PREDICTION OF IGBT POWER LOSSES AND JUNCTION TEMPERATURE IN 160KW VVVF INVERTER DRIVE

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Abstract: *Prediction of IGBT Junction Temperature is performed by making a Mathematical Model of power semiconductor device using data sheet parameter and practical measurements. Calculating or estimating accurately conduction losses and, especially, switching losses has been discussed in the literature but seems to be not well known among many engineers. Therefore, in this paper we will give an overview of this topic and propose improvements of the procedure of loss estimation in power IGBT. The proposed scheme calculates conduction losses and switching losses with minimum effort, high accuracy and does not slow down the numerical simulation. Loss calculations are based on datasheet values and/or experimental measurements. As an example, a 160kW-inverter connected to a Variable Frequency drive is set up with each bridge leg realized by a power module, where the characteristic parameters for the loss calculation scheme are extracted from datasheet diagrams and calculated result is verified with "MELCOSIM" which is power loss simulator software developed by MITSUBISHI corporation for proper selection of IGBT module in inverter within its maximum junction temperature limit.*

Key words: *Conduction losses, IGBT Junction temperature estimation by mathematical model in PSIM, switching losses, Three phase PWM inverter loss calculation.*

NOMENCLATURE

Esw(on)-IGBT turn on switching energy @ Ic and T=125
Esw(off)-IGBT turn off switching energy @ Ic and T=125
Fsw-PWM switching frequency
Ic-Peak value of sinusoidal output current
Vce(sat)-IGBT saturation voltage drop @ Ic & T=125
Vf-FWD forward voltage drop @ Ic
D-PWM duty Factor
Φ-Phase angle between output Voltage & current
Irr-Diode Peak recovery current @ Ic
Trr-Diode reverse recovery time @ Ic
Vce(pk)-Peak voltage across the fwd at recovery
Rth(c-f)-Thermal impedance between case to fin
Rth(j-c)IGBT-Thermal impedance between junction to case
Rth(j-c)fwd-Thermal impedance between junction to case

1. INTRODUCTION

The insulated gate bipolar transistor (IGBT) is popularly used in high power, high frequency power-electronic applications such as pulse width modulated (PWM) inverters. These applications require well designed thermal management systems to ensure the protection of IGBTs, which operate with smaller safety margins due to economic considerations. Hence, tools for accurate prediction of device power dissipation and junction temperature become important in achieving optimized designs. At high switching frequencies, switching losses constitute a significant portion of the device power dissipation. Therefore, accurate calculation of switching losses is an important step in the thermal management system design [1].

System design guidelines in general and, increasingly, reliability issues put emphasis on the thermal analysis of power electronic systems. Numerical simulation of the junction temperature time behavior in a circuit simulation is possible by setting up a thermal model of power semiconductors and cooling systems, and connecting these thermal equivalent circuits for the calculation of power losses in the semiconductors. Therefore, in this paper we will give an overview of this topic and propose some improvements in the procedure of loss estimation. In the following the experimental behavior of the total losses and Junction temperature of the power module CM600DU-24NF (**Fig.1**) will be discussed and calculated.

The proposed Mathematical scheme calculates total losses with minimum effort, high accuracy and does not slow down the numerical calculation in a significant way. It can be embedded directly in any circuit simulator. Loss calculations are based on datasheet values and experimental measurements. [5]

Fig.1 CM600DU-24NF Dual IGBTMOD™ NF- Séries Rating : 600 Ampères/1200 Volts [2]

2. 160KW-VVVF INVERTER LOSS CALCULATION

A. Different parameter of 160KW Drive:

Rated Current of AMT-160:- 320 Amp,
Input Voltage Vdc = 580 Volt,
Fsw = 2.5 KHz,
IGBT Module No: - CM600DY-24NF
Rating:- 600 Amp,1200 Volt, Dual-Pack.
D= 1.0
cosΦ= 0.8
Fsw= 2khz
Vce(pk)= 1200 volt
Tf= 90'c (heat sink Temp.)
Rth(c-f)= 0.019'c/Watt [2]
Rth(j-c)IGBT= 0.023'c/watt [2]
Rth(j-c)DIODE= 0.042 'c/watt [2]

One common application of power modules is the variable voltage variable frequency (VVVF) inverter. In VVVF inverters, PWM modulation is used to synthesis sinusoidal output currents. In this application the IGBT current and duty cycle are constantly changing making loss estimation very difficult. The following equations can be used for initial estimation in VVVF applications. Actual losses will depend on temperature, sinusoidal output frequency, output current ripple and other factor. Fig.2 shows typical VVVF inverter circuit. [3]

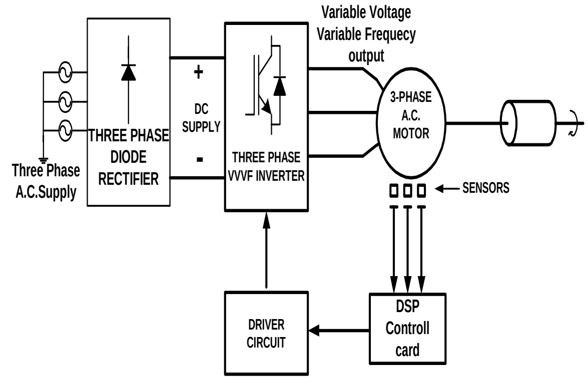

Fig. 2 Block diagram of VVVF inverter Drive

3. ESTIMATING POWER LOSSES OF IGBT

The first step in thermal design is the estimation of total power loss. In power electronics circuit using IGBTs the two most important sources of power dissipation that must be considered are conduction losses and switching losses.

A. Conduction losses

Conduction losses are the losses that occur while the IGBT is On and conducting current. The total power dissipation during conduction is computed by multiplying the On state saturation voltage by the On state current. In PWM application the conduction losses should be multiplied by the duty factor to obtain the average power dissipated. A first approximation of conduction losses can be obtained by multiplying the IGBT's rated Vce (sat) by the expected average device current. Conduction losses can be evaluated from following equation in the case of VVVF inverter application

$$Pcond = Ic \times Vce(sat) \times (\frac{1}{8} + \frac{D}{3\pi}\cos\phi)[1] \quad (1)$$

B. Switching losses

Switching loss is the powers dissipated during the turn on and turn off switching transitions. In PWM switching losses can sustainable and must be considered in thermal design. To estimate average switching power losses read the Esw (on) and Esw (off) values from the curve at the expected average operating current. Average power dissipation is then given by

$$Psw = Fsw \times \frac{(Esw(on) + Esw(off))}{\pi}[1] \quad (2)$$

The main use of the estimated power loss calculation is to provide a starting point for preliminary device selection. The final selection must be based on the rigorous power and temperature rise calculation.

C. Total loss per IGBT

Ptotal = Pcond + Psw (3)

4. COMPUTING POWER LOSS OF DIODE

A. Steady state loss per Diode

$$Pdc = Ic \times Vf \times (\frac{1}{8} - \frac{D}{3\pi}\cos\phi)[1] \quad (4)$$

B. Recovery loss per Diode

$$Prr = 0.125 \times Irr \times Trr \times Vce(pk) \times Fsw[1] \quad (5)$$

C. Total losses per arm (half module)

Ptotal = Pcond +Psw + Pdc +Prr (6)

5. ESTIMATION OF AVERAGE JUNCTION TEMPERATURE

When operating the power device contained in IGBT and intelligent power modules will have conduction and switching power losses. The heat generated as a result of these losses must be conducted away from the power chips and in to the environment using a heat sink.

If an appropriate thermal system is not used the power device will overheat which could result in failure. In many applications the maximum useable power output of module will be limited by the system thermal design. So it is very important to design very accurate system for getting maximum output from the device.

A. Calculation of case temperature

$$Tc = Tf + Ptotal \times Rth(c - f)[1] \quad (7)$$

B. Calculation of IGBT junction temperature

$$Tj_{IGBT} = Tc + Ptotal_{IGBT} \times Rth(j - c)_{IGBT}[1] \quad (8)$$

C. Calculation of diode junction temperature

$$Tj_{diode} = Tc + Ptotal_{diode} \times Rth(j - c)_{diode} \ [1] \quad (9)$$

6. DERIVATION OF POWER LOSS USING LINEAR POLYNOMIAL EQUATION FOR CM600 DU-24NF IGBT MODULE USED IN 160KW VVVF DRIVE

In this calculation we assume that practically we have known the value of output current(Ic), switching frequency (Fsw), PWM Modulation rate (D), Power Factor (cosΦ). And we have the data sheet parameter so we can easily find the power losses and hence the Junction Temperature using above derived equation [2] as follow,

Conduction losses of power semiconductors are often calculated by inserting a voltage Vce(sat) representing the voltage drop and a resistor *Ron* representing the current dependency in series with the ideal device. In this way, the non-linear characteristic of the current-voltage dependency is modeled in a simple way. [4]

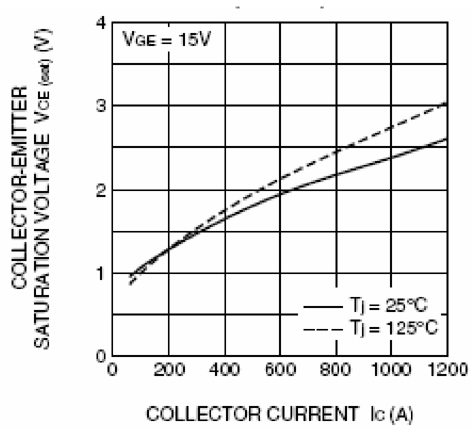

Fig 3.Vce (sat) Vs Ic Characteristic

The characteristic describing the relationship between voltage drop Vce(sat) and collector current *IC* of the IGBTs as given in the datasheet is shown in **Fig3**.[2] This nonlinear dependency is often modeled in a rough approximation as voltage source and resistor in series with an ideal switch. We propose to multiply the current *IC* with the according voltage Vce (sat) directly in the datasheet to get the conduction power loss *Pcond* dependent on the current *IC* as shown for two operating temperatures in Fig.3.

A. Conduction losses of IGBT using polynomial Equation

The advantage of this procedure is that the curves in Fig.3 can be approximated very accurately with linear polynomial fitting curve and generally be described in a form,

$$Vce(sat) = a + (b \times Ic) + (c \times Ic^2) \quad (10)$$

Where the coefficients *a, b* and *c* are derived by curve fitting. A linear polynomial approximation of the curves shown in Fig.4 gives the parameter values at Tj=125'c

$$Vce(sat) = 0.6974 + (3.06\text{e-}3 \times \text{Ic}) - (9.46\text{e-}7 \times \text{Ic}^2) \quad (11)$$

From equation (1) we get the conduction loss of IGBT by substitute the value of Vce (sat) calculated by equation (11).

B. Switching losses of IGBT using polynomial Equation

The curves in Fig.4 can be approximated very accurately with linear polynomial fitting curve and generally be described in a form,

$$Esw(Total) = 0.01256 + (0.0002843 \times \text{Ic}) - (3.358\text{e-}8 \times \text{Ic}^2) \quad (12)$$

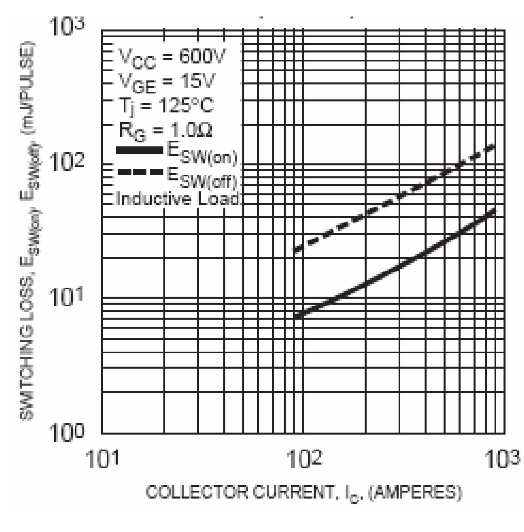

Fig 4.E(sw) Vs Ic Characteristic from data sheet

From equation (2) we get the switching loss of IGBT by substitute the value of Esw (total) calculated by equation (12).

C. Dc losses of FWD using polynomial Equation

The curves in Fig.5 [2] can be described very accurately with linear polynomial fitting curve and generally be described in a form,

$$Vf = 1.064 + (3.55\text{e-}3 \times \text{Ic}) - (1.534\text{e-}6 \times \text{Ic}^2) \quad (13)$$

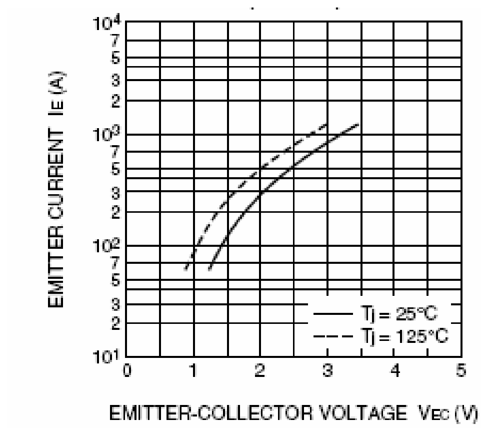

Fig.5 Ic Vs Vf Characteristic from data sheet

From equation (3) we get the dc loss of FWD by substitute the value of Vf calculated by equation (13).

D. Switching losses of FWD using polynomial Equation

The curves in Fig.6 [2] can be described very accurately with linear polynomial fitting curve and generally be described in a form,

$$Irr = 159 + (0.2222 \times \text{Ic}) \quad (14)$$

$$Trr = 1.103\text{e-}7 + (1.578\text{e-}10 \times \text{Ic}) \quad (15)$$

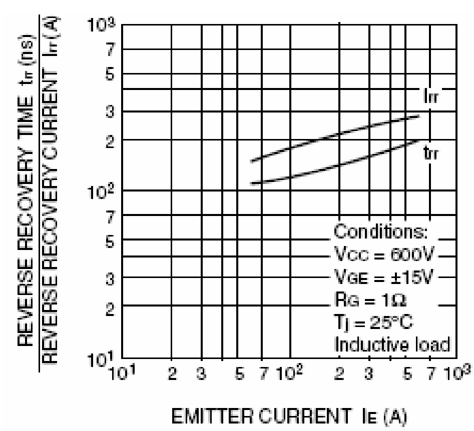

Fig.6 Irr, Trr Vs Ie characteristic from data sheet

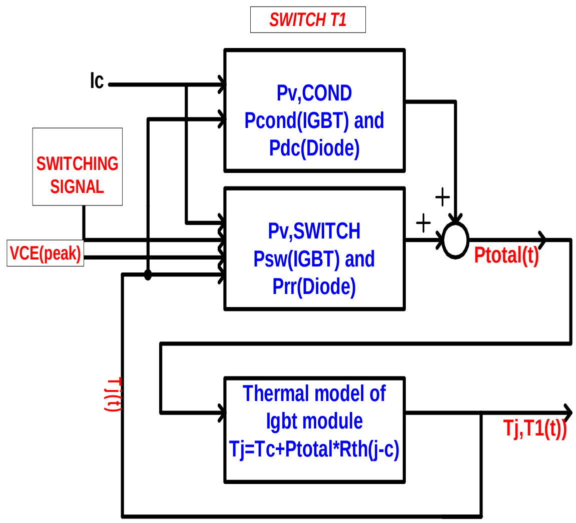

Fig.7: Implementation of the loss calculation scheme

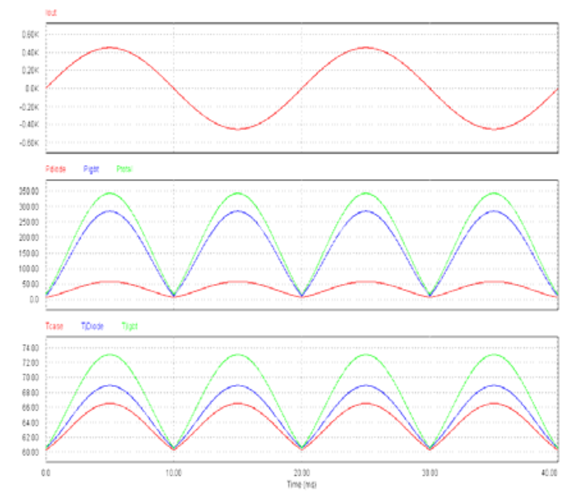

Fig. 9 Waveform in PSIM

7. NUMERICAL SCHEME IMPLEMENTED IN PSIM

Fig. 8 shows the Calculation of power loss and junction temp. For 160 KW inverter drive which has a peak amplitude current(Rated current) of 452.48 amp. Using linear polynomial Equation in PSIM with the help of Mathematical blocks.

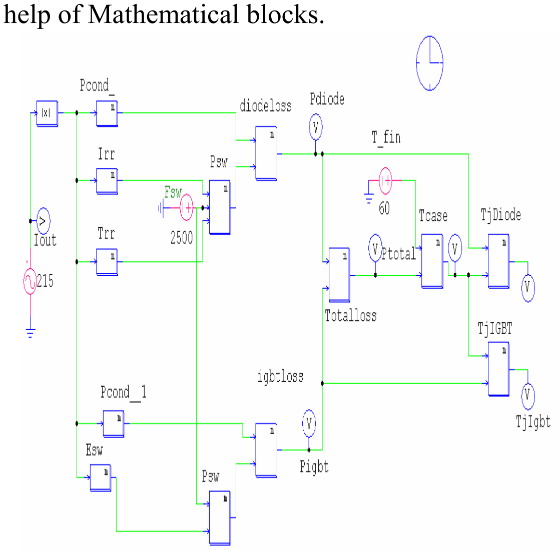

Fig. 8 Mathematical solution in PSIM

Below Fig. 9 shows the Calculated result which are verify with the Melcosim result and shown in table 1 and table 2.

Calculated Result in PSIM:

T_heatsink=60deg.
Iout=452.58Amp(Peak value)
P_{diode}=57.53watt
P_{IGBT}=285.36watt
Ptotal=342.87watt
Tcase=66.51deg.
Tj_diode=68.93deg.
Tj_IGBT=73.07deg.

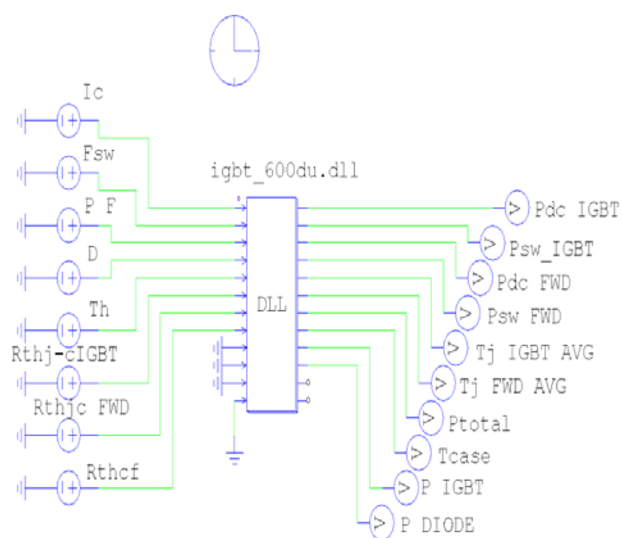

Fig. 10 DLL Model in PSIM

Table.1 Power Loss Calculation for 160KW VVVF Inverter

O/P Current	{Melcosim} LOSS/ IGBT	Calculated LOSS/ IGBT	{Melcosim} LOSS/ DIODE	Calculated LOSS/ DIODE	Melcosim Ptotal losses	Calculated Ptotal losses	Difference watt
32	23.42	24.01	7.34	7.18	30.76	31.19	**-0.43**
64	38.5	42.46	11.28	10.56	49.78	53.02	**-3.24**
96	55	63.21	15.53	14.5	70.53	77.71	**-7.18**
128	72.76	86.17	19.87	18.95	92.63	105.12	**-12.49**
160	91.31	111.22	24.34	23.88	115.65	135.1	**-19.45**
192	110.73	132.73	28.89	29.26	139.62	161.99	**-22.37**
224	130.9	160.71	33.48	35.05	164.38	195.76	**-31.38**
256	194.17	197.83	45.47	41.23	239.64	239.06	**0.58**
288	224.69	230.14	52.03	47.75	276.72	277.89	**-1.17**
320	256.58	264	58.83	54.58	315.41	318.58	**-3.17**

Table.2 IGBT and DIODE Junction Temperature Calculation for 160KW VVVF Inverter

O/P Current Io amp	Calculated Case temp	{Melcosim} Tj _IGBT	Calculated Tj _IGBT	Difference Watt	{Melcosim} Tj _Diode	Calculated Tj _Diode	Difference Watt
32	90.59	91.12	91.14	**-0.02**	90.89	90.89	**0**
64	91.01	91.83	91.98	**-0.15**	91.42	91.45	**-0.03**
96	91.48	92.61	92.93	**-0.32**	91.99	92.09	**-0.1**
128	92	93.43	93.98	**-0.55**	92.59	92.79	**-0.2**
160	92.57	94.3	95.13	**-0.83**	93.22	93.57	**-0.35**
192	93.08	95.2	96.13	**-0.93**	93.87	94.31	**-0.44**
224	93.72	96.13	97.42	**-1.29**	94.53	95.19	**-0.66**
256	94.54	99.02	99.09	**-0.07**	96.46	96.27	**0.19**
288	95.28	100.43	100.57	**-0.14**	97.44	97.29	**0.15**
320	96.05	101.89	102.13	**-0.24**	98.46	98.35	**0.11**

8. CONCLUSION

The paper discusses the simple Mathematical scheme for loss estimation of power semiconductors using PSIM environment. The proposed schemes are simple to implement, it doesn't slow down the numerical simulation time. The estimation of the losses, especially of the switching losses of the power semiconductors, is as accurate as the loss data provided by datasheets or experimental measurements. Therefore, the accuracy of the resulting total losses is principally not influenced by the proposed loss calculation scheme it is truly depend upon the datasheets or experimental measurements. From the comparison of both results we can conclude that this method is accurate and time saving for estimation of IGBT junction temperature.

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