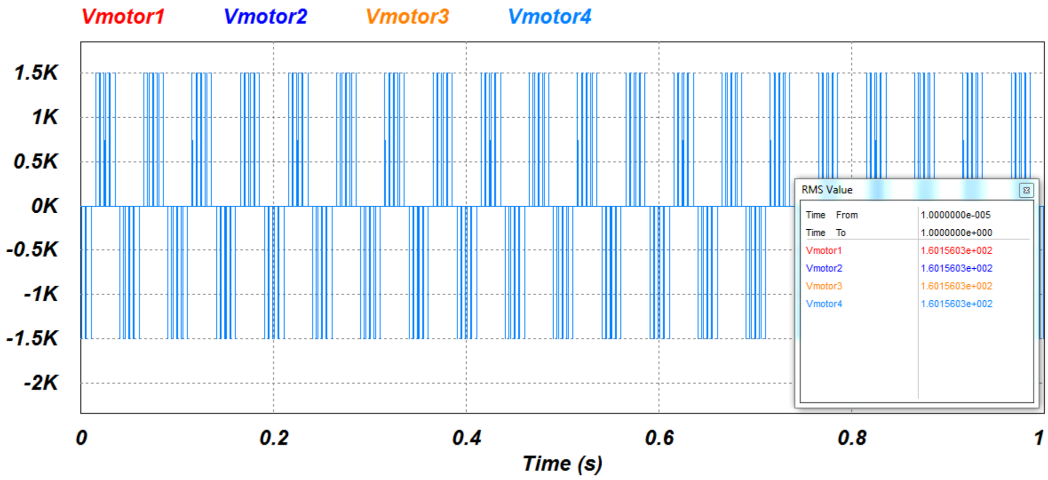
LAMPIRAN

Lampiran 1. Perhitungan rugi-rugi IGBT

1. Tegangan *output* 160,5V



Gambar 42. Gelombang tegangan *output* 160,5V pada *inverter*

Berikut ini merupakan perhitungan rugi-rugi *inverter* dengan parameter sebagai berikut;

Tabel 16. Parameter perhitungan rugi-rugi switching dan konduksi pada tegangan 160,5V

Daerah Kerja	Nilai
V_r	0,0505
V_c	4
E_{on}	225W
E_{off}	150W
V_{CESAT}	3,25V
I_C	1500A
f_{sw}	200Hz
V_{dc}	1500V
I_{nom}	1500A
V_{nom}	3300V

a. Perhitungan *Duty Cycle*

$$D = \frac{V_r}{V_c}$$

$$D = \frac{0,0505}{4}$$

$$D = 0,013$$

b. Rugi konduksi

$$P_{cond} = 6 \times V_{CESAT} \times I_C \times D$$

$$P_{cond} = 6 \times 3,25V \times 1500A \times 0.013$$

$$P_{cond} = 0,380kW$$

c. Arus puncak (I_{pk})

$$I_{pk} = \frac{\left(\frac{P_{in}}{V_{out}}\right)}{3}$$

$$I_{pk} = \frac{\left(\frac{450kW}{160,5V}\right)}{3}$$

$$I_{pk} = 934,580A$$

d. Rugi *switching*

$$P_{sw} = 6 \times \frac{(E_{on} + E_{off})xI_{pk}xf_{sw}xV_{dc}}{\pi xI_{nom}xV_{nom}}$$

$$P_{sw} = 6 \times \frac{(225W + 150W)x934,580Ax200Hzx1500V}{\pi x1500Ax3300V}$$

$$P_{sw} = 6 \times 6,761kW$$

$$\mathrm{P_{sw}} = 40,566kW$$

e. Rugi-rugi total

$$P_{total} = P_{cond} + P_{sw}$$

$$P_{total} = 0,380kW + 40,566kW$$

$$P_{total} = 40,946kW$$

f. Daya *output*

$$P_{out} = P_{in} - P_{total}$$

$$P_{out} = 450kW - 40,946kW$$

$$P_{out} = 409,054kW$$

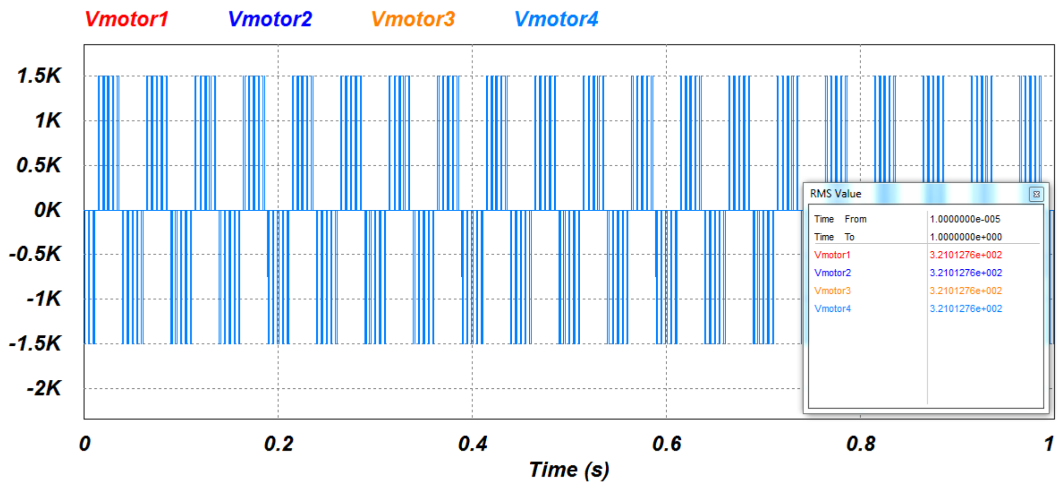
g. Efisiensi

$$\eta = \frac{P_{out}}{P_{in}} x100\%$$

$$\eta = \frac{409,054kW}{450kW} x100\%$$

$$\eta = 90,90\%$$

2. Tegangan *output* 321 V



Gambar 43. Gelombang tegangan *output* 321V pada *inverter*

Berikut ini merupakan perhitungan rugi-rugi *inverter* dengan parameter sebagai berikut;

Tabel 17. Parameter perhitungan rugi-rugi *switching* dan konduksi pada tegangan 321V

Daerah Kerja	Nilai
V_r	0,198
V_c	4
E_{on}	225W
E_{off}	150W
V_{CESAT}	3,25V
I_C	1500A
f_{sw}	200Hz
V_{dc}	1500V
I_{nom}	1500A
V_{nom}	3300V

a. Perhitungan *Duty Cycle*

$$D = \frac{V_r}{V_c}$$

$$D = \frac{0,198}{4}$$

$$D = 0,05$$

b. Rugi konduksi

$$P_{cond} = 6 \times V_{CESAT} \times I_C \times D$$

$$P_{cond} = 6 \times 3,25V \times 1500A \times 0.05$$

$$P_{cond} = 1,463kW$$

c. Arus puncak (I_{pk})

$$I_{pk} = \frac{\left(\frac{P_{in}}{V_{out}}\right)}{3}$$

$$I_{pk} = \frac{\left(\frac{450kW}{321V}\right)}{3}$$

$$I_{pk} = 467,290A$$

d. Rugi *switching*

$$P_{sw} = 6 \times \frac{(E_{on} + E_{off})xI_{pk}xf_{sw}xV_{dc}}{\pi xI_{nom}xV_{nom}}$$

$$P_{sw} = 6 \times \frac{(225W + 150W)x467,290Ax200Hzx1500V}{\pi x1500Ax3300V}$$

$$P_{sw} = 6 \times 3,381kW$$

$$\mathrm{P_{sw}} = 20,286kW$$

e. Rugi-rugi total

$$P_{total} = P_{cond} + P_{sw}$$

$$P_{total} = 1,463kW + 20,286kW$$

$$P_{total} = 21,749kW$$

f. Daya *output*

$$P_{out} = P_{in} - P_{total}$$

$$P_{out} = 450kW - 21,749kW$$

$$P_{out} = 428,251kW$$

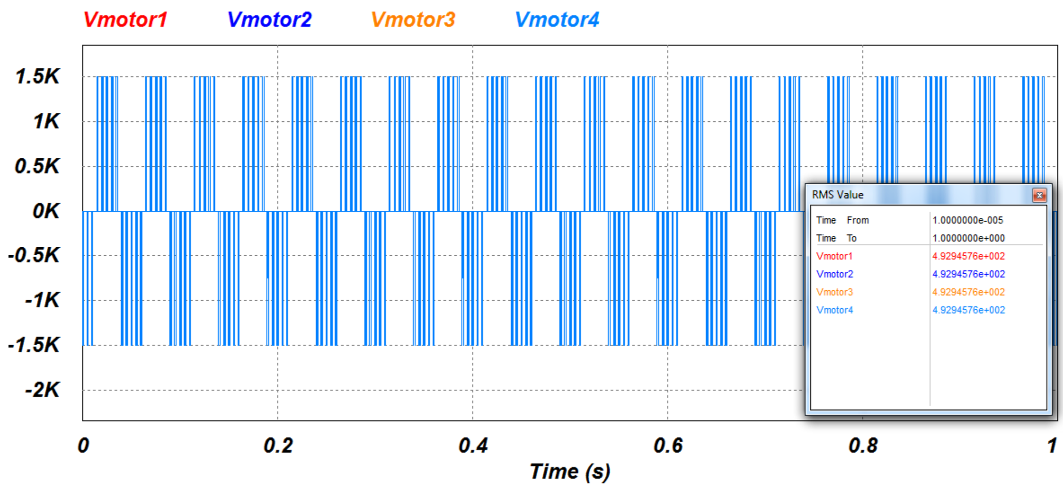
g. Efisiensi

$$\eta = \frac{P_{out}}{P_{in}} x100\%$$

$$\eta = \frac{428,251kW}{450kW} x100\%$$

$$\eta = 95,17\%$$

3. Tegangan *output* 493,9 V



Gambar 44. Gelombang tegangan *output* 493,9 V pada *inverter*

Berikut ini merupakan perhitungan rugi-rugi inverter dengan parameter sebagai berikut;

Tabel 18. Parameter perhitungan rugi-rugi *switching* dan konduksi pada tegangan 635V

Daerah Kerja	Nilai
V_r	0,475
V_c	4
E_{on}	225W
E_{off}	150W
V_{CESAT}	3,25V
I_C	1500A
f_{sw}	200Hz
V_{dc}	1500V
I_{nom}	1500A
V_{nom}	3300V

a. Perhitungan *Duty Cycle*

$$D = \frac{V_r}{V_c}$$

$$D = \frac{0,475}{4}$$

$$D = 0,119$$

b. Rugi konduksi

$$P_{cond} = 6 \times V_{CESAT} \times I_C \times D$$

$$P_{cond} = 6 \times 3,25V \times 1500A \times 0,119$$

$$P_{cond} = 3,48kW$$

c. Arus puncak (I_{pk})

$$I_{pk} = \frac{\left(\frac{P_{in}}{V_{out}}\right)}{3}$$

$$I_{pk} = \frac{\left(\frac{450kW}{493,9V}\right)}{3}$$

$$I_{pk} = 303,705A$$

d. Rugi *switching*

$$P_{sw} = 6 \times \frac{(E_{on} + E_{off})xI_{pk}xf_{sw}xV_{dc}}{\pi xI_{nom}xV_{nom}}$$

$$P_{sw} = 6 \times \frac{(225W + 150W)x303,705Ax200Hzx1500V}{\pi x1500Ax3300V}$$

$$P_{sw} = 6 \times 2,197kW$$

$$\mathrm{P_{sw}} = 13,182kW$$

e. Rugi-rugi total

$$P_{total} = P_{cond} + P_{sw}$$

$$P_{total} = 3,48kW + 13,182kW$$

$$P_{total} = 16,662kW$$

f. Daya *output*

$$P_{out} = P_{in} - P_{total}$$

$$P_{out} = 450kW - 16,662kW$$

$$P_{out} = 433,338kW$$

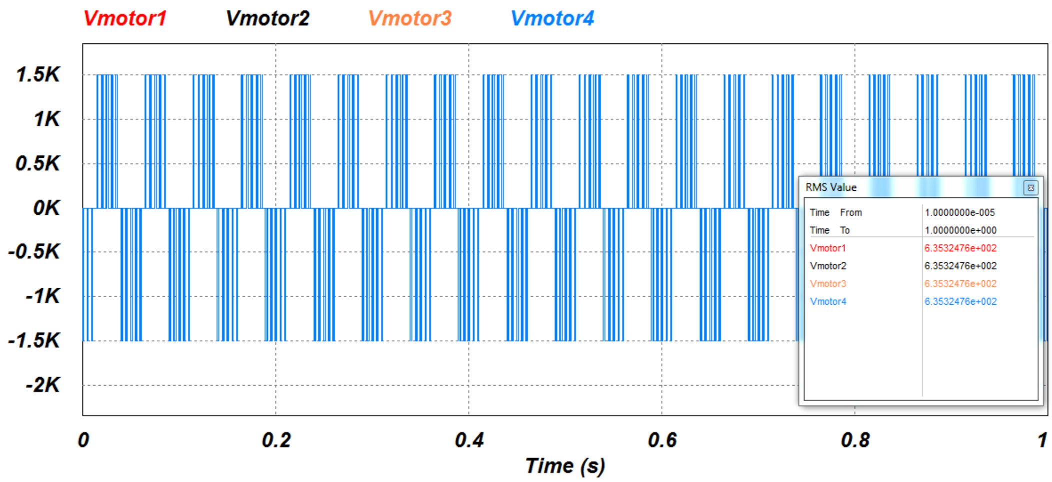
g. Efisiensi

$$\eta = \frac{P_{out}}{P_{in}} x100\%$$

$$\eta = \frac{433,338kW}{450kW} x100\%$$

$$\eta = 96,3\%$$

4. Tegangan *output* 635 V



Gambar 45. Gelombang tegangan *output* 635 V pada *inverter*

Berikut ini merupakan perhitungan rugi-rugi inverter dengan parameter sebagai berikut;

Tabel 19. Parameter perhitungan rugi-rugi *switching* dan konduksi pada tegangan 635V

Daerah Kerja	Nilai
V_r	0,793
V_c	4
E_{on}	225W
E_{off}	150W
f_{sw}	200Hz
V_{CESAT}	3,25V
I_C	1500A
V_{dc}	1500V
I_{nom}	1500A
V_{nom}	3300V

Inverter VVVF IGBT terdiri dari enam buah IGBT, sehingga besarnya rugi konduktansi dan *switching* di kali kan dengan jumlah IGBT yang digunakan.

a. Perhitungan *Duty Cycle*

$$D = \frac{V_r}{V_c}$$

$$D = \frac{0,793}{4}$$

$$D = 0,198$$

b. Rugi konduksi

$$P_{cond} = 6 \times V_{CESAT} \times I_C \times D$$

$$P_{cond} = 6 \times 3,25V \times 1500A \times 0,198$$

$$P_{cond} = 5,792kW$$

c. Arus puncak (I_{pk})

$$I_{pk} = \frac{\left(\frac{P_{in}}{V_{out}}\right)}{3}$$

$$I_{pk} = \frac{\left(\frac{450kW}{635V}\right)}{3}$$

$$I_{pk} = 236,220A$$

d. Rugi *switching*

$$P_{sw} = 6 \times \frac{(E_{on} + E_{off})xI_{pk}xf_{sw}xV_{dc}}{\pi xI_{nom}xV_{nom}}$$

$$P_{sw} = 6 \times \frac{(225+150)x236,220Ax200x1500}{\pi x1500x3300}$$

$$P_{sw} = 6 \times 1,709W$$

$$\mathrm{P_{sw}} = 10,254kW$$

e. Rugi-rugi total

$$P_{total} = P_{cond} + P_{sw}$$

$$P_{total} = 5,792kW + 10,254kW$$

$$P_{total} = 16,046kW$$

f. Daya *output*

$$P_{out} = P_{in} - P_{total}$$

$$P_{out} = 450kW - 16,046kW$$

$$P_{out} = 433,954kW$$

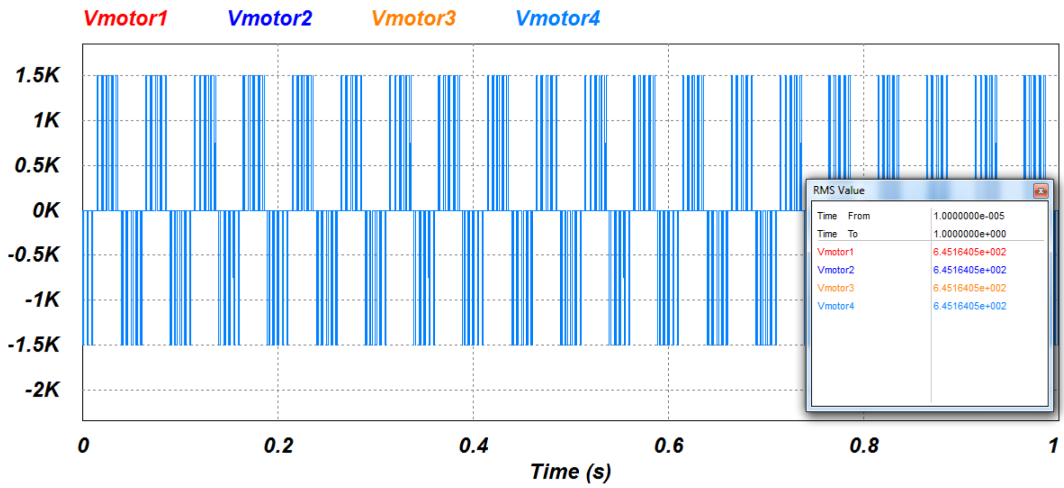
g. Efisiensi

$$\eta = \frac{P_{out}}{P_{in}} x100\%$$

$$\eta = \frac{433,954kW}{450kW} x100\%$$

$$\eta = 96,43\%$$

5. Tegangan *output* 645 V



Gambar 46. Gelombang tegangan *output* 645 V pada *inverter*

Berikut ini merupakan perhitungan rugi-rugi *inverter* dengan parameter sebagai berikut;

Tabel 20. Parameter perhitungan rugi-rugi *switching* dan konduksi pada tegangan 645V

Daerah Kerja	Nilai
V_r	0,8222
V_c	4
E_{on}	225W
E_{off}	150W
V_{CESAT}	3.25
I_C	1500A
I_{pk}	500A
f_{sw}	200Hz
V_{dc}	1500V
I_{nom}	1500A
V_{nom}	3300V

a. Perhitungan *Duty Cycle*

$$D = \frac{V_r}{V_c}$$

$$D = \frac{0,8222}{4}$$

$$D = 0,206$$

b. Rugi konduksi

$$P_{cond} = 6 \times V_{CESAT} \times I_C \times D$$

$$P_{cond} = 6 \times 3,25V \times 1500A \times 0,206$$

$$P_{cond} = 6,026kW$$

c. Arus puncak (I_{pk})

$$I_{pk} = \frac{\left(\frac{P_{in}}{V_{out}}\right)}{3}$$

$$I_{pk} = \frac{\left(\frac{450kW}{645V}\right)}{3}$$

$$I_{pk} = 232,558A$$

d. Rugi *switching*

$$P_{sw} = 6 \times \frac{(E_{on} + E_{off})xI_{pk}xf_{sw}xV_{dc}}{\pi xI_{nom}xV_{nom}}$$

$$P_{sw} = 6 \times \frac{(225W + 150W)x232,558Ax200Hzx1500V}{\pi x1500Ax3300V}$$

$$P_{sw} = 6 \times 1,682kW$$

$$\mathrm{P_{sw}} = 10,092kW$$

e. Rugi-rugi total

$$P_{total} = P_{cond} + P_{sw}$$

$$P_{total} = 6,026kW + 10,092kW$$

$$P_{total} = 16,118kW$$

f. Daya *output*

$$P_{out} = P_{in} - P_{total}$$

$$P_{out} = 450kW - 16,118kW$$

$$P_{out} = 433,882kW$$

g. Efisiensi

$$\eta = \frac{P_{out}}{P_{in}} x100\%$$

$$\eta = \frac{433,882kW}{450kW} x100\%$$

$$\eta = 96,42\%$$

Lampiran 2. Perhitungan rugi-rugi dioda

Tabel 21. Parameter perhitungan rugi-rugi dioda

Daerah kerja	Nilai
V_F	2.2V
I_F	1500A
V_{GE}	15V
R_G	1Ω

Rugi konduksi

$$Pcond = V_F \times I_F$$

$$Pcond = 2.2V \times 1500A$$

$$Pcond = 3,3kW$$

Daya recovery *reverse*

$$Erec = \frac{V_{GE}{}^2}{R_G}$$

$$Erec = \frac{15^2}{1}$$

$$Erec = 225W$$

1. **Tegangan *output* 160,5 V**
   a. Rugi-rugi *reovery reverse*

Tabel 22. Parameter perhitungan rugi-rugi dioda

Daerah Kerja	Nilai
E_{rec}	225W
I_{pk}	934,580A
f_{sw}	200Hz
V_{dc}	1500V

Tabel 23. Parameter perhitungan rugi-rugi dioda (lanjutan)

Daerah Kerja	Nilai
I_{nom}	1500A
V_{nom}	3300V

$$P_{rec.dioda} = \frac{E_{rec} \times I_{pk} \times f_{sw} \times V_{dc}}{\pi \times I_{nom} \times V_{nom}}$$

$$P_{rec.dioda} = \frac{225W \times 934,580A \times 200Hz \times 1500V}{\pi \times 1500A \times 3300V}$$

$$P_{rec.dioda} = 4,057kW$$

b. Rugi-rugi total

$$P_{tot} = 6 \times \left(P_{cond} + P_{rec.dioda}\right)$$

$$P_{tot} = 6 \times \left(3,3kW + 4,057kW\right)$$

$$P_{tot} = 44,142kW$$

2. Tegangan *output* 321V

a. Rugi-rugi *recovery reverse*

Tabel 24. Parameter perhitungan rugi-rugi dioda

Daerah Kerja	Nilai
E_{rec}	225W
I_{pk}	467,290A
f_{sw}	200Hz
V_{dc}	1500V
I_{nom}	1500A
V_{nom}	3300V

$$P_{rec.dioda} = \frac{E_{rec} \times I_{pk} \times f_{sw} \times V_{dc}}{\pi \times I_{nom} \times V_{nom}}$$

$$P_{rec.dioda} = \frac{225W \times 467,290A \times 200Hz \times 1500V}{\pi \times 1500A \times 3300V}$$

$$P_{rec.dioda} = 2,028kW$$

b. Rugi-rugi total

$$P_{tot} = P_{cond} + P_{rec.dioda}$$

$$P_{tot} = 6 \times (3,3kW + 2,028kW)$$

$$P_{tot} = 31,968kW$$

3. Tegangan *output* 493,9V

a. Rugi-rugi *recovery reverse*

Tabel 25. Parameter perhitungan rugi-rugi dioda

Daerah Kerja	Nilai
E_{rec}	225W
I_{pk}	303,705A
f_{sw}	200Hz
V_{dc}	1500V
I_{nom}	1500A
V_{nom}	3300V

$$P_{rec.dioda} = \frac{E_{rec} \times I_{pk} \times f_{sw} \times V_{dc}}{\pi \times I_{nom} \times V_{nom}}$$

$$P_{rec.dioda} = \frac{225W \times 303,705A \times 200Hz \times 1500V}{\pi \times 1500A \times 3300V}$$

$$P_{rec.dioda} = 1,318kW$$

b. Rugi-rugi total

$$P_{tot} = P_{cond} + \mathrm{P}_{rec.dioda}$$

$$P_{tot} = 6 \times (3,3kW + 1,318kW)$$

$$P_{tot} = 27,708kW$$

4. Tegangan *output* 635V

a. Rugi-rugi *recovery reverse*

Tabel 26. Parameter perhitungan rugi-rugi dioda

Daerah Kerja	Nilai
E_{rec}	225W
I_{pk}	236,220A
f_{sw}	200Hz
V_{dc}	1500V
I_{nom}	1500A
V_{nom}	3300V

$$\mathrm{P}_{rec.dioda} = \frac{E_{rec} \times I_{pk} \times f_{sw} \times V_{dc}}{\pi \times I_{nom} \times V_{nom}}$$

$$\mathrm{P}_{rec.dioda} = \frac{225W \times 236,220A \times 200Hz \times 1500V}{\pi \times 1500A \times 3300V}$$

$$\mathrm{P}_{rec.dioda} = 1,025kW$$

b. Rugi-rugi total

$$P_{tot} = P_{cond} + P_{rec.dioda}$$

$$P_{tot} = 6 \times (3,3kW + 1,025kW)$$

$$P_{tot} = 25,95kW$$

5. Tegangan *output* 645V

a. Rugi-rugi *recovery reverse*

Tabel 27. Parameter perhitungan rugi-rugi dioda

Daerah Kerja	Nilai
E_{rec}	225W
I_{pk}	232,558A
f_{sw}	200Hz
V_{dc}	1500V
I_{nom}	1500A
V_{nom}	3300V

$$P_{rec.dioda} = \frac{E_{rec} \times I_{pk} \times f_{sw} \times V_{dc}}{\pi \times I_{nom} \times V_{nom}}$$

$$P_{rec.dioda} = \frac{225W \times 232,558A \times 200Hz \times 1500V}{\pi \times 1500A \times 3300V}$$

$$P_{rec.dioda} = 1,009kW$$

b. Rugi-rugi total

$$P_{tot} = P_{cond} + P_{rec.dioda}$$

$$P_{tot} = 6 \times (3,3kW + 1,009kW)$$

$$P_{tot} = 25,854kW$$

Lampiran 3. Perhitungan rugi-rugi inverter VVVF IGBT

Tabel 28. Hasil rugi-rugi IGBT dan Dioda

Tegangan Output (V)	Pinput inverter (kW)	Prugi IGBT (kW)	Prugi Dioda (kW)
160,5	450	40,946	44,142
321	450	21,749	31,968
493	450	16,662	27,708
635	450	16,046	25,95
645	450	16,118	25,85

1. Tegangan *output* 160,5V

a. Rugi total

$$P_{tot} = \mathrm{P}_{rugi.IGBT} + \mathrm{P}_{rugi.DIODA}$$

$$P_{tot} = 40,946kW + 44,142kW$$

$$P_{tot} = 85,088kW$$

b. Daya *output* (P_{out})

$$P_{out} = P_{in} - P_{tot}$$

$$P_{out} = 450kW - 85,088kW$$

$$P_{out} = 364,912kW$$

c. Efisiensi

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

$$\eta = \frac{364,912kW}{450kW}$$

$$\eta = 81,1\%$$

2. Tegangan *output* 321V

a. Rugi total

$$P_{tot} = P_{rugi.IGBT} + P_{rugi.DIODA}$$

$$P_{tot} = 21,749kW + 31,968kW$$

$$P_{tot} = 53,717kW$$

b. Daya *output* (P_{out})

$$P_{out} = P_{in} - P_{tot}$$

$$P_{out} = 450kW - 53,717kW$$

$$P_{out} = 396,283kW$$

c. Efisiensi

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

$$\eta = \frac{396,283kW}{450kW}$$

$$\eta = 88,06\%$$

3. Tegangan output 493,9V

a. Rugi total

$$P_{tot} = P_{rugi.IGBT} + P_{rugi.DIODA}$$

$$P_{tot} = 16,662kW + 27,708kW$$

$$P_{tot} = 44,37kW$$

b. Daya *output* (P_{out})

$$P_{out} = P_{in} - P_{tot}$$

$$P_{out} = 450kW - 44,37kW$$

$$P_{out} = 405,63kW$$

c. Efisiensi

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

$$\eta = \frac{405,63kW}{450kW}$$

$$\eta = 90,14\%$$

4. Tegangan output 635V

a. Rugi total

$$P_{tot} = P_{rugi.IGBT} + P_{rugi.DIODA}$$

$$P_{tot} = 16,046kW + 25,95kW$$

$$P_{tot} = 41,996kW$$

b. Daya *output* (P_{out})

$$P_{out} = P_{in} - P_{tot}$$

$$P_{out} = 450kW - 41,996kW$$

$$P_{out} = 408,004kW$$

c. Efisiensi

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

$$\eta = \frac{408,004 kW}{450 kW}$$

$$\eta = 90,67\%$$

5. Tegangan output 645V

a. Rugi total

$$P_{tot} = \mathrm{P}_{rugi.IGBT} + \mathrm{P}_{rugi.DIODA}$$

$$P_{tot} = 16,118 kW + 25,85 kW$$

$$P_{tot} = 41,968 kW$$

b. Daya *output* (P_{out})

$$P_{out} = P_{in} - P_{tot}$$

$$P_{out} = 450 kW - 41,968 kW$$

$$P_{out} = 408,032 kW$$

c. Efisiensi

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

$$\eta = \frac{408,032 kW}{450 kW}$$

$$\eta = 90,67\%$$

Lampiran 4. Perhitungan rugi-rugi motor traksi dengan lima kondisi

1. Kondisi Pengujian I (Tegangan *Input* 160,5V)

Tabel 29. Parameter kondisi pengujian I

Daerah Kerja	Nilai	Daerah Kerja	Nilai
P_{out}	44,95 kW	P_{FW}	23,84 W
V	160,5 V	L_S	0,921 mH
f	9,1 Hz	L_R	0.422 mH
I_{in}	247,64 A	L_C	22,567 mH
I_{out}	68,9 A	R_S	0,04581 Ω
M	1800	R_R	0,04080 Ω
$\cos\theta$	0,87	R_C	108,621 Ω
η	74,76	P	4
N	238		

a. Daya *Input* *(Pin)*

$$P_{in} = \sqrt{3} x V_T x I_L x Cos\theta$$

$$P_{in} = \sqrt{3} \times 160,5V \times 247,64A \times 0,87$$

$$P_{in} = 59,893kW$$

b. Rugi Tembaga Stator (P_{SCL})

$$P_{SCL} = 3.I_{in}^{2}.R_1$$

$$P_{SCL} = 3.(247,64)^2.0,04581$$

$$P_{SCL} = 8,428kW$$

c. Rugi Inti Stator (P_{CORE})

$$P_{CORE} = \frac{3.V_{in}^{\ 2}}{R_C}$$

$$P_{CORE} = \frac{3.(160,5)^2}{108,621}$$

$$P_{CORE} = 0,711kW$$

d. Total Rugi Stator

$$P_{rugi-stator} = P_{SCL} + P_{CORE}$$

$$P_{rugi-stator} = 8,428kW + 0,711kW$$

$$P_{rugi-stator} = 9,139kW$$

e. Daya *Input* Rotor ($P_{in\text{-}rotor}$)

$$P_{in-rotor} = P_{in} - P_{rugi-stator}$$

$$P_{in-rotor} = 59,893kW - 9,139kW$$

$$P_{in-rotor} = 50,754kW$$

f. Rugi Tembaga Rotor (P_{RCL})

$$N_S = \frac{120f}{P} = \frac{120 \times 9,1}{4} = 273$$

$$s = \frac{N_S - N_R}{N_S} = \frac{273 - 238}{273} = 0,128$$

$$P_{RCL} = (P_{in} - P_{SCL} - P_{CORE}) \times s$$

$$P_{RCL} = (59,93kW - 8,428kW - 0,711kW) \times 0,128$$

$$P_{RCL} = 6,497kW$$

g. Daya Mekanik (P_m)

$$P_m = \mathrm{P}_{in-rotor} - P_{RCL}$$

$$P_m = 50,754kW - 6,497kW$$

$$P_m = 44,257kW$$

h. Rugi Gesekan (P_W)

$$P_W = 0,0238kW$$

i. Rugi *Stray* (P_{STRAY})

$$P_{STRAY} = 1,5\% \times \left(P_m - P_W\right)$$

$$P_{STRAY} = 1,5\% \times \left(44,257kW - 0,0238kW\right)$$

$$P_{STRAY} = 1,5\% \times 44,233kW$$

$$P_{STRAY} = 0,663kW$$

j. Daya *Output* (P_{out})

$$P_{out} = P_m - P_W - P_{STRAY}$$

$$P_{out} = 44,257kW - 0,0238kW - 0,663kW$$

$$P_{out} = 43,570kW$$

k. Efisiensi (η)

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

$$\eta = \frac{43,570kW}{59,893kW} \times 100\%$$

$$\eta = 72,75\%$$

2. Kondisi Pengujian II (Tegangan *Input* 321V)

Tabel 30. Parameter kondisi pengujian II

Daerah Kerja	Nilai	Daerah Kerja	Nilai
P_{out}	98 kW	P_{FW}	95,34 W
V	321 V	Ls	0,921 mH
f	18,2 Hz	L_R	0.422 mH
I_{in}	224,4 A	L_C	22,567 mH
I_{out}	68,9 A	R_1	0,04581 Ω
M	1800	R_R	0,04080 Ω
$\cos\theta$	0,89	R_C	205,038 Ω
η	88,47	P	4
N	518		

a. Daya *Input (Pin)*

$$P_{in} = \sqrt{3} x V_T x I_L x Cos\theta$$

$$P_{in} = \sqrt{3} \times 321V \times 224,4A \times 0,89$$

$$P_{in} = 111,04kW$$

b. Rugi Tembaga Stator (P_{SCL})

$$P_{SCL} = 3.I_{in}^{2}.R_1$$

$$P_{SCL} = 3.(224,4)^2 .0,04581$$

$$P_{SCL} = 6,92KW$$

c. Rugi Inti Stator (P_{CORE})

$$P_{CORE} = \frac{3.V_{in}^{2}}{R_C}$$

$$P_{CORE} = \frac{3.(321)^2}{205,038}$$

$$P_{CORE} = 1,508kW$$

d. Total Rugi Stator

$$P_{rugi-stator} = P_{SCL} + P_{CORE}$$

$$P_{rugi-stator} = 6,92kW + 1,51kW$$

$$P_{rugi-stator} = 8,428kW$$

e. Daya *Input* Rotor ($P_{in-rotor}$)

$$P_{in-rotor} = P_{in} - P_{rugi-stator}$$

$$P_{in-rotor} = 111,04KW - 8,43KW$$

$$P_{in-rotor} = 102,612KW$$

f. Rugi Tembaga Rotor (P_{RCL})

$$N_S = \frac{120f}{P} = \frac{120 \times 18,2}{4} = 546$$

$$s = \frac{N_s - N_R}{N_s} = \frac{546 - 518}{546} = 0,051$$

$$P_{RCL} = (P_{in} - P_{SCL} - P_{CORE}) \times s$$

$$P_{RCL} = (111,04kW - 6,92kW - 1,508kW) \times 0,051$$

$$P_{RCL} = 5,233kW$$

g. Daya Mekanik (P_m)

$$P_m = \mathrm{P}_{in-rotor} - P_{RCL}$$

$$P_m = 102,612kW - 5,233kW$$

$$P_m = 97,379kW$$

h. Rugi Gesekan (P_W)

$$P_W = 0,095kW$$

i. Rugi *Stray* (P_{STRAY})

$$P_{STRAY} = 1,5\% \times (P_m - P_W)$$

$$P_{STRAY} = 1,5\% \times (97,379kW - 0,095kW)$$

$$P_{STRAY} = 1,5\% \times 97,284kW$$

$$P_{STRAY} = 1,459kW$$

j. Daya *Output* (P_{out})

$$P_{out} = P_m - P_W - P_{STRAY}$$

$$P_{out} = 97,379kW - 0,095kW - 1,459kW$$

$$P_{out} = 95,825kW$$

k. Efisiensi (η)

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

$$\eta = \frac{95,825kW}{111,04kW} \times 100\%$$

$$\eta = 86,30\%$$

3. Kondisi Pengujian III (Tegangan *Input* 493,9V)

Tabel 31. Parameter kondisi pengujian III

Daerah Kerja	Nilai	Daerah Kerja	Nilai
P_{out}	153 kW	P_{FW}	225,66 W
V	493,9 V	Ls	0,921 mH
f	28 Hz	L_R	0.422 mH
I_{in}	217,9 A	L_C	22,570 mH
I_{out}	68,9 A	R_S	0,04581 Ω
M	1800	R_R	0,04080 Ω
$\cos\theta$	0,89	R_C	297,478 Ω
η	92,47	P	4
N	813		

a. Daya *Input (Pin)*

$$P_{in} = \sqrt{3} x V_T x I_L x Cos\theta$$

$$P_{in} = \sqrt{3} \times 493,9V \times 217,9A \times 0,89$$

$$P_{in} = 165,9kW$$

b. Rugi Tembaga Stator (P_{SCL})

$$P_{SCL} = 3.I_{in}^{2}.R_1$$

$$P_{SCL} = 3.(217,9)^2.0,04581$$

$$P_{SCL} = 6,525kW$$

c. Rugi Inti Stator (P_{CORE})

$$P_{CORE} = \frac{3.V_{in}^{2}}{R_C}$$

$$P_{CORE} = \frac{3.(493,9)^2}{297,478}$$

$$P_{CORE} = 2,46kW$$

d. Total Rugi Stator

$$P_{rugi-stator} = P_{SCL} + P_{CORE}$$

$$P_{rugi-stator} = 6,525kW + 2,46kW$$

$$P_{rugi-stator} = 8,985kW$$

e. Daya *Input* Rotor ($P_{in\text{-}rotor}$)

$$P_{in-rotor} = P_{in} - P_{rugi-stator}$$

$$P_{in-rotor} = 165,9kW - 8,985kW$$

$$P_{in-rotor} = 156,915kW$$

f. Rugi Tembaga Rotor (P_{RCL})

$$N_S = \frac{120f}{P} = \frac{120 \times 28}{4} = 840$$

$$s = \frac{N_S - N_R}{N_S} = \frac{840 - 813}{840} = 0,032$$

$$P_{RCL} = (P_{in} - P_{SCL} - P_{CORE}) \times s$$

$$P_{RCL} = (165,9kW - 6,525kW - 2,46kW) \times 0,032$$

$$P_{RCL} = 5,021kW$$

g. Daya Mekanik (P_m)

$$P_m = \mathrm{P}_{in-rotor} - P_{RCL}$$

$$P_m = 156,915kW - 5,021kW$$

$$P_m = 151,894kW$$

h. Rugi Gesekan (P_W)

$$P_W = 0,227kW$$

i. Rugi *Stray* (P_{STRAY})

$$P_{STRAY} = 1,5\% \times (P_m - P_W)$$

$$P_{STRAY} = 1,5\% \times (151,894kW - 0,227kW)$$

$$P_{STRAY} = 1,5\% \times 151,667kW$$

$$P_{STRAY} = 2,26kW$$

j. Daya *Output* (P_{out})

$$P_{out} = P_m - P_W - P_{STRAY}$$

$$P_{out} = 151,894kW - 0,227kW - 2,26kW$$

$$P_{out} = 149,407kW$$

k. Efisiensi (η)

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

$$\eta = \frac{149,407kW}{165,9kW} \times 100\%$$

$$\eta = 90,06\%$$

4. Kondisi Pengujian IV (Tegangan *Input* 635 V)

Tabel 32. Parameter kondisi pengujian IV

Daerah Kerja	Nilai	Daerah Kerja	Nilai
P_{out}	200 kW	P_{FW}	373,03 W
V	635 V	Ls	0,921 mH
f	36,38 Hz	L_R	0.422 mH
I_{in}	217,6 A	L_C	22,569 mH
I_{out}	68,9 A	R_S	0,04581 Ω
M	1800	R_R	0,04080 Ω
$\cos\theta$	0,89	R_C	365,442 Ω
η	93,97	P	4
N_R	1064		

a. Daya *Input (Pin)*

$$P_{in} = \sqrt{3} x V_T x I_L x Cos\theta$$

$$P_{in} = \sqrt{3} \times 635V \times 217,6A \times 0,89$$

$$P_{in} = 213kW$$

b. Rugi Tembaga Stator (P_{SCL})

$$P_{SCL} = 3.I_{in}^{2}.R_1$$

$$P_{SCL} = 3.(217,6)^2.0,04581$$

$$P_{SCL} = 6,5kW$$

c. Rugi Inti Stator (P_{CORE})

$$P_{CORE} = \frac{3.V_{in}^{2}}{R_C}$$

$$P_{CORE} = \frac{3.(635)^2}{365,442}$$

$$P_{CORE} = 3,3kW$$

d. Total Rugi Stator

$$P_{rugi-stator} = P_{SCL} + P_{CORE}$$

$$P_{rugi-stator} = 6,5kW + 3,3kW$$

$$P_{rugi-stator} = 9,8kW$$

e. Daya *Input* Rotor ($P_{in-rotor}$)

$$P_{in-rotor} = P_{in} - P_{rugi-stator}$$

$$P_{in-rotor} = 213kW - 9,8kW$$

$$P_{in-rotor} = 203,2kW$$

f. Rugi Tembaga Rotor (P_{RCL})

$$N_S = \frac{120f}{P} = \frac{120 \times 36.38}{4} = 1091,4$$

$$s = \frac{N_S - N_R}{N_S} = \frac{1091,4 - 1064}{1091,4} = 0,025$$

$$P_{RCL} = (P_{in} - P_{SCL} - P_{CORE}) \times s$$

$$P_{RCL} = (213kW - 6,5kW - 3,3kW) \times 0,025$$

$$P_{RCL} = 5,08kW$$

g. Daya Mekanik (P_m)

$$P_m = \mathrm{P}_{in-rotor} - P_{RCL}$$

$$P_m = 203,2kW - 5,08kW$$

$$P_m = 198,12kW$$

h. Rugi Gesekan (P_W)

$$P_W = 0,373kW$$

i. Rugi *Stray* (P_{STRAY})

$$P_{STRAY} = 1,5\% \times \left(P_m - P_W\right)$$

$$P_{STRAY} = 1,5\% \times \left(198,12kW - 0,373kW\right)$$

$$P_{STRAY} = 1,5\% \times 197,747kW$$

$$P_{STRAY} = 2,966kW$$

j. Daya *Output* (P_{out})

$$P_{out} = P_m - P_W - P_{STRAY}$$

$$P_{out} = 198,12kW - 0,373kW - 2,966kW$$

$$P_{out} = 194,781kW$$

k. Efisiensi (η)

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

$$\eta = \frac{194,781kW}{213kW} \times 100\%$$

$$\eta = 91,45\%$$

5. Kondisi Pengujian V (Tegangan Input 645V)

Tabel 33. Parameter kondisi pengujian V

Daerah Kerja	Nilai	Daerah Kerja	Nilai
P_{out}	200 kW	P_{FW}	2331,44 W
V	645 V	Ls	0,921 mH
f	90 Hz	L_R	0.422 mH
I_{in}	197,28 A	L_C	25,326 mH
I_{out}	25,09 A	R_S	0,04581 Ω
M	740	R_R	0,04080 Ω
$\cos\theta$	0,87	R_C	667,490 Ω
η	93,44	P	4
N	2634		

a. Daya *Input (Pin)*

$$P_{in} = \sqrt{3} x V_T x I_L x Cos\theta$$

$$P_{in} = \sqrt{3} \times 645V \times 197,28A \times 0,87$$

$$P_{in} = 191,744kW$$

b. Rugi Tembaga Stator (P_{SCL})

$$P_{SCL} = 3.I_{in}^{2}.R_1$$

$$P_{SCL} = 3.(197,28)^2.0,04581$$

$$P_{SCL} = 5,349kW$$

c. Rugi Inti Stator (P_{CORE})

$$P_{CORE} = \frac{3.V_{in}^{\;2}}{R_C}$$

$$P_{CORE} = \frac{3.(645)^2}{667,490}$$

$$P_{CORE} = 1,870kW$$

d. Total Rugi Stator

$$P_{rugi-stator} = P_{SCL} + P_{CORE}$$

$$P_{rugi-stator} = 5,349kW + 1,870kW$$

$$P_{rugi-stator} = 7,219kW$$

e. Daya *Input* Rotor ($P_{in-rotor}$)

$$P_{in-rotor} = P_{in} - P_{rugi-stator}$$

$$P_{in-rotor} = 191,744kW - 7,219kW$$

$$P_{in-rotor} = 184,525kW$$

f. Rugi Tembaga Rotor (P_{RCL})

$$N_S = \frac{120f}{P} = \frac{120 \times 90}{4} = 2700$$

$$s = \frac{N_S - N_R}{N_S} = \frac{2700 - 2634}{2700} = 0,024$$

$$P_{RCL} = (P_{in} - P_{SCL} - P_{CORE}) \times s$$

$$P_{RCL} = (191,744kW - 5,349kW - 1,870kW) \times 0,024$$

$$P_{RCL} = 4,429kW$$

g. Daya Mekanik (P_m)

$$P_m = \mathrm{P}_{in-rotor} - P_{RCL}$$

$$P_m = 184,525kW - 4,429kW$$

$$P_m = 180,096kW$$

h. Rugi Gesekan (P_W)

$$P_W = 2,33kW$$

i. Rugi *Stray* (P_{STRAY})

$$P_{STRAY} = 1,5\% \times (P_m - P_W)$$

$$P_{STRAY} = 1,5\% \times (180,096kW - 2,33kW)$$

$$P_{STRAY} = 1,5\% \times 177,766kW$$

$$P_{STRAY} = 2,667kW$$

j. Daya *Output* (P_{out})

$$P_{out} = P_m - P_W - P_{STRAY}$$

$$P_{out} = 180,096kW - 2,33kW - 2,667kW$$

$$P_{out} = 175,099kW$$

k. Efisiensi (η)

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

$$\eta = \frac{175,099kW}{191,744kW} \times 100\%$$

$$\eta = 91,32\%$$

Lampiran 5. Hasil pengujian motor traksi 200kW

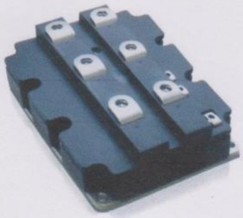
Daerah Kerja (*Operating area*)		S1	11	12	14	21
P_{shaft}	[kW]	200	44,95	98	153	200
Tegangan (*Voltage*)	[V]	635	160,5	321	493,9	645
Frekuensi (*Frequency*)	[Hz]	36,38	9,1	18,2	28	90
Arus (*Current*)	[A]	217,6	247,64	224,4	217,9	197,28
Putaran (*Speed*)	[rpm]	1064	238	518	813	2634
Momen (*Moment*)	[Nm]	1800	1800	1800	1800	740
Cos phi		0,89	0,87	0,89	0,89	0,87
Efisiensi (*Efficiency*)	[%]	93,97	74,76	88,47	92,47	93,44
P_{FW} Gesekan (*Friction*)	[W]	373,03	23,84	95,34	225,66	2331,44
I_o	[A]	68,9	68,9	68,9	68,9	25,09
X1σ	[Ω]	0,21332	0,06980	0,11486	0,16839	0,52286
X2'σ	[Ω]	0,10386	0,04741	0,06321	0,08475	0,24223
Xh	[Ω]	5,10502	1,29032	2,58064	3,97066	14,32132
Φg	mVs	48,05	48,05	48,05	48,05	19,52
L1σ	[mH]	0,921	0,921	0,921	0,921	0,921
L2'σ	[mH]	0,422	0,422	0,422	0,422	0,422
Lh	[mH]	22,569	22,567	22,567	22,570	25,326
Rc	[Ω]	365,442	108,621	205,036	297,478	667,490
R1 (115° C)	[Ω]	0,04581				
R2' (115° C)	[Ω]	0,04080				

Lampiran 6. Datasheet IGBT 5SYA 3300V/1500A

Data Sheet, Doc. No. 5SYA 1407-07 02-2014

5SNA 1500E330305
HiPak IGBT Module

V_{CE} = 3300 V
I_C = 1500 A



Ultra low-loss, rugged SPT+ chip-set
Smooth switching SPT+ chip-set for good EMC
AlSiC base-plate for high power cycling capability
AlN substrate for low thermal resistance
Improved high reliability package

Maximum rated values [1]

Parameter	Symbol	Conditions	min	max	Unit
Collector-emitter voltage	V_{CES}	V_{GE} = 0 V, T_{vj} ≥ 25 °C		3300	V
DC collector current	I_C	T_C = 100 °C, T_{vj} = 150 °C		1500	A
Peak collector current	I_{CM}	t_p = 1 ms		3000	A
Gate-emitter voltage	V_{GES}		-20	20	V
Total power dissipation	P_{tot}	T_C = 25 °C, T_{vj} = 150 °C		14700	W
DC forward current	I_F			1500	A
Peak forward current	I_{FRM}	t_p = 1 ms		3000	A
Surge current	I_{FSM}	V_R = 0 V, T_{vj} = 150 °C, t_p = 10 ms, half-sinewave		13500	A
IGBT short circuit SOA	t_{psc}	V_{CC} = 2500 V, $V_{CEM\,CHIP}$ ≤ 3300 V, V_{GE} ≤ 15 V, T_{vj} ≤ 150 °C		10	µs
Isolation voltage	V_{isol}	1 min, f = 50 Hz		6000	V
Junction temperature	T_{vj}			175	°C
Junction operating temperature	$T_{vj(op)}$		-50	150	°C
Case temperature	T_C		-50	150	°C
Storage temperature	T_{stg}		-50	125	°C
Mounting torques [2]	M_s	Base-heatsink, M6 screws	4	6	Nm
	M_{t1}	Main terminals, M8 screws	8	10	
	M_{t2}	Auxiliary terminals, M4 screws	2	3	

[1] Maximum rated values indicate limits beyond which damage to the device may occur per IEC 60747
[2] For detailed mounting instructions refer to ABB Document No. 5SYA 2039

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IGBT characteristic values [3)]

Parameter	Symbol	Conditions		min	typ	max	Unit
Collector (-emitter) breakdown voltage	$V_{(BR)CES}$	V_{GE} = 0 V, I_C = 10 mA, T_{vj} = 25 °C		3300			V
Collector-emitter [4)] saturation voltage	$V_{CE\,sat}$	I_C = 1500 A, V_{GE} = 15 V	T_{vj} = 25 °C		2.5	2.9	V
			T_{vj} = 125 °C		3.1	3.4	V
			T_{vj} = 150 °C		3.25		V
Collector cut-off current	I_{CES}	V_{CE} = 3300 V, V_{GE} = 0 V	T_{vj} = 25 °C		0.06	1	mA
			T_{vj} = 125 °C		20	40	mA
			T_{vj} = 150 °C		100		mA
Gate leakage current	I_{GES}	V_{CE} = 0 V, V_{GE} = ± 20 V, T_{vj} = 125 °C		-500		500	nA
Gate-emitter threshold voltage	$V_{GE(th)}$	I_C = 240 mA, V_{CE} = V_{GE}, T_{vj} = 25 °C		5		7	V
Gate charge	Q_G	I_C = 1500 A, V_{CE} = 1800 V, V_{GE} = -15 V ..15 V			11.0		μC
Input capacitance	C_{ies}	V_{CE} = 25 V, V_{GE} = 0 V, f = 1 MHz, T_{vj} = 25 °C			151		nF
Output capacitance	C_{oes}				12.6		nF
Reverse transfer capacitance	C_{res}				3.85		nF
Internal gate resistance	R_{Gint}				0.6		Ω
Turn-on delay time	$t_{d(on)}$	V_{CC} = 1800 V, I_C = 1500 A, R_G = 1.0 Ω, C_{GE} = 330 nF, V_{GE} = ±15 V, L_σ = 100 nH, inductive load	T_{vj} = 25 °C		650		ns
			T_{vj} = 125 °C		590		ns
			T_{vj} = 150 °C		590		ns
Rise time	t_r		T_{vj} = 25 °C		240		ns
			T_{vj} = 125 °C		270		ns
			T_{vj} = 150 °C		280		ns
Turn-off delay time	$t_{d(off)}$	V_{CC} = 1800 V, I_C = 1500 A, R_G = 1.5 Ω, C_{GE} = 330 nF, V_{GE} = ±15 V, L_σ = 100 nH, inductive load	T_{vj} = 25 °C		1600		ns
			T_{vj} = 125 °C		1750		ns
			T_{vj} = 150 °C		1800		ns
Fall time	t_f		T_{vj} = 25 °C		390		ns
			T_{vj} = 125 °C		440		ns
			T_{vj} = 150 °C		470		ns
Turn-on switching energy	E_{on}	V_{CC} = 1800 V, I_C = 1500 A, R_G = 1.0 Ω, C_{GE} = 330 nF, V_{GE} = ±15 V, L_σ = 100 nH, inductive load	T_{vj} = 25 °C		1600		mJ
			T_{vj} = 125 °C		2150		mJ
			T_{vj} = 150 °C		2350		mJ
Turn-off switching energy	E_{off}	V_{CC} = 1800 V, I_C = 1500 A, R_G = 1.5 Ω, C_{GE} = 330 nF, V_{GE} = ±15 V, L_σ = 100 nH, inductive load	Tvj = 25 °C		2100		mJ
			Tvj = 125 °C		2800		mJ
			T_{vj} = 150 °C		3000		mJ
Short circuit current	I_{SC}	t_{psc} ≤ 10 μs, V_{GE} = 15 V, V_{CC} = 2500 V, $V_{CEM\,CHIP}$ ≤ 3300 V	Tvj = 150 °C		6400		A

[3)] Characteristic values according to IEC 60747 - 9
[4)] Collector-emitter saturation voltage is given at chip level

Diode characteristic values [5)]

Parameter	Symbol	Conditions		min	typ	max	Unit
Forward voltage [6)]	V_F	I_F = 1500 A	T_{vj} = 25 °C		2.05	2.5	V
			T_{vj} = 125 °C		2.25	2.6	V
			T_{vj} = 150 °C		2.20		V
Reverse recovery current	I_{rr}	V_{CC} = 1800 V, I_F = 1500 A, V_{GE} = ±15 V, R_G = 1.0 Ω, C_{GE} = 330 nF, di/dt = 6 kA/µs $L_σ$ = 100 nH, inductive load	T_{vj} = 25 °C		1700		A
			T_{vj} = 125 °C		1850		A
			T_{vj} = 150 °C		1900		A
Recovered charge	Q_{rr}		T_{vj} = 25 °C		950		µC
			T_{vj} = 125 °C		1550		µC
			T_{vj} = 150 °C		1800		µC
Reverse recovery time	t_{rr}		T_{vj} = 25 °C		1050		ns
			T_{vj} = 125 °C		1350		ns
			T_{vj} = 150 °C		1500		ns
Reverse recovery energy	E_{rec}		T_{vj} = 25 °C		1150		mJ
			T_{vj} = 125 °C		1900		mJ
			T_{vj} = 150 °C		2250		mJ

[5)] Characteristic values according to IEC 60747 - 2
[6)] Forward voltage is given at chip level

Package properties [7)]

Parameter	Symbol	Conditions		min	typ	max	Unit
IGBT thermal resistance junction to case	$R_{th(j-c)IGBT}$					0.0085	K/W
Diode thermal resistance junction to case	$R_{th(j-c)DIODE}$					0.017	K/W
IGBT thermal resistance [2)] case to heatsink	$R_{th(c-s)IGBT}$	IGBT per switch, λ grease = 1W/m x K			0.009		K/W
Diode thermal resistance [2)] case to heatsink	$R_{th(c-s)DIODE}$	Diode per switch, λ grease = 1W/m x K			0.018		K/W
Comparative tracking index	CTI			600			
Module stray inductance	$L_{σ CE}$				8		nH
Resistance, terminal-chip	$R_{CC'+EE'}$		T_C = 25 °C		0.055		mΩ
			T_C = 125 °C		0.075		
			T_C = 150 °C		0.080		

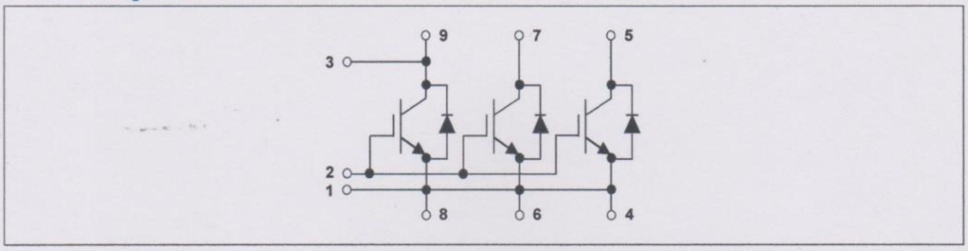
[2)] For detailed mounting instructions refer to ABB Document No. 5SYA 2039

Mechanical properties [7)]

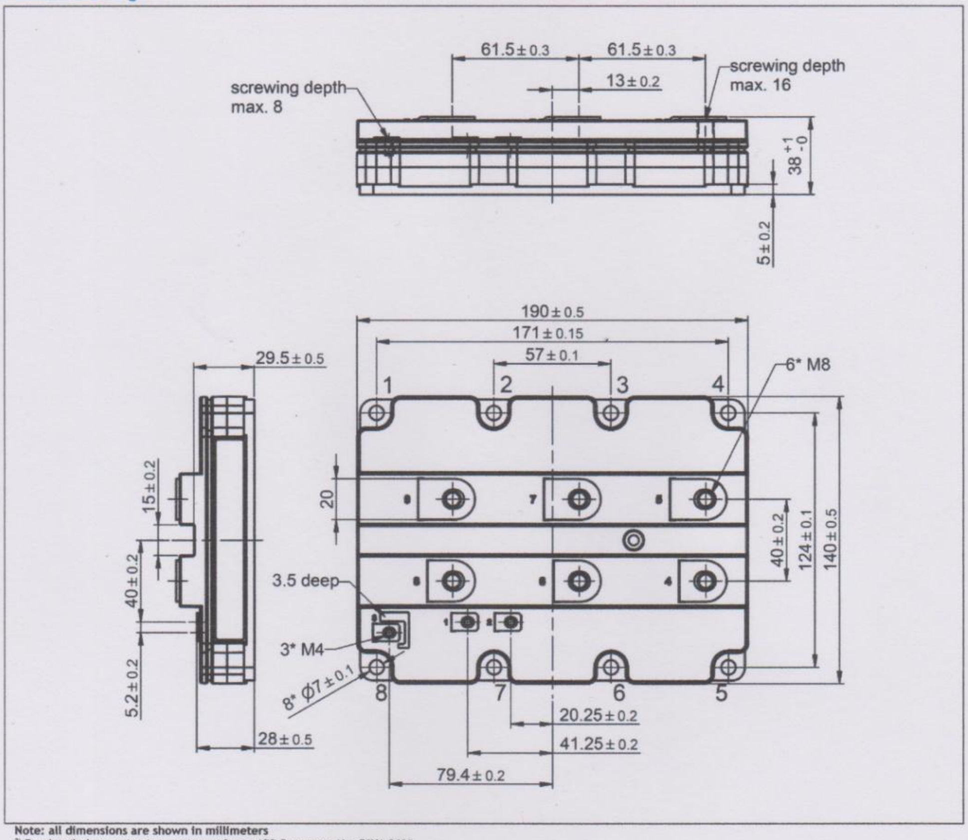
Parameter	Symbol	Conditions		min	typ	max	Unit
Dimensions	L x W x H	Typical			190 x 140 x 38		mm
Clearance distance in air	d_a	according to IEC 60664-1 and EN 50124-1	Term. to base:	23			mm
			Term. to term:	19			
Surface creepage distance	d_s	according to IEC 60664-1 and EN 50124-1	Term. to base:	28.2			mm
			Term. to term:	28.2			
Mass	m				1210		g

[7)] Package and mechanical properties according to IEC 60747 - 15

Electrical configuration



Outline drawing [2)]



Note: all dimensions are shown in millimeters
[2)] For detailed mounting instructions refer to ABB Document No. 5SYA 2039

This is an electrostatic sensitive device, please observe the international standard IEC 60747-1, chap. IX.
This product has been designed and qualified for Industrial Level.

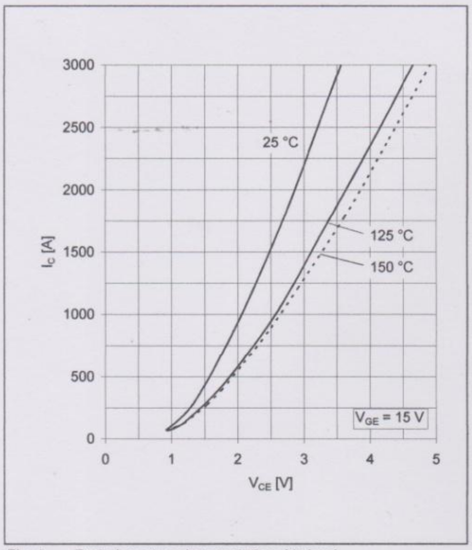


Fig. 1 Typical on-state characteristics, chip level

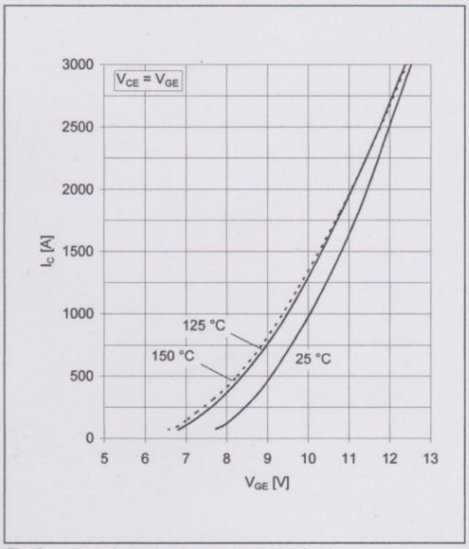


Fig. 2 Typical transfer characteristics, chip level

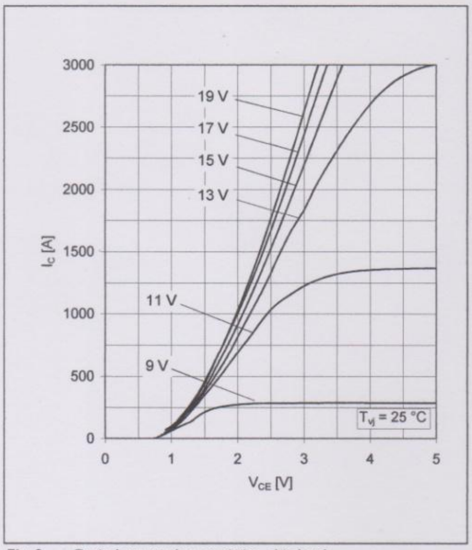


Fig. 3 Typical output characteristics, chip level

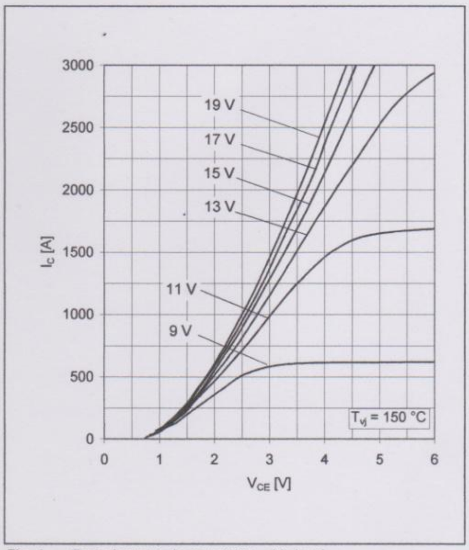


Fig. 4 Typical output characteristics, chip level

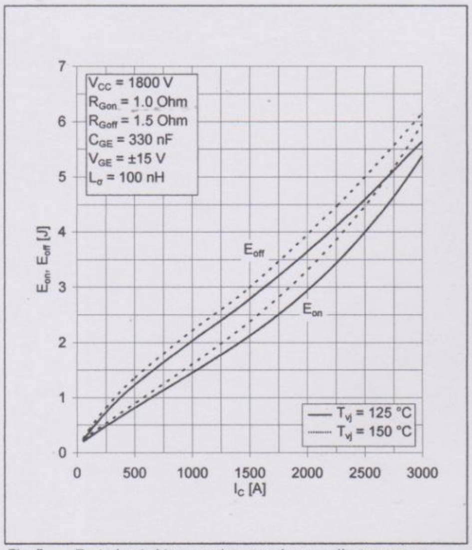


Fig. 5 Typical switching energies per pulse vs. collector current

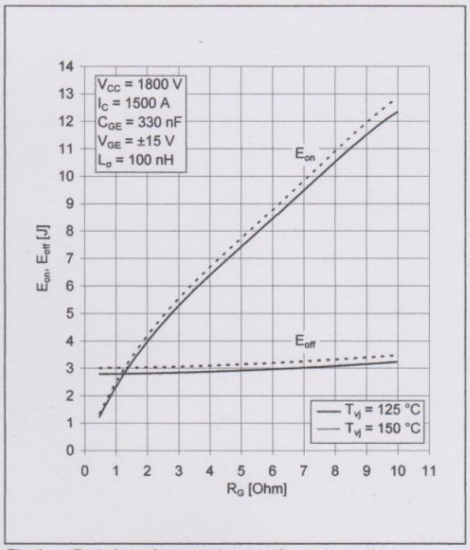


Fig. 6 Typical switching energies per pulse vs. gate resistor

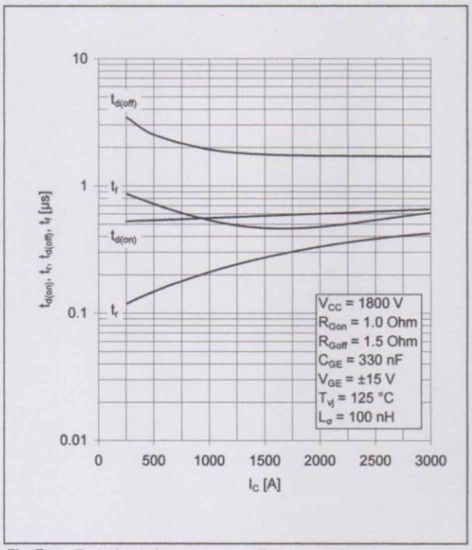


Fig. 7 Typical switching times vs. collector current

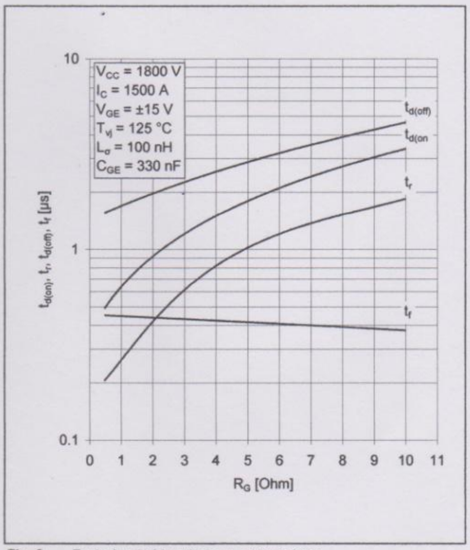


Fig. 8 Typical switching times vs. gate resistor

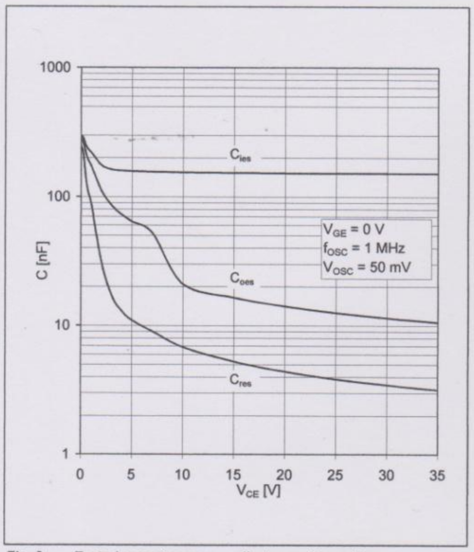


Fig. 9 Typical capacitances vs. collector-emitter voltage

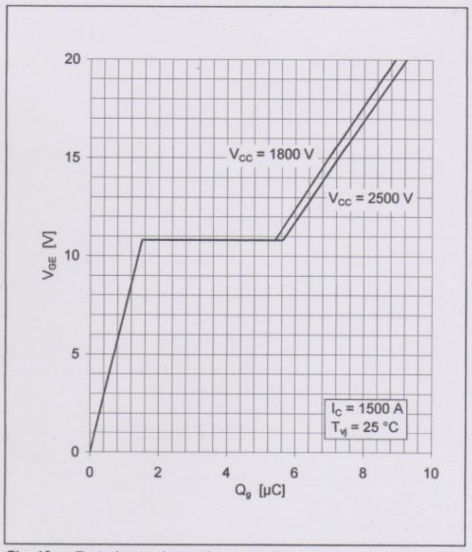


Fig. 10 Typical gate charge characteristics

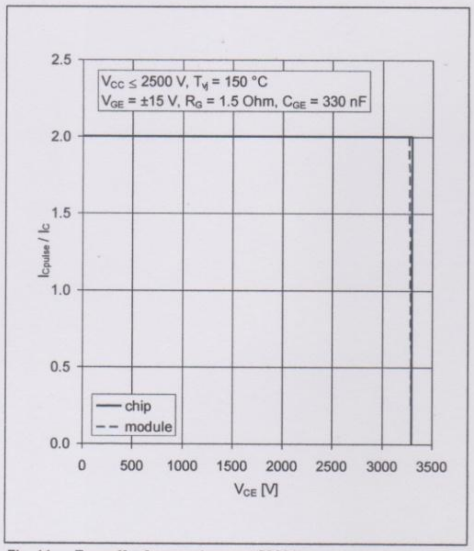


Fig. 11 Turn-off safe operating area (RBSOA)

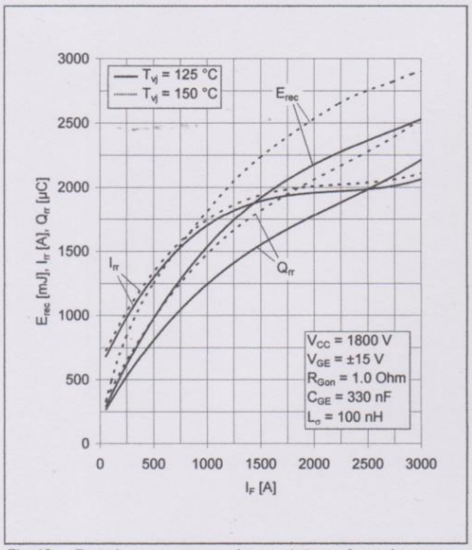


Fig. 12 Typical reverse recovery characteristics vs. forward current

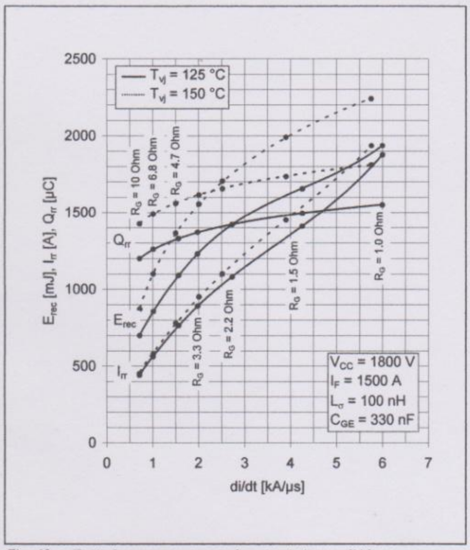


Fig. 13 Typical reverse recovery characteristics vs. di/dt

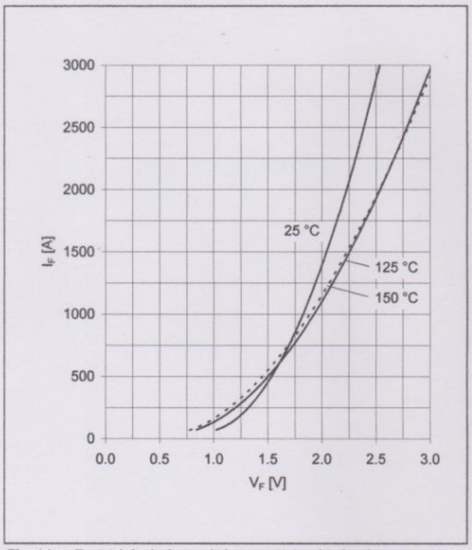


Fig. 14 Typicial diode forward characteristics chip level

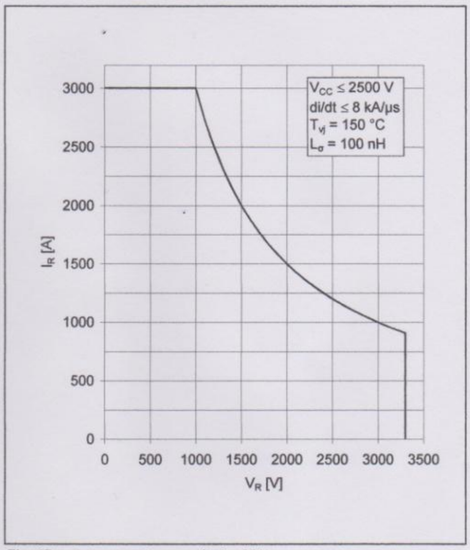


Fig. 15 Safe operating area diode (SOA)

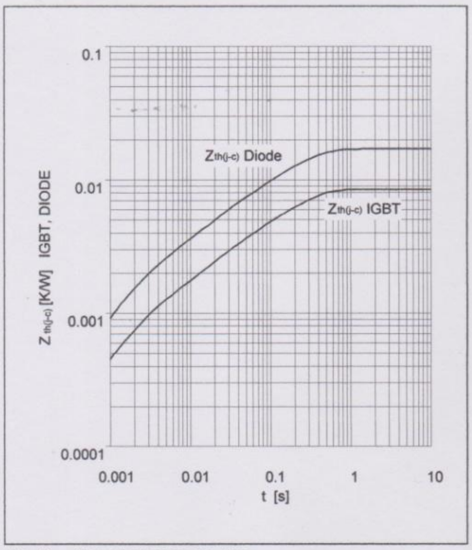


Fig. 16 Thermal impedance vs. time

Analytical function for transient thermal impedance:

$$Z_{th\,(j\text{-}c)}(t) = \sum_{i=1}^{n} R_i \left(1 - e^{-t/\tau_i}\right)$$

	i	1	2	3	4	5
IGBT	Ri(K/kW)	5.854	1.375	0.641	0.632	
	τi(ms)	207.4	30.1	7.55	1.57	
DIODE	Ri(K/kW)	11.54	2.887	1.229	1.295	
	τi(ms)	203.6	30.1	7.53	1.57	

Related documents:

5SYA 2042 Failure rates of HiPak modules due to cosmic rays
5SYA 2043 Load - cycle capability of HiPaks
5SYA 2045 Thermal runaway during blocking
5SYA 2053 Applying IGBT
5SYA 2058 Surge currents for IGBT diodes
5SYA 2093 Thermal design of IGBT modules
5SYA 2098 Paralleling of IGBT modules
5SZK 9111 Specification of environmental class for HiPak Storage
5SZK 9112 Specification of environmental class for HiPak Transportation
5SZK 9113 Specification of environmental class for HiPak Operation (Industry)
5SZK 9120 Specification of environmental class for HiPak

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