https://doi.org/10.21289/KSIC.2021.24.4.411

A Study on the Power Loss Simulation of IGBT for HVDC Power Conversion System

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〈Abstract〉

In this study, IGBT_Total_Loss and DIODE_Total_Loss were used to analyze the slope of the junction temperature for each section for temperature and duty variables in order to simply calculate the junction temperature of the power semiconductor (IGBT). As a result of the calculation, IGBT_Max_Junction_Temp and DIODE_Max_Junction_Temp form a proportional relationship with temperature for each duty. This simulation data shows that the power loss of a power semiconductor is calculated in a complex manner according to the current dependence index, voltage dependence index, and temperature coefficient. By applying the slope for each condition and section, the junction temperature of the power semiconductor can be calculated simply.

Keywords : HVDC, Life Time, Power Loss, IGBT, Look-up tabe, Conduction Loss, Switching Loss, Thermal Equivalent Model, Junction Temperature

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1. Introduction

A power semiconductor is configured in an electronic component circuit such as a power converter. However, power semiconductors that are generally composed of power MOSFETs (Metal Oxide Semiconductor Field Effect Transistors),IPDs (Intelligent Power Devices), DIODEs, IGBTs (Insulated Gate Bipolar Transistors), power modules, bipolar transistors, and SiC (silicon carbide) drive Since the loss of function due to heat generation is large and the service life is also reduced due to self-deterioration, a cooling mechanism for cooling the driving heat generation should be configured in the corresponding electronic component. There is a need to introduce and develop a technology capable of predicting and diagnosing the driving life of electronic components in advance and replacing them, and also efficiently and economically performing the prediction and diagnosis made during facility operation. For this purpose, it is necessary to calculate the loss of the power conversion device. However, there is a difficulty in calculating the loss under various conditions such as current and voltage, switching frequency, duty, and temperature. Therefore, the applicability of the proposed method was checked by varying the duty and temperature in order to calculate it in a simple look-up table format.

2. Main subject

2.1 Power Loss of IGBT

The power loss of the power semiconductor (IGBT) is expressed as the sum of the conduction loss and the switching loss in equation 1. Conduction loss is represented by IGBT Forward Characteristics (Static) in Figure 1, and is represented by the slope of temperature and r_{ce} in equation 2. Switching loss is expressed as the product of switching frequency and switching power loss consumption according to current, voltage, and temperature in equation 3. In equation 4, the switching energy consumption is calculated differently according to Ki (current dependence index), Kv (voltage dependence index), TC_{sw}(temperature coefficient), and measurement rating of current, voltage, and temperature, which are makes calculation of junction temperature difficult.

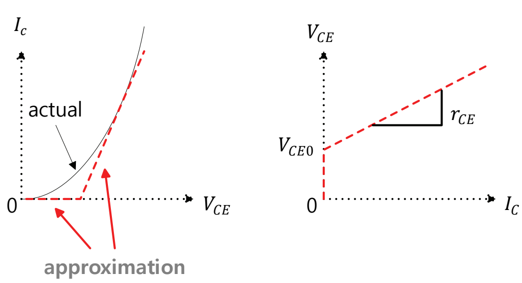


Fig. 1 IGBT forward characteristics(Static)

$$\text{Power loss} = P_{cond} + P_{sw} \qquad (1)$$

P_{cond} : $conduction\,loss, P_{sw}$: $switching\,loss$

$$V_{CE(sat)} = f(I_c) = V_{CEO} + r_{ce} \times I_c,\quad V_{CEO} = V_{CEO-25℃} + TC_V \times (T_j - 25℃),\quad r_{ce} = r_{ce-25℃} + TC_r \times (T_j - 25℃) \tag{2}$$

$$\text{Switching loss} = f_{sw} \times E_{sw} \quad (I : V_{CC} : T_J) \tag{3}$$

$$E_{sw} = E_{swref} \times \left(\frac{I_{out}}{I_{ref}}\right)^{Ki} \times \left(\frac{V_{\in}}{V_{ref}}\right)^{Kv} \times (1 + TC_{sw}(T_j - T_{jref})) \tag{4}$$

Ki : Exponent of current dependency, Kv : Exponent of voltage dependency, TC_{sw}*: Temperature coefficient,* $I_{ref}, V_{ref}, T_{jref}$ *: Measurement rating of current, voltage, and temperature*

2.2 Thermal Equivalent Model of Power Semiconductor (IGBT)

The mathematical thermal equivalent circuit shown in figure 3 is called the natural or physical equivalent circuit of heat conduction and accurately depicts the internal heat distribution. Through this equivalent circuit, it is possible to accurately know the correlation between the equivalent element and the actual structural element. The thermal equivalent network in figure 2 is often used to accurately represent the thermal behavior at the input terminals of a black box. The thermal equivalent network in figure 2 is often used to accurately represent the thermal behavior at the input terminals of a black box. Each RC element represents the partial fraction terms of the heat transfer function of the system. Using the partial fractional expression, the step response of the thermal impedance can be expressed as equation 5. The equivalent input impedance of the input terminal can be expressed as equation 6. A curve fitting algorithm in a computer software tool such as Matlab is derived from the transient thermal impedance curve to determine the individual R_{th} and C_{th} components. Transient thermal impedance curves are usually provided in the device's data sheet. This simple model was based on the parameterization of equivalent circuit elements using curve fittings related to the measurement data. In practice, the usual

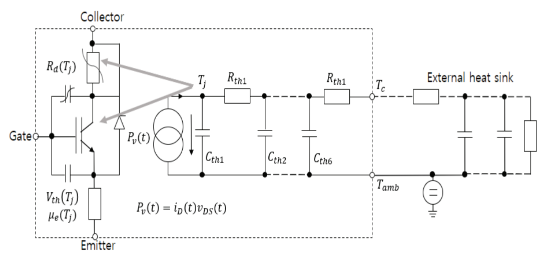


Fig. 2 Combination of electrical and thermal components for IGBT

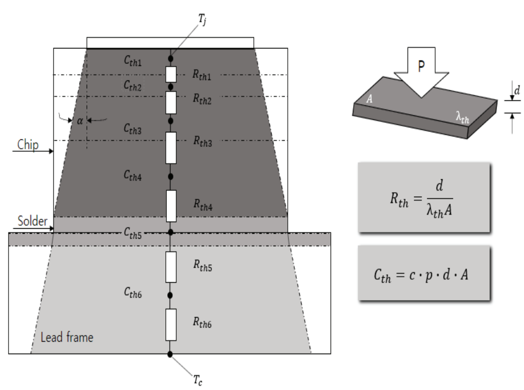


Fig. 3 Thermal equivalent factors for modeling heat conduction of IGBT

procedure for a cooling curve is to first heat up with a component of a given power dissipation P_k until a fixed temperature T_{jk} is assumed. If the exact temperature dependence of a parameter of the chip is known, such as the forward voltage drop, the $T_j(t)$ curve, known as the cooling curve, can be determined by gradually reducing the power dissipation P_k to zero. This cooling curve is used to find the transient thermal impedance of the device.

This cooling curve is used to find the transient thermal impedance of the device.

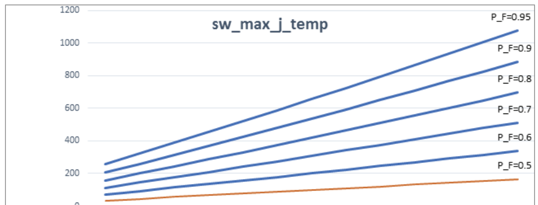
$$Z_{th}(t) = \sum_{i=1}^{n} R_i \left(1 - e^{\frac{t}{R_i C_i}}\right) \qquad (5)$$

$$Z_{th} = \cfrac{1}{sC_{th,1} + \cfrac{1}{sR_{th,1} + \cfrac{1}{sC_{th,2} + \cdots + \cfrac{1}{sR_{th,n}}}}} \qquad (6)$$

$$Z_{th} = \frac{T_{jk} - T_j(t)}{P_k} \qquad (7)$$

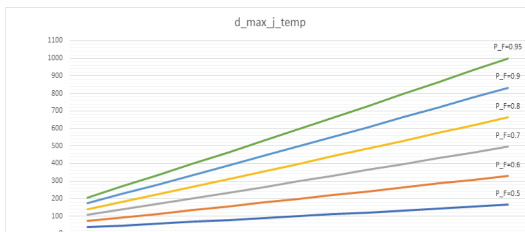
2.3 Power loss simulation of power semiconductor (IGBT) for HVDC

To calculate the lifespan of the IGBT of the SM (Sub Module) for MMC (Modular Multi Level Converter) Type HVDC (High Voltage Direct Current), Ki (current dependence index), Kv (voltage dependence index), TC_{sw} (temperature coefficient), The IGBT junction temperature should be calculated according to I_{ref}, V_{ref}, T_{jref}(rating of current, voltage, and temperature). For this purpose, IGBT_Total_Loss and DIODE_Total_Loss were calculated for temperature variable and P_F variable.



	0℃	10℃	20℃	30℃	40℃	50℃	60℃	70℃	80℃	90℃	100℃	110℃	120℃
P_F=0.95	50.5	61.8	73	84.5	96	107.6	119.4	131.3	143.5	155.7	168	180.2	192.4
P_F=0.9	48.3	59.5	70.7	82	93.4	105	116.7	128.4	140.5	152.6	164.7	176.8	189
P_F=0.8	44.5	55.5	66.6	77.7	88.9	100.2	111.7	123.3	135	146.9	158.8	170.7	182.6
P_F=0.7	40.9	51.7	62.6	73.6	84.7	95.8	107.1	118.4	129.9	141.5	153.2	164.9	176.6
P_F=0.6	37.1	47.8	58.5	69.4	80.2	91.2	102.2	113.3	124.5	135.9	147.3	158.7	170.2
P_F=0.5	34.7	45.4	56	66.8	77.5	88.4	99.3	110.3	121.3	132.5	143.7	155	166.3

Fig. 4 IGBT_Max_Junction_Temp



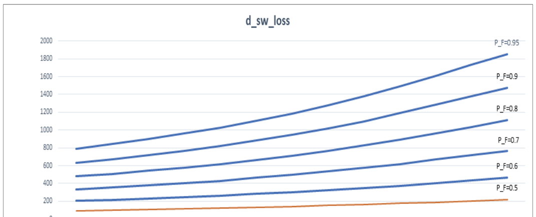
	0℃	10℃	20℃	30℃	40℃	50℃	60℃	70℃	80℃	90℃	100℃	110℃	120℃
P_F=0.95	32.3	43.1	53.9	64.9	75.9	87	98.3	109.6	121.2	132.8	144.5	156.2	168
P_F=0.9	33.1	43.8	54.6	65.5	76.5	87.6	98.8	110.1	121.5	133.1	144.8	156.4	168.1
P_F=0.8	34.2	44.9	55.6	66.4	77.3	88.3	99.3	110.5	121.8	133.2	144.7	156.2	167.7
P_F=0.7	35	45.6	56.2	66.9	77.7	88.5	99.4	110.5	121.5	132.8	144.1	155.4	166.7
P_F=0.6	35.3	45.7	56.2	66.8	77.4	88.1	98.9	109.7	120.6	131.6	142.7	153.8	164.9
P_F=0.5	36.4	46.8	57.2	67.8	78.3	88.9	99.5	110.3	121.1	131.9	142.9	153.9	164.8

Fig. 5 DIODE_Max_Junction_Temp

	0℃	10℃	20℃	30℃	40℃	50℃	60℃	70℃	80℃	90℃	100℃	110℃	120℃
P_F=0.95	571.4	586.9	602.9	622.7	644.3	669.6	698.7	731.4	770.5	809.8	849.2	888.6	928
P_F=0.9	537.8	551.7	566.7	584.2	604.6	626.9	654.5	683.3	720.5	757.8	795.3	832.7	870.1
P_F=0.8	476.4	487.3	500.5	514.2	532.3	550.4	574.2	599	629.7	663.3	696.9	730.5	764.1
P_F=0.7	418.3	426.7	438.2	449.7	464.5	480.4	499.3	521.1	545.3	575.1	605	634.9	664.8
P_F=0.6	352.9	359.7	368.4	378	389	402.5	416.3	434.9	453.5	477.8	503.3	528.8	554.3
P_F=0.5	326.7	333	340.4	349.3	358.6	371	383.4	399.7	416.8	437.3	460.7	484.1	507.5

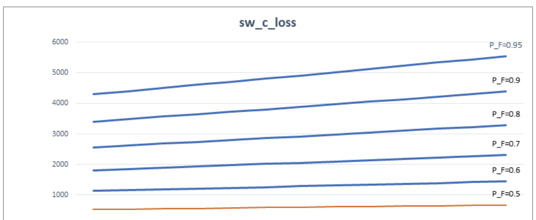
Fig. 6 IGBT_Switching_Loss

The simulation conditions are (switching frequency: 180[hz], rated current: 1010[Arms], rated voltage: 2400[V]), and the duty is varied (D = 0.5,0.6,0.7,0.8,0.9,0.95) for correlation analysis between IGBT and DIODE. For temperature correlation analysis, the ambient temperature (Ta) was varied as 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120[℃].



	0℃	10℃	20℃	30℃	40℃	50℃	60℃	70℃	80℃	90℃	100℃	110℃	120℃
P_F=0.95	158.1	168.3	179.1	192.1	205.2	221.3	237.7	256.9	277.4	300.4	325.5	350.5	375.6
P_F=0.9	155.3	165.2	176	188.6	201.4	217.1	233.1	251.9	271.9	294.3	318.7	343.1	367.5
P_F=0.8	145.2	154.3	164.4	176	187.9	202.5	217.1	234.5	252.8	273.4	295.8	318.1	340.5
P_F=0.7	130.5	138.6	147.7	158	168.6	181.5	194.4	209.9	225.9	244	263.7	283.5	303.2
P_F=0.6	107.5	114.1	121.5	129.9	138.4	148.9	159.4	171.8	184.8	199	215	230.9	246.8
P_F=0.5	95.5	101.3	107.9	115.3	122.9	132.1	141.3	152.2	163.5	176.1	190	203.9	217.8

Fig. 7 DIODE_Switching_Loss

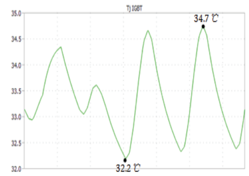


	0℃	10℃	20℃	30℃	40℃	50℃	60℃	70℃	80℃	90℃	100℃	110℃	120℃
P_F=0.95	894.2	915.4	936.6	958	979.5	1001.3	1023.3	1045.5	1068.1	1091	1113.7	1136.2	1159
P_F=0.9	842.6	862.6	882.7	902.9	923.2	943.7	964.4	985.3	1006.6	1028	1049.4	1070.8	1092.4
P_F=0.8	754.2	772	789.9	807.8	825.8	844.1	862.5	881	899.7	918.7	937.7	956.6	975.6
P_F=0.7	674.9	690.6	706.4	722.2	738.2	754.2	770.3	786.6	802.8	819.5	836.2	852.9	869.5
P_F=0.6	600.9	614.6	628.4	642.2	656.1	670.1	684	698.1	712.3	726.6	741	755.4	769.8
P_F=0.5	532.5	544.4	556.3	568.3	580.3	592.3	604.4	616.5	628.7	641	653.4	665.8	678.2

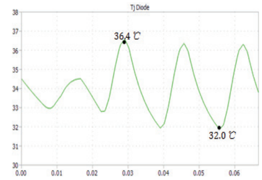
Fig. 8 IGBT_Conduction_Loss

	0℃	10℃	20℃	30℃	40℃	50℃	60℃	70℃	80℃	90℃	100℃	110℃	120℃
P_F=0.95	208.3	207.3	206.4	205.5	204.6	203.8	202.9	202.1	201.4	200.7	200	199.2	198.6
P_F=0.9	256.9	255.8	254.7	253.8	252.8	251.9	250.9	250.1	249.2	248.4	247.7	246.9	246.1
P_F=0.8	340	338.8	337.7	336.7	335.7	334.8	333.8	332.9	332.1	331.2	330.4	329.6	328.8
P_F=0.7	414.8	413.7	412.7	411.7	410.7	409.8	408.9	408.1	407.3	406.5	405.8	405	404.3
P_F=0.6	485	484	483.1	482.3	481.4	480.6	479.8	479.1	478.4	477.7	477	476.3	475.7
P_F=0.5	552.3	551.5	550.7	550	549.3	548.7	548	547.4	546.8	546.2	545.6	545.1	544.5

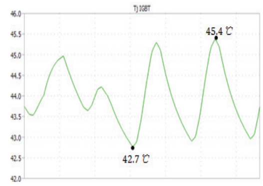
Fig. 9 DIODE_Conduction_Loss



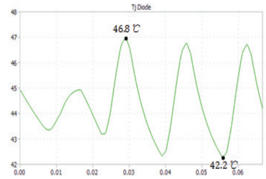
T_{amb} = 0 ℃, Δ $T_{(j-c)}$ = 34.7 ℃ − 32.2 ℃ = 2.5 ℃



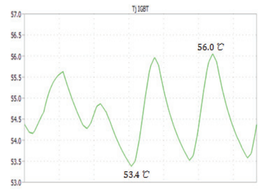
T_{amb} = 0 ℃, Δ $T_{(j-c)}$ = 36.4 ℃ − 32 ℃ = 4.4 ℃



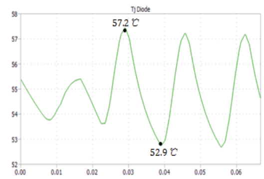
T_{amb} = 10 ℃, Δ $T_{(j-c)}$ = 45.4 ℃ − 42.7 ℃ = 2.7 ℃



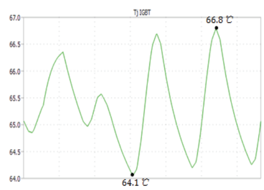
T_{amb} = 10 ℃, Δ $T_{(j-c)}$ = 46.8 ℃ − 42.2 ℃ = 4.6 ℃



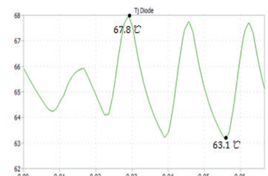
T_{amb} = 20 ℃, Δ $T_{(j-c)}$ = 56.0 ℃ − 53.4 ℃ = 2.6 ℃



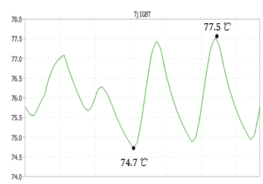
T_{amb} = 20 ℃, Δ $T_{(j-c)}$ = 57.2 ℃ − 52.9 ℃ = 4.3 ℃



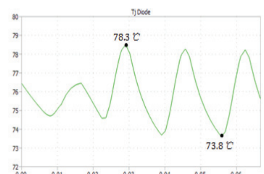
T_{amb} = 30 ℃, Δ $T_{(j-c)}$ = 66.8 ℃ − 64.1 ℃ = 2.7 ℃



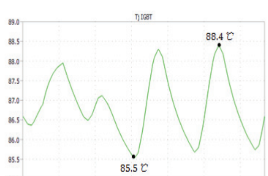
T_{amb} = 30 ℃, Δ $T_{(j-c)}$ = 67.8 ℃ − 63.1 ℃ = 4.7 ℃



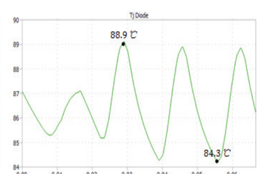
T_{amb} = 40 ℃, Δ $T_{(j-c)}$ = 77.5 ℃ − 74.7 ℃ = 2.8 ℃



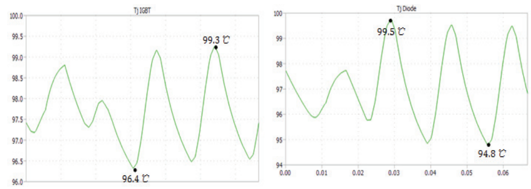
T_{amb} = 40 ℃, Δ $T_{(j-c)}$ = 78.3 ℃ − 73.8 ℃ = 4.5 ℃



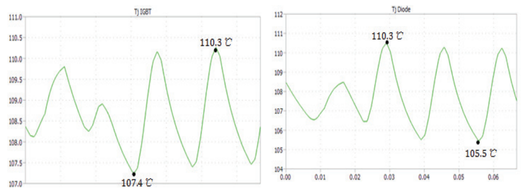
T_{amb} = 50 ℃, Δ $T_{(j-c)}$ = 88.4 ℃ − 85.5 ℃ = 2.9 ℃



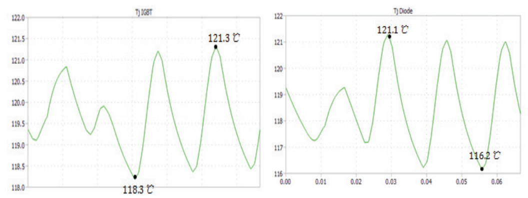
T_{amb} = 50 ℃, Δ $T_{(j-c)}$ = 88.9 ℃ − 84.3 ℃ = 4.6 ℃



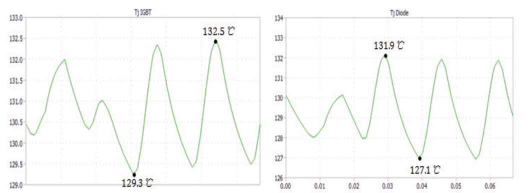
T_{amb} = 60 ℃, $\Delta T_{(j-c)}$ = 99.3 ℃ − 96.4 ℃ = 2.9 ℃ T_{amb} = 60 ℃, $\Delta T_{(j-c)}$ = 99.5 ℃ − 94.8 ℃ = 4.7 ℃



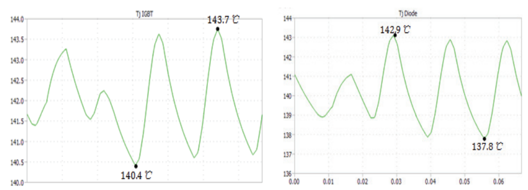
T_{amb} = 70 ℃, $\Delta T_{(j-c)}$ = 110.3 ℃ − 107.4 ℃ = 2.9 ℃ T_{amb} = 70 ℃, $\Delta T_{(j-c)}$ = 110.3 ℃ − 105.5 ℃ = 4.8 ℃



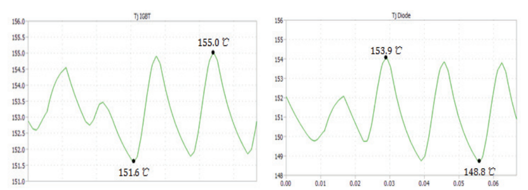
T_{amb} = 80 ℃, $\Delta T_{(j-c)}$ = 121.3 ℃ − 118.3 ℃ = 3.0 ℃ T_{amb} = 80 ℃, $\Delta T_{(j-c)}$ = 121.1 ℃ − 116.2 ℃ = 4.9 ℃



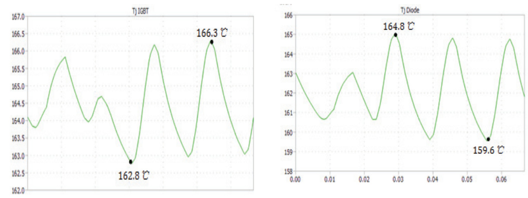
T_{amb} = 90 ℃, $\Delta T_{(j-c)}$ = 132.5 ℃ − 129.3 ℃ = 3.2 ℃ T_{amb} = 90 ℃, $\Delta T_{(j-c)}$ = 131.9 ℃ − 127.1 ℃ = 4.8 ℃



T_{amb} = 100 ℃, $\Delta T_{(j-c)}$ = 143.7 ℃ − 140.4 ℃ = 3.3 ℃ T_{amb} = 100 ℃, $\Delta T_{(j-c)}$ = 142.9 ℃ − 137.8 ℃ = 5.1 ℃

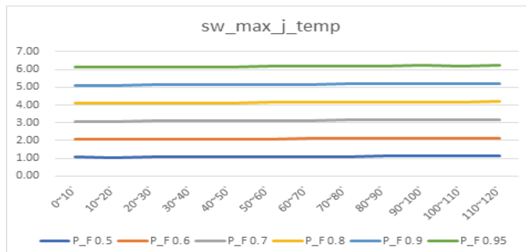


T_{amb} = 110 ℃, $\Delta T_{(j-c)}$ = 155.0 ℃ − 151.6 ℃ = 3.4 ℃ T_{amb} = 110 ℃, $\Delta T_{(j-c)}$ = 153.9 ℃ − 148.8 ℃ = 5.1 ℃



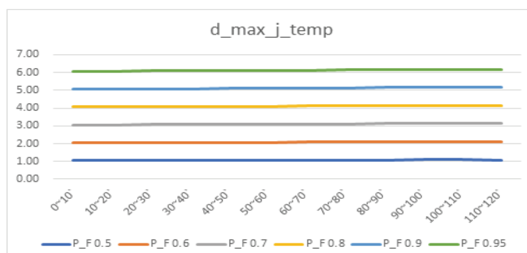
T_{amb} = 120 ℃, $\Delta T_{(j-c)}$ = 166.3 ℃ − 162.8 ℃ = 3.5 ℃ T_{amb} = 120 ℃, $\Delta T_{(j-c)}$ = 164.8 ℃ − 159.6 ℃ = 5.2 ℃

Fig. 10 Junction temperature distribution of IGBT and DIODE according to ambient temperature



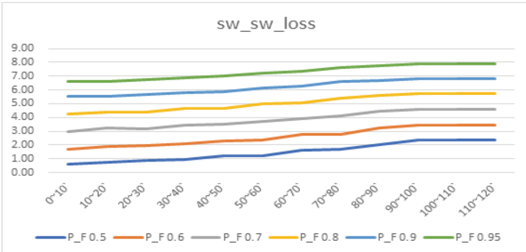
	0~10`	10~20`	20~30`	30~40`	40~50`	50~60`	60~70`	70~80`	80~90`	90~100`	100~110`	110~120`
P_F 0.5	1.07	1.06	1.08	1.07	1.09	1.09	1.10	1.10	1.12	1.12	1.13	1.13
P_F 0.6	1.00	1.01	1.01	1.01	1.01	1.01	1.01	1.02	1.02	1.02	1.01	1.02
P_F 0.7	1.01	1.02	1.01	1.03	1.01	1.03	1.02	1.03	1.02	1.03	1.03	1.02
P_F 0.8	1.02	1.02	1.01	1.01	1.02	1.02	1.03	1.02	1.03	1.02	1.02	1.02
P_F 0.9	1.02	1.01	1.02	1.02	1.03	1.02	1.01	1.03	1.02	1.02	1.02	1.03
P_F 0.95	1.01	1.00	1.02	1.01	1.00	1.01	1.02	1.01	1.01	1.02	1.01	1.00

Fig. 11 Slope of IGBT_Max_Junction_Temp. according to ambient temperature by power factor



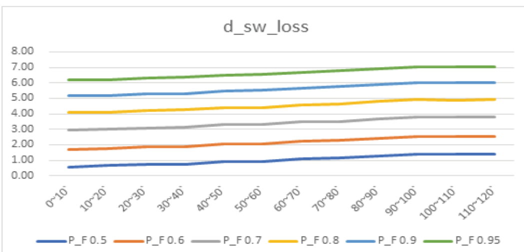
	0~10`	10~20`	20~30`	30~40`	40~50`	50~60`	60~70`	70~80`	80~90`	90~100`	100~110`	110~120`
P_F 0.5	1.04	1.04	1.06	1.05	1.06	1.06	1.08	1.08	1.08	1.10	1.10	1.09
P_F 0.6	1.00	1.01	1.00	1.01	1.01	1.02	1.00	1.01	1.02	1.01	1.01	1.02
P_F 0.7	1.02	1.01	1.01	1.02	1.01	1.01	1.03	1.01	1.03	1.02	1.02	1.02
P_F 0.8	1.01	1.01	1.01	1.01	1.02	1.01	1.01	1.03	1.01	1.02	1.02	1.02
P_F 0.9	1.00	1.01	1.01	1.01	1.01	1.02	1.01	1.01	1.02	1.02	1.01	1.02
P_F 0.95	1.01	1.00	1.01	1.00	1.00	1.01	1.00	1.02	1.00	1.00	1.01	1.01

Fig. 12 Slope of DIODE_Max_Junction_Temp. according to ambient temperature by power factor



	0~10`	10~20`	20~30`	30~40`	40~50`	50~60`	60~70`	70~80`	80~90`	90~100`	100~110`	110~120`
P_F 0.5	0.63	0.74	0.89	0.93	1.24	1.24	1.63	1.71	2.05	2.34	2.34	2.34
P_F 0.6	1.08	1.18	1.08	1.18	1.09	1.11	1.14	1.09	1.19	1.09	1.09	1.09
P_F 0.7	1.24	1.32	1.20	1.35	1.18	1.37	1.17	1.30	1.23	1.17	1.17	1.17
P_F 0.8	1.30	1.15	1.19	1.22	1.14	1.26	1.14	1.27	1.13	1.12	1.12	1.12
P_F 0.9	1.28	1.14	1.28	1.13	1.23	1.16	1.16	1.21	1.11	1.12	1.11	1.11
P_F 0.95	1.12	1.07	1.13	1.06	1.13	1.05	1.14	1.05	1.05	1.05	1.05	1.05

Fig. 13 Slope of IGBT_Switching_Loss according to ambient temperature by power factor

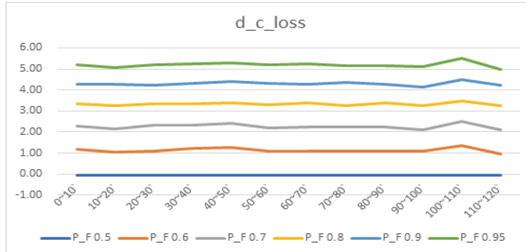


	0~10`	10~20`	20~30`	30~40`	40~50`	50~60`	60~70`	70~80`	80~90`	90~100`	100~110`	110~120`
P_F 0.5	0.58	0.66	0.74	0.76	0.92	0.92	1.09	1.13	1.26	1.39	1.39	1.39
P_F 0.6	1.14	1.12	1.14	1.12	1.14	1.14	1.14	1.15	1.13	1.15	1.14	1.14
P_F 0.7	1.23	1.23	1.23	1.25	1.23	1.23	1.25	1.23	1.27	1.23	1.25	1.24
P_F 0.8	1.12	1.11	1.13	1.12	1.13	1.13	1.12	1.14	1.14	1.14	1.13	1.14
P_F 0.9	1.09	1.07	1.09	1.08	1.08	1.10	1.08	1.09	1.09	1.09	1.09	1.09
P_F 0.95	1.03	1.00	1.03	1.02	1.03	1.03	1.02	1.03	1.03	1.03	1.02	1.03

Fig. 14 Slope of DIODE_Switching_Loss according to ambient temperature by power factor

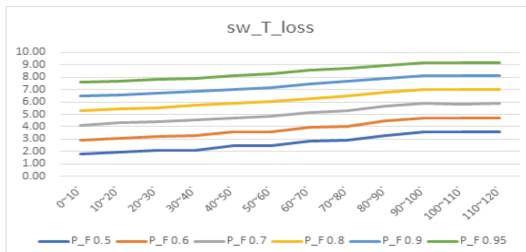
	0~10`	10~20`	20~30`	30~40`	40~50`	50~60`	60~70`	70~80`	80~90`	90~100`	100~110`	110~120`
P_F 0.5	1.19	1.19	1.20	1.20	1.20	1.21	1.21	1.22	1.23	1.24	1.24	1.24
P_F 0.6	1.15	1.16	1.15	1.16	1.17	1.15	1.17	1.16	1.16	1.16	1.16	1.16
P_F 0.7	1.15	1.14	1.14	1.15	1.14	1.16	1.16	1.14	1.17	1.16	1.16	1.15
P_F 0.8	1.13	1.13	1.13	1.13	1.14	1.14	1.13	1.15	1.14	1.14	1.13	1.14
P_F 0.9	1.12	1.12	1.13	1.13	1.12	1.13	1.13	1.14	1.13	1.13	1.13	1.14
P_F 0.95	1.06	1.05	1.06	1.06	1.06	1.06	1.06	1.06	1.07	1.06	1.05	1.06

Fig. 15 Slope of IGBT_Conduction_Loss according to ambient temperature by power factor



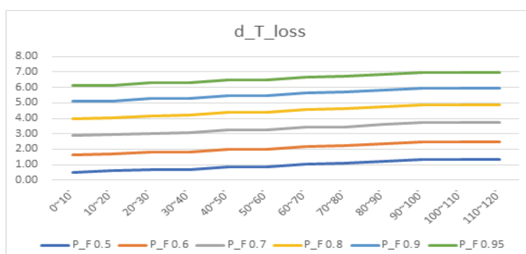
	0~10`	10~20`	20~30`	30~40`	40~50`	50~60`	60~70`	70~80`	80~90`	90~100`	100~110`	110~120`
P_F 0.5	-0.08	-0.08	-0.07	-0.07	-0.06	-0.07	-0.06	-0.06	-0.06	-0.06	-0.05	-0.06
P_F 0.6	1.25	1.13	1.14	1.29	1.33	1.14	1.17	1.17	1.17	1.17	1.40	1.00
P_F 0.7	1.10	1.11	1.25	1.11	1.13	1.13	1.14	1.14	1.14	1.00	1.14	1.17
P_F 0.8	1.09	1.10	1.00	1.00	1.00	1.11	1.13	1.00	1.13	1.14	1.00	1.14
P_F 0.9	0.92	1.00	0.90	1.00	1.00	1.00	0.89	1.13	0.89	0.88	1.00	1.00
P_F 0.95	0.91	0.82	1.00	0.90	0.89	0.90	1.00	0.78	0.88	1.00	1.00	0.75

Fig. 16 Slope of DIODE_Conduction_Loss according to ambient temperature by power factor



	0~10`	10~20`	20~30`	30~40`	40~50`	50~60`	60~70`	70~80`	80~90`	90~100`	100~110`	110~120`
P_F 0.5	1.81	1.95	2.08	2.13	2.44	2.45	2.84	2.93	3.29	3.58	3.57	3.58
P_F 0.6	1.14	1.15	1.12	1.17	1.12	1.13	1.15	1.12	1.17	1.11	1.12	1.11
P_F 0.7	1.17	1.21	1.17	1.23	1.17	1.26	1.17	1.23	1.20	1.17	1.17	1.17
P_F 0.8	1.19	1.14	1.16	1.18	1.14	1.20	1.14	1.23	1.13	1.13	1.13	1.13
P_F 0.9	1.18	1.13	1.20	1.13	1.17	1.15	1.15	1.18	1.12	1.12	1.12	1.12
P_F 0.95	1.08	1.07	1.09	1.06	1.10	1.06	1.10	1.05	1.06	1.05	1.05	1.05

Fig. 17 Slope of IGBT_Total_Loss acording to ambient temperature by power factor



	0~10`	10~20`	20~30`	30~40`	40~50`	50~60`	60~70`	70~80`	80~90`	90~100`	100~110`	110~120`
P_F 0.5	0.50	0.59	0.66	0.69	0.85	0.86	1.03	1.07	1.20	1.33	1.34	1.33
P_F 0.6	1.14	1.08	1.15	1.10	1.15	1.13	1.13	1.15	1.13	1.15	1.13	1.15
P_F 0.7	1.25	1.25	1.22	1.26	1.22	1.25	1.26	1.24	1.28	1.24	1.25	1.24
P_F 0.8	1.11	1.13	1.14	1.14	1.13	1.14	1.13	1.14	1.14	1.14	1.13	1.14
P_F 0.9	1.10	1.08	1.09	1.09	1.09	1.09	1.09	1.10	1.10	1.09	1.10	1.09
P_F 0.95	1.05	1.02	1.04	1.03	1.03	1.04	1.03	1.03	1.03	1.03	1.03	1.03

Fig. 18 Slope of DIODE_Total_Loss acording to ambient temperature by power factor

As a result of the calculation, in figures 4, 5, 6, 7, 8, and 9, IGBT_Max_Junction_Temp and DIODE_Max_Junction_Temp form a proportional relationship with the temperature for each duty. In figures 10, 11, 12, 13, 14, 15, 16, 17, and 18, IGBT_Switching_Loss, DIODE_Switching_Loss, IGBT_Conduction_Loss, etc. show that it can be expressed as a temperature gradient for each constant temperature section.

3. Conclusion

In this study, in order to simply calculate the junction temperature of the power semiconductor (IGBT), the slope of the junction temperature was analyzed for each section for the temperature variable IGBT_ Total_Loss and DIODE_Total_Loss and the P_F variable.

As a result of the calculation, in figures 4, 5, 6, 7, 8, and 9, IGBT_Max_Junction_Temp and DIODE_Max_Junction_Temp form a proportional relationship with the temperature for each duty.

In figures 10, 11, 12, 13, 14, 15, 16, 17, and 18, IGBT_Switching_Loss, DIODE_Switching_Loss, IGBT_Conduction_ Loss, etc. show that it can be expressed as a temperature gradient for each constant temperature section. The power loss of a power semiconductor is complicatedly calculated according to Ki, Kv, and TC_{sw} of equations 2 and 4. This simulation data makes it possible to calculate the junction temperature of the power semiconductor simply and easily by applying the slope for each condition and section. The proposed method is that can dramatically reduce the calculation time when estimating the thermal resistance of the HVDC MMC type power converter. In the future, in order to more precisely and easily calculate and measure the junction temperature of power semiconductors, it is necessary to conduct an experiment on the proposed method and further analyze the errors of calculation and measurement.

Acknowledgements

This research was supported by Ministry of Trade, Industry and Energy (MOTIE) and the Korea Energy Technology Evaluation and Planning(KETEP). (No. 20179310100050)

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(Manuscript received July 18, 2021;
revised August 05, 2021; accepted August 06, 2021)