International Journal of Nanoelectronics and Materials
Volume 16 January 2023 [177-185]

Modelling of Power Semiconductor Devices Switching and Conduction Losses in a Power Electronic System

N. S. Hashim[1], B. Poobalan[1,2,*], N. F. Zakaria[1,3], Manikandan Natarajan[4], and Safizan Shaari[1]

[1]Faculty of Electronic Engineering Technology, Universiti Malaysia Perlis (UniMAP), 02600, Arau, Perlis, Malaysia
[2]MicroSystem Technology, Centre of Excellence (CoE), Universiti Malaysia Perlis (UniMAP), 02600, Arau, Perlis, Malaysia
[3]Advanced Communication Engineering, Centre of Excellence (CoE), Universiti Malaysia Perlis (UniMAP), 02600, Arau, Perlis, Malaysia
[4]Faculty of Dentistry, AIMST University, 08100 Bedong, Kedah

Received 28 Jul 2022, Revised 9 Mar 2023, Accepted 20 March 2023

ABSTRACT

In power converters, power semiconductor devices, mainly Insulated-Gate Bipolar Transistor (IGBT), are generally used as they are less costly and capable of converting electrical energy into high frequency and voltage. It is critical to accurately determine the switching and conduction losses of power devices before they are assembled into an electronic system. The accurate values help to minimize power loss in a power converter system. With the aid of simulation, design problems are identified to help eliminate device destruction, and critical parameters are monitored. In addition, costly equipment for measuring purposes and testing prototypes is not required at the initial design stage. This research uses simulation work in a power converter system to predict IGBT and diode losses with varied frequencies and voltages. The predictive modelling is produced using regression analysis. The models have been validated by R square (R^2) and Mean Absolute Percentage Error (MAPE) techniques. This work is aimed at providing a supervised learning technique mainly used in a machine learning environment, in line with the technological development in the semiconductor industry. With the simulation performed in this work, the efficiency of a boost converter system is enhanced as it shows the models have a good fit with an R^2 value of almost 1, and MAPE values are noticed to be less than 5%.

Keywords: Power semiconductor devices, regression analysis, numerical simulation, switching and conduction losses

1. INTRODUCTION

A power converter is an energy conversion device that changes the electric energy from one form into another desired form, which is optimized and fed into a particular load [1,2]. One type of power converter is a boost converter or a DC-DC converter that increases the voltage from the input (supply) to the output while decreasing the current (load)[3]. A switched-mode power supply (SMPS) is made up of energy storage components like capacitors and inductors as well as semiconductor devices like diodes and transistors [4,5]. At both the converter's input and output (the load-side filter and supply-side filter, respectively) filters consisting of capacitors or combined with inductors are typically added in order to reduce voltage ripple [5,6]. Boost converters are commonly used in various applications, such as computer power supplies, board-level power conversion, photovoltaic systems, and electric vehicles [7].

* banu@unimap.edu.my

The primary advantage of a boost converter is its ability to step up voltages in high-power applications, as this enables the reduction of the number of battery cells and space requirements. In addition, the boost converter serves to increase the battery's output voltage when it drops too low to power the provided circuit, extending the battery's lifespan [8].

The power semiconductor devices equally play an important role in the power converter system. Power converters in SMPS frequently employ Insulated-Gate Bipolar Transistors (IGBTs) since they are less expensive and have the ability to convert electrical energy at high frequency and voltage [9,10]. For higher and better efficiency, the SMPS switch needs to turn on and off fast for minimal losses [10]. However, in a power converter system, there are losses in terms of conduction and switching during the process of power conversion [11,12,13]. The calculation of losses is important for the designers as they can be able to determine the suitable components for the system accordingly. The requirement of all voltage-levels to remain within safe ranges is important for device functionality. The requirement to study the power converter system at higher frequency and voltage has become important lately due to the emergence of high-power applications such as photovoltaic systems and electric vehicles [7]. Thus, simulations have become essential in the field of power electronics as they save time and money.

In this work, the amounts of switching and conduction losses in IGBT and Schottky diodes are calculated using simulation software with varied frequencies and voltages. To evaluate the performance and losses of the IGBT and diode, a boost DC to DC converter switching at different frequencies, between 250 Hz and 1000 Hz, with an input voltage of 200V and an output voltage between 600 V and 1200 V of nominal power, has been tested. Based on the obtained results, predictive modelling is developed using regression analysis. The switching and conduction losses of IGBT and diode are compared with the aim of predicting the devices' performance and validating the models using R square (R^2) and Mean Absolute Percentage Error (MAPE).

1.1 Mechanism of Power Semiconductor Devices In A Boost Converter

The inductor is crucial in a boost converter system because it creates and destroys the magnetic field, which helps it resist variations in current. It is well known that a boost converter has a higher output voltage than an input voltage [1,2,3] in the power conversion system. The circuit of a boost converter is presented in Figure 1, and the current paths of a boost converter, subjected to the state of the switch S, are shown in Figure 2. In the boost converter system,

a) As the switch is in a closed position, the current flows through the inductor in a clockwise direction, and some energy is stored in the inductor by creating a magnetic field. The inductive has a positive polarity on the left side.
b) As the switch is in the open position, the current flow is reduced as the impedance gets higher.

In order to maintain the current flow towards the load, the magnetic field previously created is destroyed. As a result, the polarity is reversed and the left side of the inductor turns negative. Due to the series connection of the two sources, the capacitor gets charged at a higher voltage via the diode, D.

As long as the switch is turned on and off fast enough, the inductor will not be discharged fully in between the charging stages. At this stage, the load voltage is more than the input source alone, and in addition, the capacitor in parallel with the load is charged to this combined voltage. On the other hand, as the switch is closed, the right portion of the circuit is shorted out from the left side and the capacitor becomes the voltage source for the load. The function of the blocking diode is to prevent the capacitor from discharging through the switch. To prevent the capacitor from discharging excessively, the capacitor has to be opened again quicker [1,2,3].

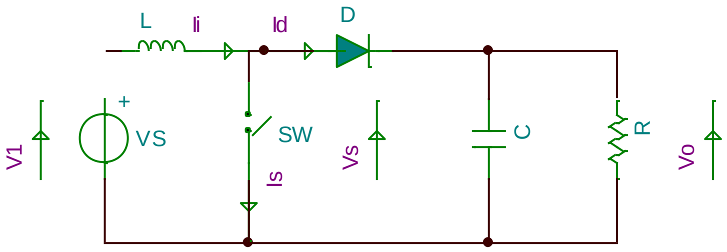
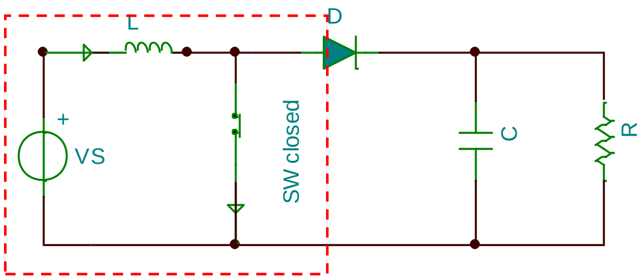
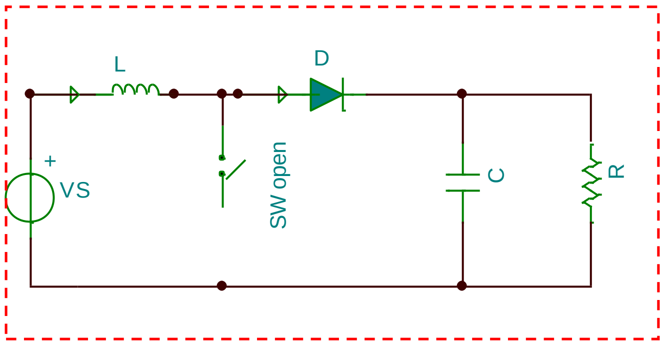


Figure 1. The complete circuit of a boost converter schematic.



(a)



(b)

Figure 2. The current paths of a boost converter, subjected to the (a) on state and (b) off state of the switch S.

2. METHODOLOGY

In this study, the predictive modelling has been developed using the simulation of IGBT and diode conduction/switching losses in a power converter system. The module used is a 2 mm C-series module with a Trench/Fieldstop IGBT4 and an Emitter Controlled diode from Infineon Technologies [14]. Analytical and simulator tools are used to calculate the amount of switching and conduction losses in IGBTs and diodes at various frequencies and voltages. To analyze the performance of IGBT and diode and losses, a boost DC to DC converter switching at different frequencies, between 250 Hz and 1000 Hz, with an input voltage of 200 V and an output voltage of between 600 V and 1200 V of nominal power, was tested. The input duty cycle has been maintained at a constant 0.5. The switching and conduction losses of the switch and diode components have been determined using the defined formulas. After obtaining the values for switching and conduction losses with the respective components, the values are tabulated accordingly. Then, the values are plotted based on conduction/switching losses versus frequency for each varied voltage. Based on the obtained graph, the regression analysis is applied and an

equation is generated. In addition, the value of the regression ratio of R^2 is recorded. Then, the MAPE is calculated for each simulated value with the original value. The MAPE is tabulated and compared accordingly to verify the modelling accuracy.
A duty cycle (ratio) is defined as Eq. (1)[1,3]:

$$D = \frac{PW}{T} \tag{1}$$

where: D is the duty cycle, PW is the pulse width (pulse active time), and T is the total period of the signal.

The theoretical DC output voltage (V_o) is determined by the input voltage (V_i) divided by 1 minus the duty cycle (D) of the switching waveform, which is between 0 and 1 (corresponding to 0 to 100%) and therefore can be determined using the following formula Eq. (2) [1,2]:

$$V_0 = V_i(1 - D) \tag{2}$$

The conduction losses are given by Eq. (3) [15,16]:

$$P_{cond,IGBT} = \frac{1}{T_0}\int_0^{\frac{T_0}{2}} V_{CE}(t).\,i(t).\,\tau'(t)dt \tag{3}$$

With

$i(t) = i' \sin(\omega t)$: sinusoidal output current.
$V_{CE}(t) = V_{CEO} + r.\,i(t)$: on-state voltage according to the output characteristic i=f(V_{CE}).
$\tau'(t)$: function of pulse pattern with IGBT turned-on =1 and IGBT turned-off=0.

The duty cycle of the IGBT is the duration over the switching period denoted as τ'. It can be replaced by a phase angle, a function of modulation and time, resultant from an extrapolation of the intersections of a reference sinus with a saw tooth. The formula is attained by assuming switching frequency and duty cycle variation over time as infinite (discrete to continuous integration).

When all turn-on and turn-off energy at the switching instants are integrated, the switching losses are represented by the equation Eq. (4)[15].

$$P_{SW,IGBT} = f_{SW,IGBT}\frac{1}{T}\int_0^{\frac{T_0}{2}}(E_{on} + E_{off})(t, i')dt \tag{4}$$

With the measured turn-on and turn-off energy dissipation per switching pulse, the energy of the single switching event at a temporary current i' can be expected to be linear.

Similarly, the diode losses can be calculated as Eq. (5) [15,16]:

$$P_{cond,diode} = \frac{1}{2}\left(V_{T0}\,.\frac{i'}{\pi} + r.\frac{i'^2}{4}\right) - m.\cos.\left(V_{T0}\,.\frac{i'}{8} + \frac{1}{3\pi}\,.\,rTi'^2\right) \tag{5}$$

In the diode switching losses, the diode's turn-on losses can be neglected. The turn-off recovery losses are calculated by summing up the recovery energies as Eq. (6) [12]:

$$P_{SW,diode} = \frac{1}{T_0}\sum\nolimits_n E_{rec}\,(I_{nom}, V_{nom})\frac{i_n}{i_{nom}}\frac{V_{dc}}{V_{nom}} \tag{6}$$

where i_n is the instantaneous phase leg current according to $i(t) = i' \sin(\omega t)$.

MAPE, also known as mean absolute percentage deviation (MAPD), is a measure of the prediction accuracy of a forecasting method in modeling. MAPE is generally expressed as a percentage and defined by Eq. (7) [17]:

$$M = \frac{100\%}{n}\sum_{t=1}^{n}\left|\frac{A_t - F_t}{A_t}\right| \qquad (7)$$

where A_t is the actual value and F_t is the forecast value. In Eq. (5), the difference between A_t and F_t is divided by the actual value of At. In this method, the absolute value is totaled for each predicted time point and divided by the number of fitted points, denoted by the value n. This is followed by the multiplication by 100%, which converts it to a percentage error.

3. RESULTS AND DISCUSSION

Table 1 Results of diode and switch switching/conduction losses for varying output voltage (V_{out}) versus frequency (Hz)

Vout(V)	Duty Cycle		Frequecy :250 Hz			Frequecy :500 Hz			Frequecy :750 Hz			Frequecy :1000 Hz		
			Losses (W)			Losses(W)			Losses(W)			Losses(W)		
			Switching	Conduction	Total	Switching	Conduction	Total	Switching	Conduction	Total	Switching	Conduction	Total
600	**0.5**	**Switch**	24.00	260.70	284.80	49.10	263.90	313.00	75.30	266.80	342.10	102.30	269.70	372.10
		Diode	5.90	186.10	192.00	12.30	186.30	198.50	18.70	186.50	205.20	25.30	186.70	212.00
800	**0.5**	**Switch**	32.10	261.00	293.50	66.20	265.20	331.40	102.00	269.20	371.20	139.70	273.20	412.90
		Diode	7.60	186.30	193.90	16.20	186.40	202.60	25.00	186.60	211.60	33.90	186.80	220.70
1000	**0.5**	**Switch**	40.30	262.20	302.50	83.50	266.70	350.20	129.70	271.70	401.40	179.30	276.90	456.20
		Diode	9.20	186.60	195.80	20.10	186.50	206.50	31.10	186.70	217.90	42.50	187.00	229.50
1200	**0.5**	**Switch**	48.70	263.30	312.00	101.30	268.20	369.50	158.40	274.30	432.70	221.70	280.80	502.50
		Diode	10.70	186.90	197.60	23.80	186.60	210.40	37.30	186.90	224.20	51.20	187.20	238.40

From Table 1, it can be deduced that as the output voltage increases, conduction losses for both the switch and the diode increase. The same trend is noticed for switching losses. As the output voltage increases, switching losses for both the switch and the diode increase. Conduction losses are considerably larger than switching losses. Load current, duty cycle and junction temperature all have a significant impact on conduction losses. Conversely, switching losses depend on the DC link voltage, junction temperature, load current and switching frequency.

On the other hand, power losses in switches are noticed to be higher than diodes. As V_{out} increases, the losses in both switching and conduction for switch and diode increase as well. The same trend is noticed for the increment in frequency. As the frequency increases, the losses in both switching and conduction for switch and diode increase gradually. Significant losses are noticed in switches rather than diodes as V_{out} and frequency are increased. When the switching frequency is increased, the ripple of inductance current and capacitance-voltage are reduced. However, it causes an enhancement of power loss. The selection of an IGBT used in power switching is determined by the current, switching speed, voltage and cost considerations. High-power IGBT modules must be provided with an appropriate heatsink; otherwise, they may experience thermal runaway.

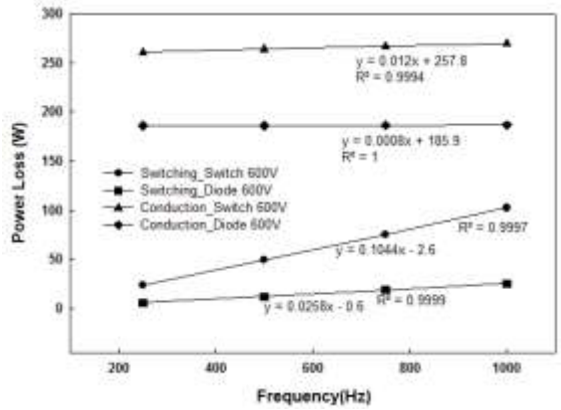
Table 2 Results of the diode and switch switching/conduction losses calculated from modelling equations for varying output voltage (V_{out}) versus frequency (Hz)

Vout(V)	Duty Cycle		Frequecy :250 Hz Losses (W) (From Equation)			Frequecy :500 Hz Losses(W) (From Equation)			Frequecy :750 Hz Losses (W)(From Equation)			Frequecy :1000 Hz Losses (W) (From Equation)		
			Switching	Conduction	Total	Switching	Conduction	Total	Switching	Conduction	Total	Switching	Conduction	Total
600	**0.5**	**Switch**	23.50	260.80	284.30	49.60	263.80	313.40	75.70	266.80	342.50	101.80	269.80	371.60
		Diode	5.85	186.10	191.95	12.30	186.30	198.60	18.75	186.50	205.25	25.20	186.70	211.90
800	**0.5**	**Switch**	31.20	261.05	292.25	67.05	265.10	332.15	102.90	269.15	372.05	138.75	273.20	411.95
		Diode	7.53	186.28	193.80	16.30	186.45	202.75	25.08	186.63	211.70	33.85	186.80	220.65
1000	**0.5**	**Switch**	38.73	262.00	300.73	85.05	266.90	351.95	131.38	271.80	403.18	177.70	276.70	454.40
		Diode	9.10	186.50	195.60	20.20	186.65	206.85	31.30	186.80	218.10	42.40	186.95	229.35
1200	**0.5**	**Switch**	46.10	262.85	308.95	103.70	268.70	372.40	161.30	274.55	435.85	218.90	280.40	499.30
		Diode	10.50	186.73	197.23	24.00	186.85	210.85	37.50	186.98	224.48	51.00	187.10	238.10

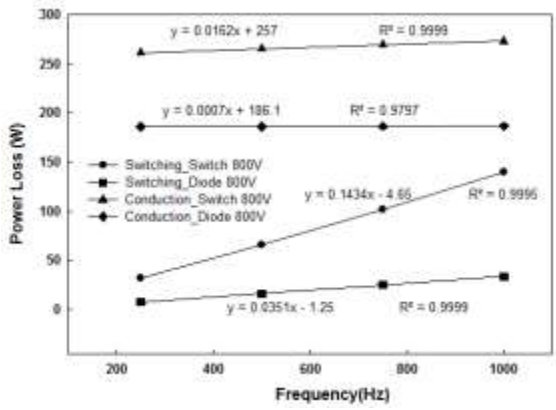
Table 2 shows the results of switching and conduction losses of the diode and switch calculated from modelling equations for varied output voltage versus frequency. The modelling equation is obtained by using a linear regression. It can be deduced that conduction losses for both the switch and the diode increase as the output voltage is increased. The same trend is noticed for switching losses. As the output voltage increases, switching losses for both the switch and the diode are increased. Conduction losses are considerably larger than switching losses. On the other hand, Table 3 shows the MAPE results, which display the difference between values obtained from simulation and modelling for diode and switch losses during switching and conduction in percentage. It is observed that the MAPE values are below 5%, which confirms the accuracy of the generated models using a linear regression.

Table 3 Results of diode and switch switching/conduction losses calculated from MAPE (%) for varying output voltage (V_{out}) versus frequency (Hz)

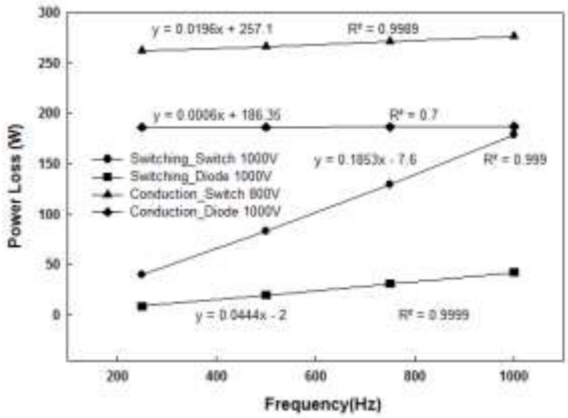
Vout(V)	Duty Cycle		Frequecy :250 Hz Losses (MAPE%)			Frequecy :500 Hz Losses (MAPE%)			Frequecy :750 Hz Losses (MAPE%)			Frequecy :1000 Hz Losses (MAPE%)		
			Switching	Conduction	Total	Switching	Conduction	Total	Switching	Conduction	Total	Switching	Conduction	Total
600	**0.5**	**Switch**	2.08	-0.04	0.18	-1.02	0.04	-0.13	-0.53	0.00	-0.12	0.49	-0.04	0.13
		Diode	0.85	0.00	0.03	0.00	0.00	-0.05	-0.27	0.00	-0.02	0.40	0.00	0.05
800	**0.5**	**Switch**	2.80	-0.02	0.43	-1.28	0.04	-0.23	-0.88	0.02	-0.23	0.68	0.00	0.23
		Diode	0.99	0.01	0.05	-0.62	-0.03	-0.07	-0.30	-0.01	-0.05	0.15	0.00	0.02
1000	**0.5**	**Switch**	3.91	0.08	0.59	-1.86	-0.07	-0.50	-1.29	-0.04	-0.44	0.89	0.07	0.39
		Diode	1.09	0.05	0.10	-0.50	-0.08	-0.17	-0.64	-0.05	-0.09	0.24	0.03	0.07
1200	**0.5**	**Switch**	5.34	0.17	0.98	-2.37	-0.19	-0.78	-1.83	-0.09	-0.73	1.26	0.14	0.64
		Diode	1.87	0.09	0.19	-0.84	-0.13	-0.21	-0.54	-0.04	-0.12	0.39	0.05	0.13



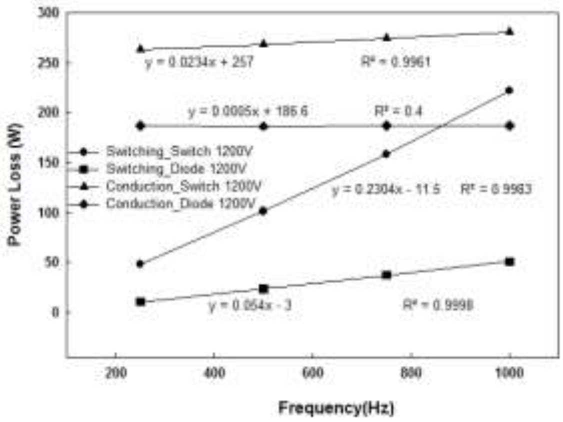
(a)



(b)



(c)



(d)

Figure 3. Power losses during switching and conduction mechanism for switch and diode with varied frequency at (a) 600 V (b) 800 V (c) 1000 V (d) 1200 V output voltage. In the graph, the linear regression equation and R^2 values are shown for each switching and conduction condition.

Figure 1 (a)-(d) show that as the frequency increases, so do the power losses for output voltages ranging from 600 V to 1200 V. Conduction losses are larger than switching losses for both the diode and the switch. The losses in the switch are higher than the diode counterpart. Based on regression fitting, the R^2 value is almost 1 for all the conditions except for diode losses at 1000 V_{out} and 1200 V_{out} conduction states. In terms of MAPE, all the deviation values are below 5%. Therefore, prediction modelling using the regression method is efficient in predicting the value for frequency and V_{out} to keep the losses to a minimum. A regression equation is generated for each plot function as a predictive modelling output.

4. CONCLUSION

Based on the simulation and modelling performed in this work, it is shown that regression analysis can be used to predict the switching and conduction losses efficiently in IGBT and diodes. The losses of power semiconductor devices in a boost converter system are analyzed for various frequencies and output voltages. The selection of components for device assembly is done with ease using an accurate predictive simulation tool. With the simulation performed in this work, the efficiency of a boost converter system is enhanced by analyzing the conduction or switching losses of power devices. The accuracy of the regression model is verified with R^2 and it showed the models have good fitting with values of almost 1. In addition, the MAPE values are also noticed to be less than 5%. Therefore, the proposed modelling and fitting technique in this work is able to save both cost and time as it can be utilized in selecting the suitable components for the power converter design. This outcome of this work can be used in a machine learning environment, in line with the technological development in the semiconductor industry.

ACKNOWLEDGEMENT

One of the authors (BP) would like to acknowledge the financial aid from the Fundamental Research Grant Scheme (FRGS) under grant number FRGS/1/2020/STG05/UniMAP/02/7(9003-00862) from the Ministry of Higher Education Malaysia for funding this work. A special thanks to Universiti Malaysia Perlis for its support throughout the completion of this work. A special appreciation to Infineon Technologies AG for making this work possible by providing an accessible platform to power semiconductor applications resources.

REFERENCES

[1] A. I. Pressman, Switching Power Supply Design (McGraw-Hill) (1997) ISBN 0-07-052236-7.
[2] Mohan, N., Undeland, T. M. and Robbins, W. P., Power Electronics: Converters, Applications, and Design (Wiley)(2002) ISBN 0-471-22693-9.
[3] Luo, F. L. and Ye, H., Advanced DC/DC Converters (CRC Press) (2004) ISBN 0-8493-1956-0.
[4] Taheri, B. and Sedaghat, M., A., New General Controller for DC-DC Converters Based on SMC Methods, 6th International Istanbul Smart Grids and Cities Congress and Fair (ICSG), (2018) pp. 49-53.
[5] Pollmeier, W. Semi-Conductor Switching Circuit with Transistor Switching Power Loss Means, United States Patent, 4,093,877, (1978) pp.1-3.
[6] Lee, P. W, Lee, Y. S., Cheng, D. K. W. and Liu, X. C. Steady-State Analysis of an Interleaved Boost Converter with Coupled Inductors, IEEE Transactions on Industrial Electronics, (2000) Vol. 47, No. 4, pp.787-795.
[7] Muhammad H. Rashid, Power Electronics Handbook: Devices, Circuits and Applications, Elsevier Inc. (2010) ISBN: 978-0-12-382036-5.
[8] Du, Y. and Lu, D. D. C. Battery-integrated Boost Converter Utilizing Distributed MPPT Configuration for Photovoltaic Systems, Solar Energy 85, (2011) pp. 1992–2002.
[9] Veprikov, A. A. and Abramovich, B. N. Prospects for IGBT Application in Electrical Power Converters For Industrial High-Current DC Loads, IOP Conf. Ser.: Mater. Sci. Eng. (2019) 560012131, pp.1-6.
[10] Francis, R. and Soldano, M. New SMPS Non-Punch Thru IGBT Replace MOSFET in SMPS High Frequency Applications, International Rectifier Corporation Applied Power Electronics Conference and Exposition, APEC '03. Eighteenth Annual IEEE Vol: 2, (2003) pp.953-957.
[11] Schafmeister, F., Rytz, C. and Kolar, J.W., Analytical Calculation of The Conduction and Switching Losses Of The Conventional Matrix Converter And The (Very) Sparse Matrix Converter, Twentieth Annual IEEE Applied Power Electronics Conference and Exposition, 2005. APEC 2005, (2005) pp.875-881.
[12] Kim, T. J., Kang, D. W., Lee, Y. H. and Hyun, D. S., The Analysis of Conduction and Switching Losses In Multi-Level Inverter System, 2001 IEEE 32nd Annual Power Electronics Specialists Conference (IEEE Cat. No.01CH37230), (2001) pp.1363-1368.
[13] Aghdam, M. G. H., Fathi, S. H. and Ghasemi, A. The Analysis of Conduction and Switching Losses in Three-Phase OHSW Multilevel Inverter Using Switching Functions, International Conference on Power Electronics and Drives Systems, (2005) pp.209-218.
[14] Feldstopp IGBT4 und Emitter Controlled Diode datasheet, Technical Documentation Infineon Technologies AG, (2018) pp.1-8.

[15] Dimensioning program IPOSIM for loss and thermal calculation of Infineon IGBT modules, Technical Documentation Infineon Technologies AG, pp.1-21
[16] Srajber D. and Lukasch, W. The Calculation Of The Power Inside Dissipation For The IGBT and The Inverse Diode In Circuits With Sinusoidal Output Voltage, (1992) pp.51-58.
[17] Khair, U., Fahmi, H., Al Hakim, S. and Rahim, R., Forecasting Error Calculation with Mean Absolute Deviation and Mean Absolute Percentage Error, International Conference on Information and Communication Technology (IconICT) IOP Conf. Series: Journal of Physics: Conf. Series 930, (2017) pp.1-6.