Inverter-Motor System for Electric Vehicles

Shreyas Ravi 18029106

Course: M.Sc. Motorsport Engineering

Module: Electric Vehicles

Date: 8 March, 2019

Word Count: 1985

Contents

Introduction and Previous Work

Inverter is one of the most crucial part of an electric vehicle powertrain system. Inverter is a device that uses the battery to power the electronic devices in the car. In this particular document an inverter motor system is designed and proposed for a typical formula type car. The car is proposed to have two in-hub motors with epicyclic gear train driving the rear wheels.

In the previous document, an energy storage device was designed which had the following parameters.

Accumulator Parameters	
Voltage, V_b	540 V
Current, I_b	200 A
Power, P_b	108 kW

Ultracapacitor Pack Parameters	
Power Output, P_c	27 kW (25% of Batt. Power)
Time, t	100 sec
Voltage, V_c	100 V

Previous work also highlighted the motor and touched the motor selection criteria. In this section, the selection of motor is further highlighted and justified for. A decision matrix is formed, which helped in motor selection. The motor is judged on 3 basis, it's torque, power-to weight ratio and the volume.

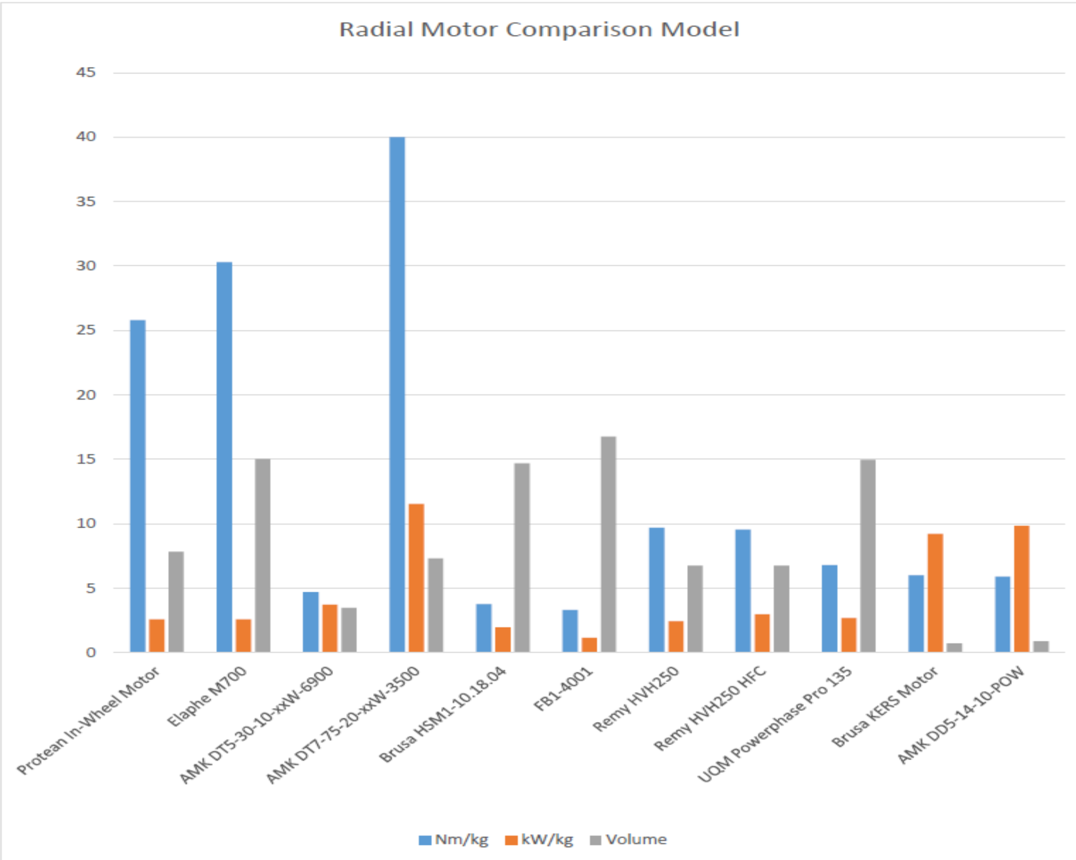


Figure 24: Radial Motor Research – Motors Suitable for Formula Student

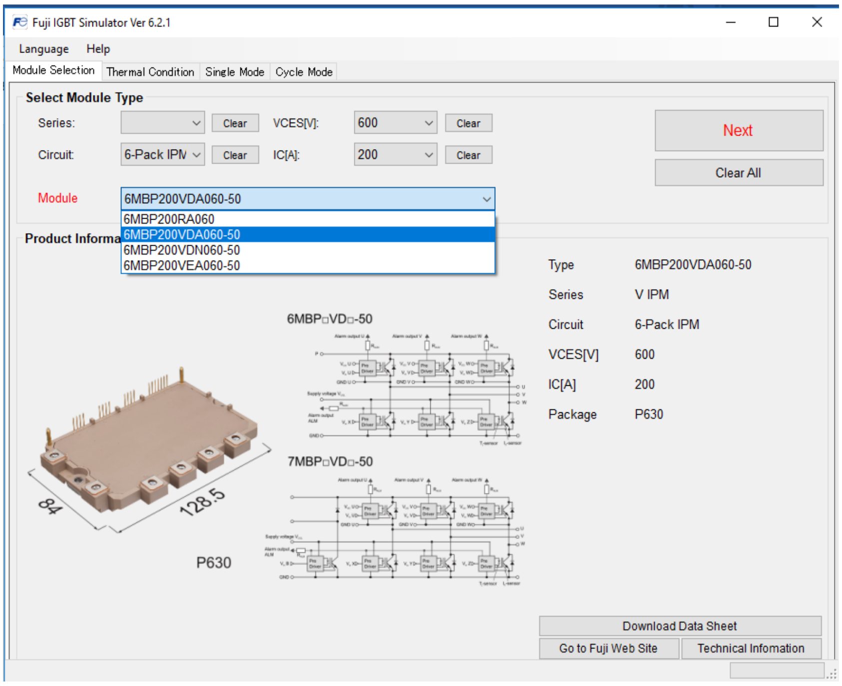
The AMK DD5 motor shows the best result and also satisfies the design requirements. The AMK motor is compact and can be used for the in-hub assembly planned initially. A synchronous permanent magnet motor that provides 35 kW power and 21Nm of torque when supplied with 600V DC. Detailed specification of the motor can be found in the figure below.

Inverter Power Circuit and Power Switches

To select the inverter power circuit ad power switches, Fuji IGBT simulator was used. Fuji simulator helps in selection of the IGBTs, which is an integral part of the inverter.

IGBTs are currently the largest segment of the market for EV power systems. The IGBT is a high-voltage, high-current switch connected directly to the traction motor in a hybrid electric or electric vehicle. It takes direct current energy from the car's battery and, through the inverter, converts the alternating current control signals into the high-current, high-voltage energy needed to commutate or turn the motor. The IGBT is an ideal motor inverter switch for 35 KW to 85 KW EV motors due to its high efficiency and fast switching. The more efficient the IGBT, the less power is lost to wasted heat, resulting in better mileage or "miles per watt" (MPW) of energy.

To select the modules from a range, fuji's IGBT simulator is used. The 6-pack IPM module was selected for the input voltage of 600V, Current of 200 Amps. This gave a possibility of four modules to choose from.



Several were done on various different settings to analyse the thermal condition of the module selected. The table below gives a list of the parameter used for the analysis. Two types of simulations were carried out. One with fixed Heatsink Temperature and other with calculated Heatsink Temperature. Both types were tested for single mode and cycle mode.

The switching frequency is calculated using the standard formulas.

Motor Specification From Datasheet	
p	10
Io	53.1 A
Nmax	20000 rpm

fb	1666 Hz
fsw	16.66 kHz

Formula used
$N = (120 * fb)/p$

In the fixed Heatsink Temperature only two simulations could be done, the results of which are shown below.

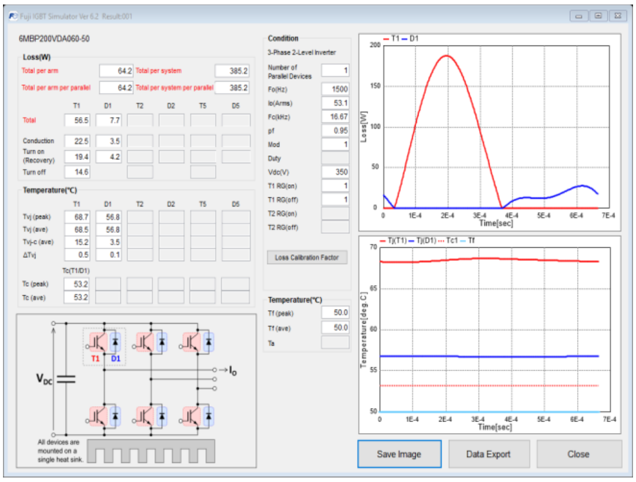


Figure 1: single mode fixed heatsink temperature

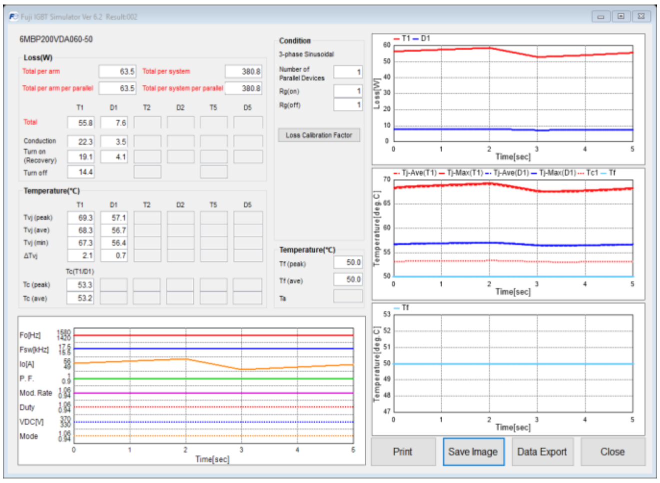


Figure 2: cycle mode fixed heatsink temperature

For the 'calculate heatsink temperature' option, ambient temperatures of 20, 35, 40, 45 & 50 degrees was used for the analysis. The details of which are presented below. R_{th} value is chosen such as to keep to the limits of maximum temperature.

Ambient Temp.	Values of R_{TH} Analysed	
	Single	Cycle
20	0.09; 0.1; 0.2	0.2
35	0.1; 0.2	0.09; 0.2
40	0.09; 0.1; 0.2	0.09; 0.1; 0.15
45	0.09; 0.1; 0.2	0.09; 0.1; 0.15
50	0.09; 0.1; 0.2	0.09; 0.1; 0.2

Fuji simulator results for the above analysis is shown below.

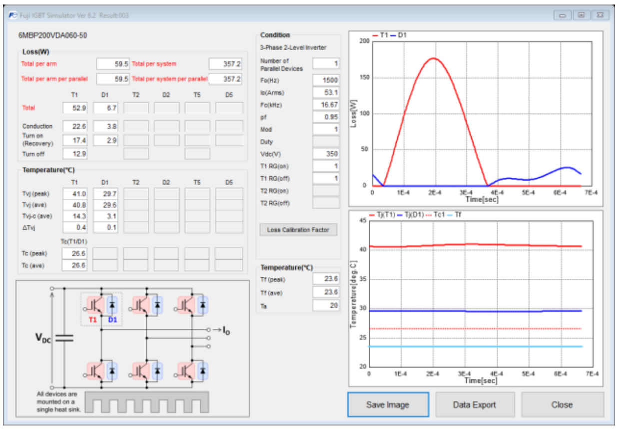


Figure 4: rth=0.01, ambt temp=20deg C

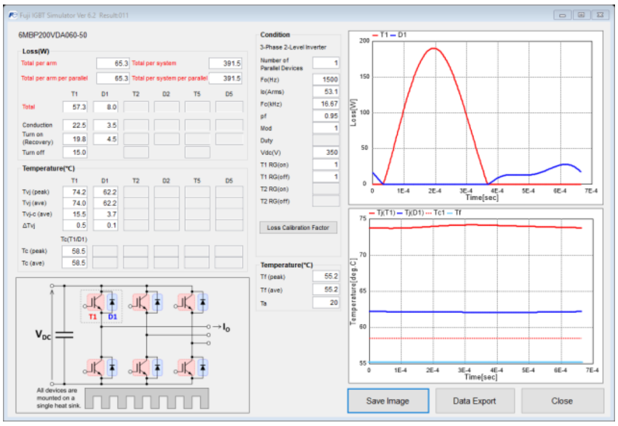


Figure 3: rth=0.09, ambt temp=20degC

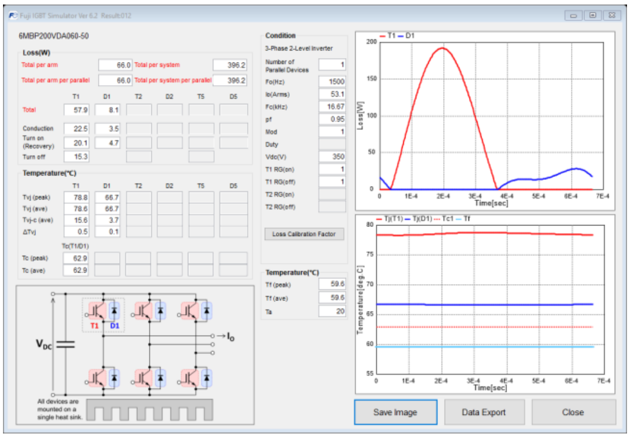


Figure 6:rth=0.1, ambt temp=20degC

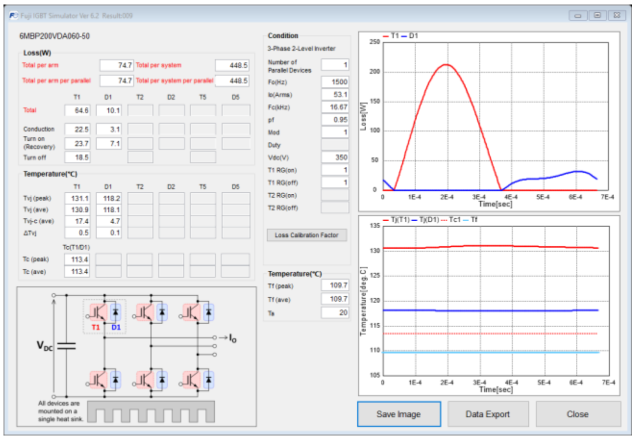


Figure 5: rth=0.2, ambt temp=20degC

The simulations above were carried out for an ambient temperature of 20 degrees C, while the Rth value is varied from 0.01 to 0.2. The temperature at 0.2 reaches the maximum operational temperature of the IGBT is at the limits. While the losses encountered in the worst case scenario of rth=0.2 is in excess of 200W.

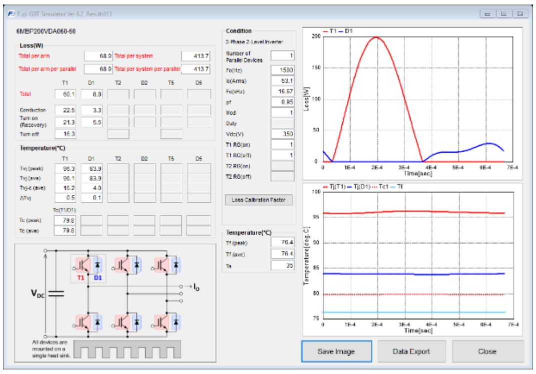
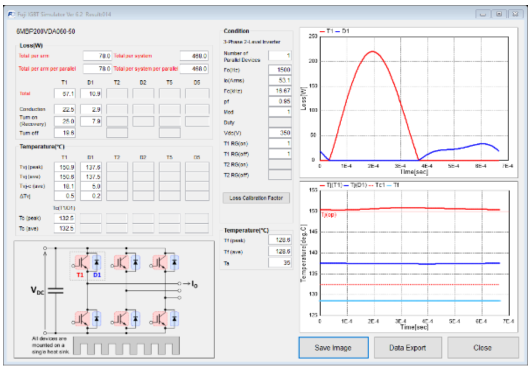


Figure 7: Rth=0.1, ambt temp=35



rth=0.2, ambt temp= 35

For Rth value of 0.1 and 0.2 at an increased ambient temperature of 35deg C, the above results are obtained. The losses well in excess of 200W and with the increased Rth value of 0.2 the operating temperature is above the limit, resulting in the overheating of the component. Similarly for different Rth values with varied ambient temperatures of 40, 45 and 50 degrees in single mode is analysed and the analysis graphs are shown below.

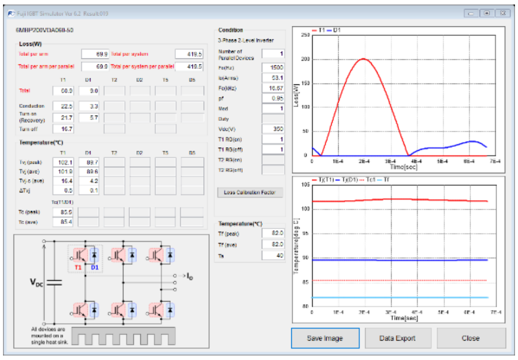


Figure 9: rth=0.1, ambt=40

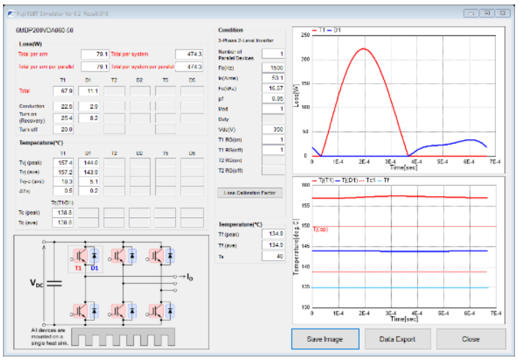


Figure 8: Rth=0.2

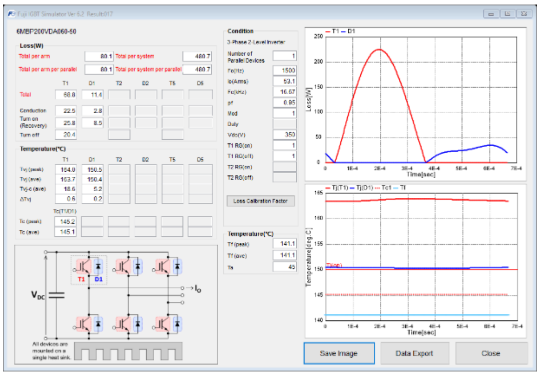


Figure 11: Rth=0.2, ambt temp=45

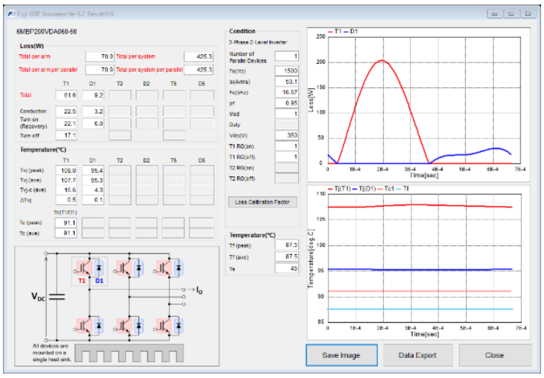


Figure 10: Rth=0.1, ambt =45

The single cycle simulation results are presented above with the analysis image being self-explanatory and the fairly consistent with varying ambient temperature.

The cycle mode analysis helps in better understanding of the thermal situation of the IGBT module. The cycle mode analysis results are shown below in image format.

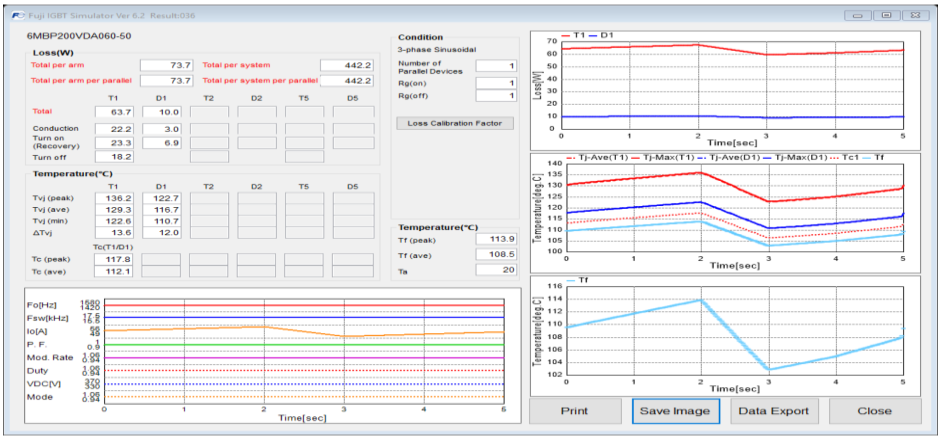


Figure 12:cycle mode Rth=0.2, ambt = 20

Further results for ambient temperature of 35, 40, 45 and 50 were conducted.

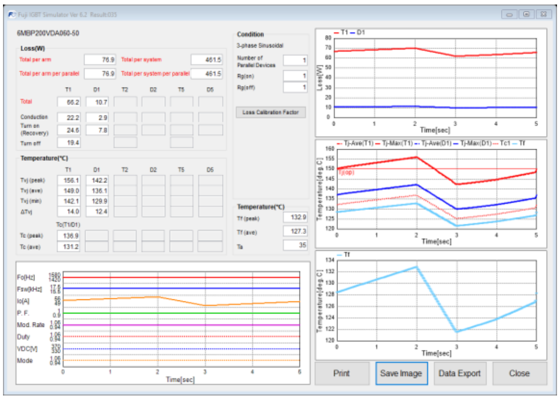


Figure 15: Rth=0.2 ambt= 35

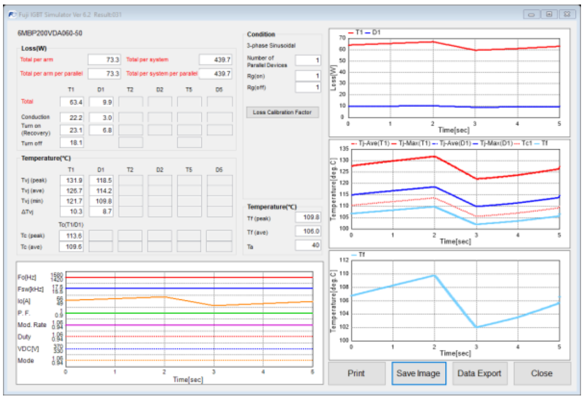


Figure 13: Rth=0.15, ambt= 40

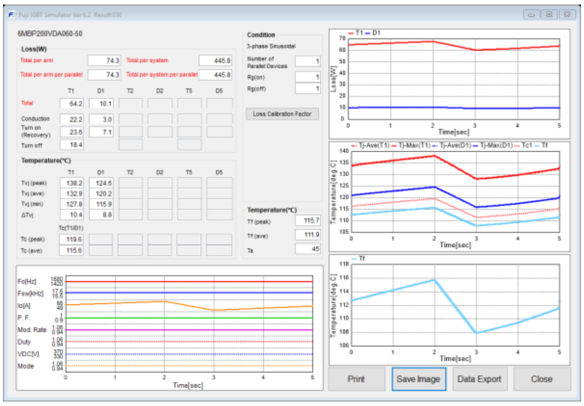


Figure 16: Rth=0.15, ambt=45

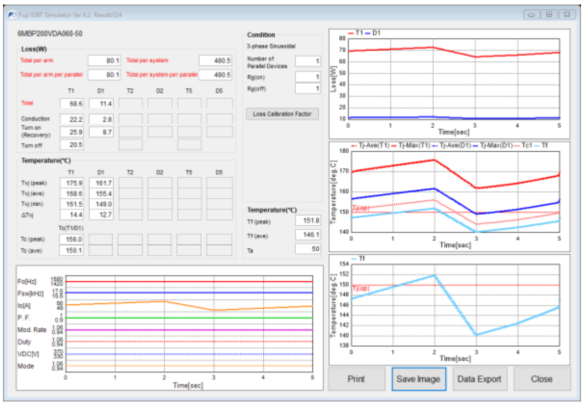


Figure 14: Rth=0.2, ambt= 50

Electric Motor

The motor selected, as stated in the previous sections is the AMK DD5. It's a synchronous permanent magnet motor, with liquid cooling type operating at a rated voltage of 350 V with a constant stall current of 53.1 Amps. The details of the motor can be found by contacting AMK service and the datasheet is attached below.

Motor-Datenblatt *motor data sheet* — AMK

Bezeichnung/name **DD5-14-10-POW** - 18600-B5

Teile-Nr:/part number **A2370DD** — Zeichn.-Nr:/drawing no.:12703-01260

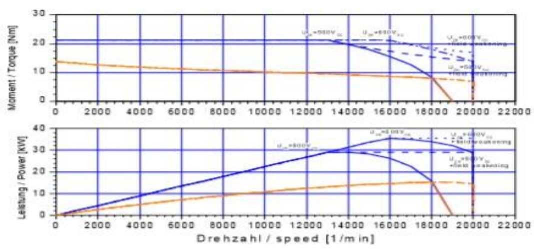
Motorbeschreibung ***motor description:***

Motorprinzip/motor principle:		synchron
Kühlart/cooling type:	Flüssigkeit	liquid
Bauform/mounting type:		IMB5
Schutzart/degree of protection:		IP 65
Isolierklasse/insulation class:		F

Leistungsdaten ***performance data:***

Betriebsart/duty type:	S1 dT=100K
Dauerstillstandsmoment/continuous Stall Torque "Mo":	13,8 Nm
Maximales Moment/maximum torque "Mmax":	21 Nm
Bemessungsmoment/rated torque "Mn" (ID32771):	9,8 Nm
Bemessungsleistung/rated power "Pn":	12,3 kW
Bemessungsdrehzahl/rated speed "Nn" (ID32772):	12000 rpm
Theo. Leerlaufdrehzahl/theor. no-load-speed "No":	18617 rpm

Motorkennlinien ***performance - characteristics:***



Kennlinie kann die maximal zulässige Drehzahl übersteigen! / Characteristic may exceed mechanical speed limit of motor

Elektrische Daten ***electrical data:***

Nennspannung/rated voltage "Un" (ID32768):	350 V
Nennstrom/rated current "In" (ID111):	41 Arms
Dauerstillstandsstrom/cont. stall current " Io" (ID34096):	53,1 Arms
Maximalstrom/maximum current "Imax" (ID109):	105 Arms
Maximale Dauer für/duration for "Imax" (ID34168):	1,24 s
Drehmomentkonstante/torque constant " kt":	0,26 Nm/Arms
Spannungskonstante/voltage constant "ke" (ID 34234):	18,8 V/kU/min
Schaltung/connection type:	D
Polzahl/number of poles "2p" (ID32775):	10 Pole
Klemmenwiderstand/terminal resistance "Rtt" (ID34164):	0,135 Ohm
Klemmeninduktivität/terminal inductance "Ltt" (ID34167):	0 mH
Querachseninduktivität/quadrature axis inductance "Lq" (ID34046)	0,12 mH
Hauptachseninduktivität/direct axis inductance "Ld" (ID34045):	0,24 mH
Magn.-Strom/magn. current "Im" (ID32769):	35 Arms
Magn.-Strom/magn. current "Im1" (ID32770):	0 Arms
Rotorzeitkonstante/rotor time constant "Tr" (ID32774):	0,01 s

Reglereinstellungen ***controller settings:***

Stromregler ***current controller:***	
Verstärkung q-Achse/gain q-axis "Kpq" (ID34151):	0,64 V/A
Verstärkung d-Achse/gain d-axis "Kpd" (ID34152):	0,58 V/A
Nachstellzeitkonstante/time constant "Tnq" (ID34050):	1,2 ms
Nachstellzeitkonstante/time constant "Tnd" (ID34052):	1,2 ms
Adaption Verstärkung/adaption gain "Kpq2" (ID 34179)	20 %
Adaption Nachstellzeit/adaption time constant "Tnq2" (ID 34180)	400 %
Untere Anpaßschwelle/lower adaption limit "Iua" (ID34177):	19 %
Obere Anpaßschwelle/upper adaption limit "Ioa" (ID34178):	68 %
Drehzahlregler ***speed controller (default for plain motor):***	
Verstärkung/gain "Kp_n" (ID100):	40
Nachstellzeitkonstante/time constant "Tn_n" (ID101):	20 ms
Spannungsregler ***voltage controller:***	
Spannungsregler/voltage controller "Kp" (ID34148):	0,08 A/V
Spannungsregler/voltage controller "Tn" (ID34149):	6 ms
Spannungsüberhöhung "dU" (ID34235):	116 %
Systemwiderstand "Rs" (ID34233):	0 Ohm

The inverter efficiency is estimated at around 98% and the motor efficiency sheet is attached below.

Efficiency: DD5-14-10-xxW-19000 "calculated values @ operating temp. - differences up to 2% possible" AMK

		speed [rpm]									
Current [Arms]	Torque [Nm]	500	1000	2000	3000	4000	6000	10000	12000	15000	19000
5	1,3	64,37	71,33	73,64	74,70	75,43	76,57	77,00	77,08	77,56	78,14
10	2,7	58,42	70,48	77,57	80,40	82,01	83,92	85,16	85,44	85,97	86,50
20	5,4	44,94	60,81	73,35	78,82	81,94	85,43	88,20	88,88	89,71	90,44
30	7,9	35,59	51,90	67,02	74,26	78,54	83,42	87,58	88,65	89,84	90,86
40	10,4	29,14	44,78	61,01	69,41	74,57	80,62	85,93	87,34	88,86	90,16
50	12,5	24,17	38,71	55,22	64,39	70,24	77,30	83,73	85,48	87,37	88,98
60	14,4	20,41	33,76	50,04	59,65	65,99	73,88	81,33	83,42	85,66	87,59
70	16,0	17,31	29,40	45,10	54,87	61,55	70,10	78,56	80,97	83,56	85,81
80	17,4	14,82	25,75	40,67	50,41	57,28	66,34	75,70	78,40	81,34	83,91
90	18,5	12,81	22,67	36,72	46,30	53,25	62,67	72,77	75,75	79,02	81,91
100	19,6	11,17	20,05	33,21	42,51	49,44	59,09	69,82	73,06	76,63	79,83

Field weakening	600VDC	speed [rpm]									
Current [Arms]	Torque [Nm]	500	1000	2000	3000	4000	6000	10000	12000	15000	19000
5	1,3	64,37	71,33	73,64	74,70	75,43	76,57	77,00	77,08	77,56	78,14
10	2,7	58,42	70,48	77,57	80,40	82,01	83,92	85,16	85,44	85,97	86,50
20	5,4	44,94	60,81	73,35	78,82	81,94	85,43	88,20	88,88	89,71	90,44
30	7,9	35,59	51,90	67,02	74,26	78,54	83,42	87,58	88,65	89,84	90,86
40	10,4	29,14	44,78	61,01	69,41	74,57	80,62	85,93	87,34	88,86	90,16
50	12,5	24,17	38,71	55,22	64,39	70,24	77,30	83,73	85,48	87,37	88,98
60	14,4	20,41	33,76	50,04	59,65	65,99	73,88	81,33	83,42	85,66	87,59
70	16,0	17,31	29,40	45,10	54,87	61,55	70,10	78,56	80,97	83,56	85,81
80	17,4	14,82	25,75	40,67	50,41	57,28	66,34	75,70	78,40	81,34	82,71
90	18,5	12,81	22,67	36,72	46,30	53,25	62,67	72,77	75,75	79,02	76,96
100	19,6	11,17	20,05	33,21	42,51	49,44	59,09	69,82	73,06	67,66	69,28

Figure 17: AMK efficiency data

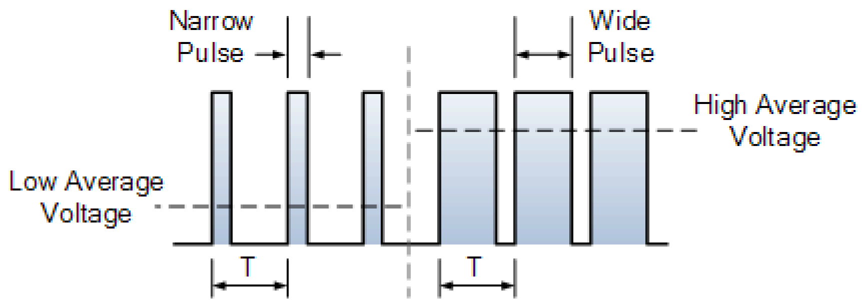
Inverter Design Details	
Rated input V	540 V DC
Inout current	48A
Supply Volt for LV	24VDC
Control method switching freq	PWM 16KHz
Efficiency	98%
Fo	0-1500Hz
Output Voltage(@HV=540VDC)	350VAC

Control Systems

Modulation Techniques

One of the easiest ways to control the DC motor is by the use of PWM controller. Digital signals are usually represented with the term Pulse Width Modulation (PWM). Pulse width describes the width or duration of a signal for transmission. The amplitude of a signal is encoded right into the duration of the other signal.

The main purpose of the PWM controller here is to control the inertial power load supplied to the AC/DC motors. It controls the power in relation to voltage and by changing the cycle of on-off phase quickly and changing the pulse width of ON- phase. It would appear to have steady power output with an average voltage value.



The biggest advantage of using PWM is the amount of power loss in modulating is minimum. PWM technique does not limit the power output when not needed, but rather turns it off for a short duration and turns it ON again when required. This also results in better speed stability. As the amplitude of the motor is always at full strength, the motor can be spun ever more slowly without stall.

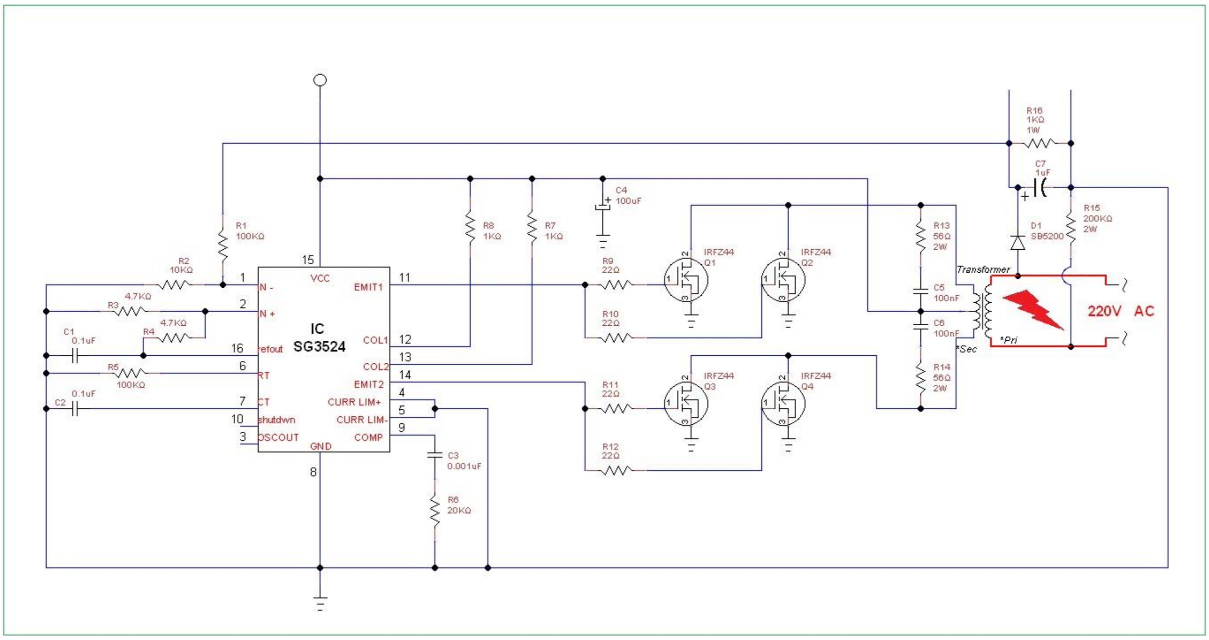


Figure 18: PWM inverter Circuit

Pulse Width Modulation is the best way to control the amount of power without wasting the dissipated power. The above shown circuit is used as the PWM circuit for controlling the Inverter designed in this project. The above shown circuit can also be used for controlling other DC devices like fan, LEDs, etc.

Feedback Circuits

Feedback circuits are used for a number of reasons that influences the Circuit characteristics, such as gain, can be precisely controlled, and made relatively independent of wide variations in active device parameters also the characteristics of the circuits can be made relatively independent of operating conditions such as supply voltages or temperature.   Apart from these the frequency response of the circuit can also be controlled by properly designing the feedback circuit.

There are primarily two types of feedback circuits that can be used based on the requirement, they are positive and negative feedback.

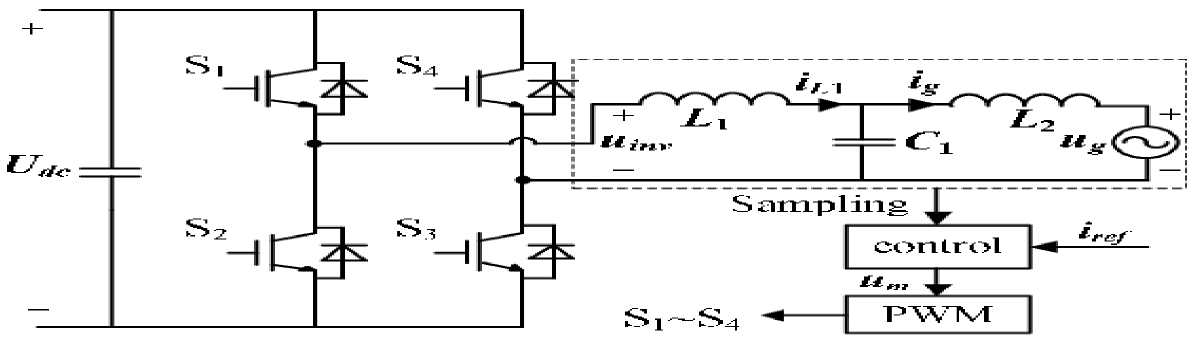


Fig. 1. Grid-connected LCL-filtered inverter

Figure 19: Current Feedback Circuit

The Current feedback circuit for the inverter is shown above. The circuit also represents the use of PWM controller for the modulation of signals. Working of the current feedback circuit is shown using the circuit diagram shown below.

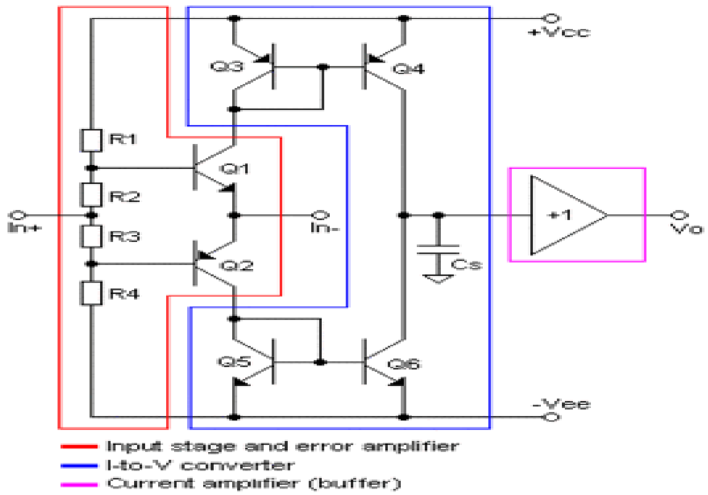


Figure 20: current Feedback Working

Input stage and error amplifier is represented using red line at the left of the image. It can be noted that there is a I to V converter loop included in the circuit and the buffer is at the right end of image highlighted with pink box.

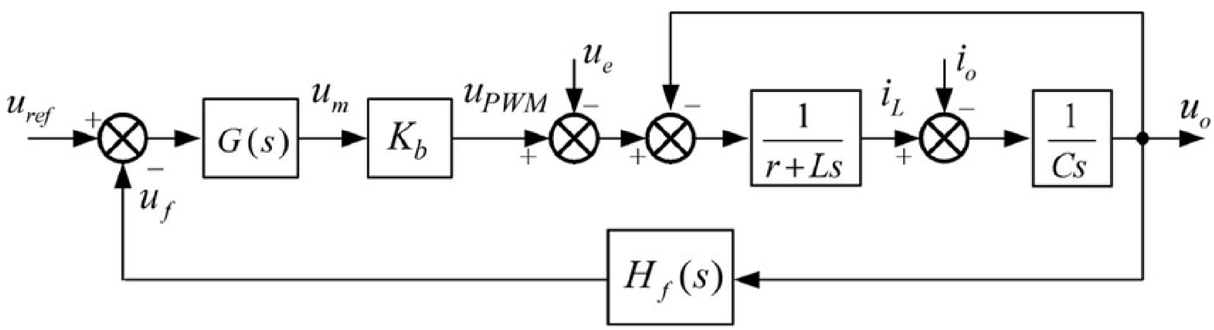


Figure 21:Voltage Feedback Block Diagram

A block diagram is used to understand the processes of voltage feedback circuit. Voltage input is shown as Uref and the amplified voltage is represented as Uo. G represents Gain, K is amplitude factor and the Upwm is the modulated signal voltage. Block diagram represents the circuit in an easier way. The closed loop voltage feedback circuit is represented below.

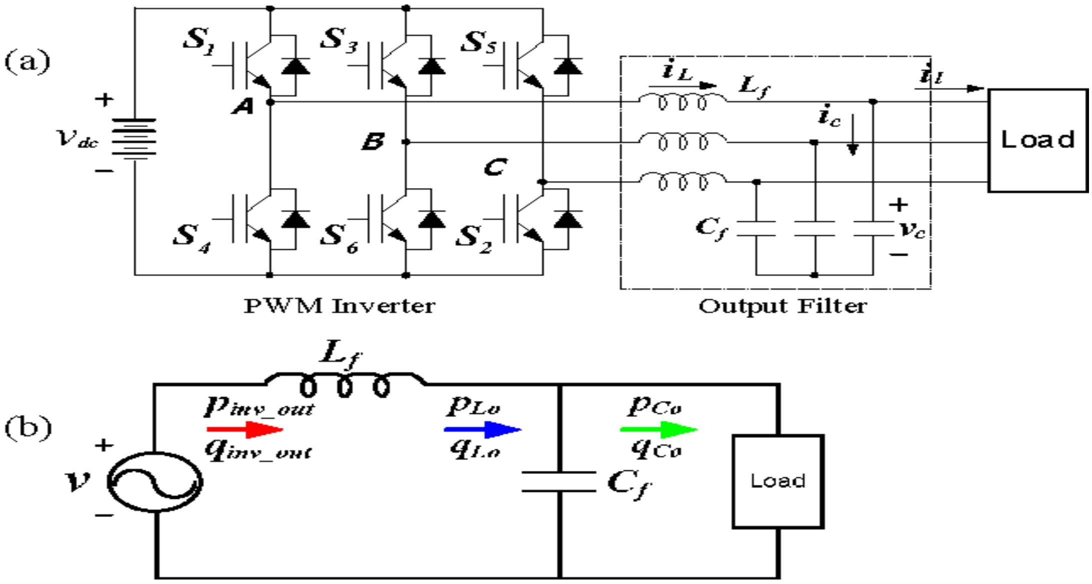
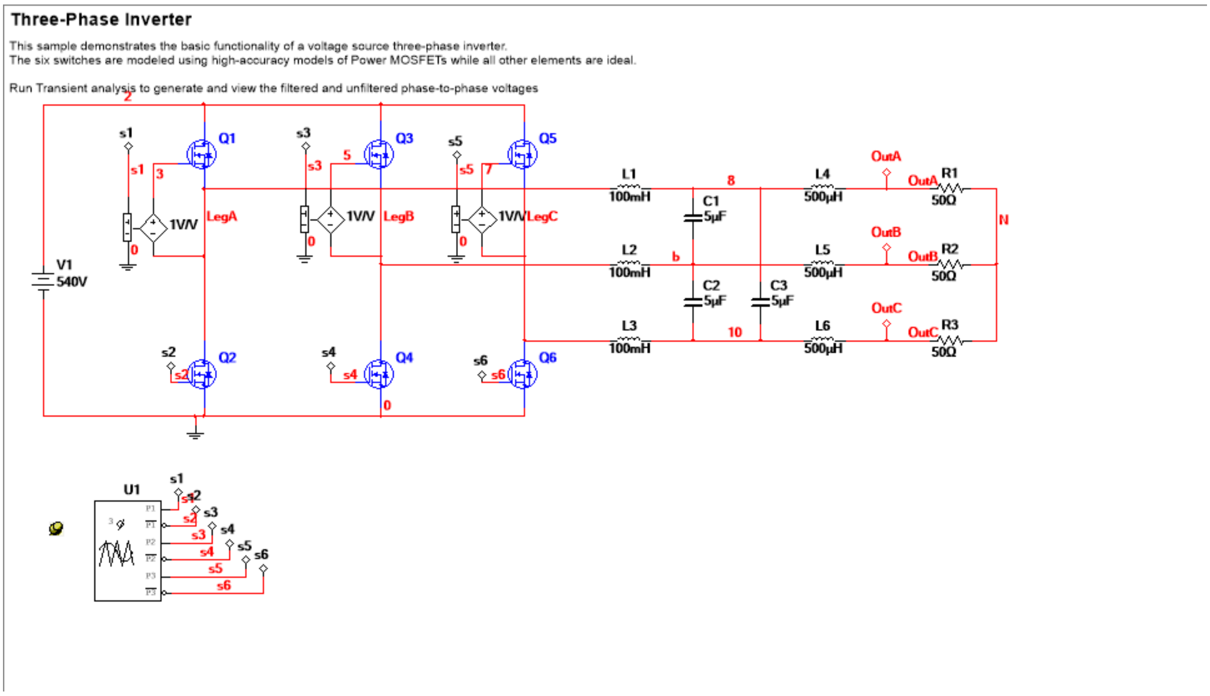


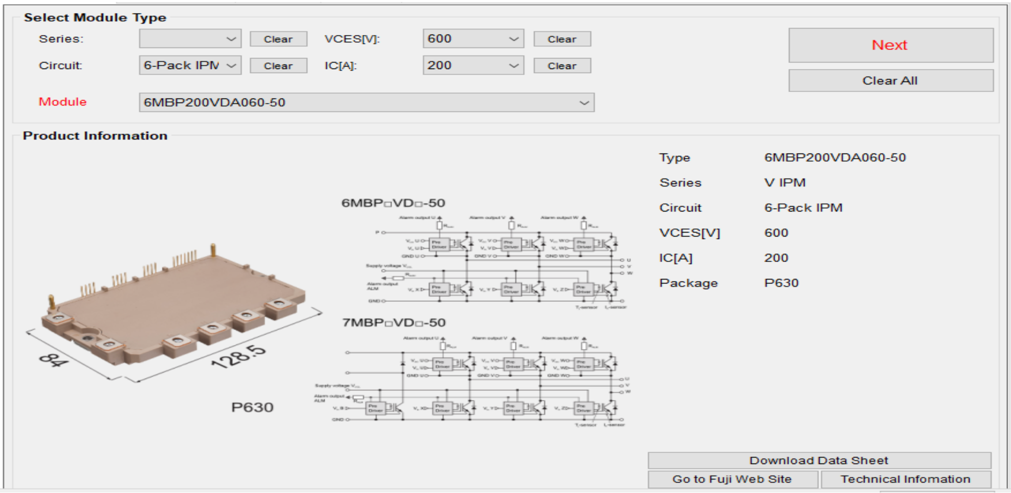
Figure 22: Voltage feedback control circuit

The voltage feedback circuit is shown in tandem with all the components discussed upon in this research so far. The load is representative of the AMK motor, while the output filter is representative of the control by PWM. S1, S2…, S6 represents Fuji' IGBT module that was selected earlier. Figure b represents only the voltage feedback circuit with respect to the motor.

Modelling and Simulation of Energy-Storage- Inverter-Motor

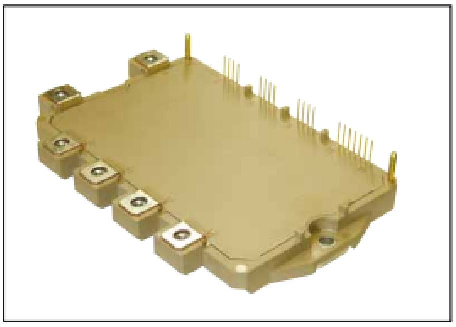


Energy storage-inverter-motor system is modelled and simulated in NI-Multisim. Accumulator is 540V and the IGBT data is obtained using Fuji IGBT.



■ Features

- **Temperature protection provided by directly detecting the junction temperature of the IGBTs**
- Low power loss and soft switching
- High performance and high reliability IGBT with overheating protection
- Higher reliability because of a big decrease in number of parts in built-in control circuit



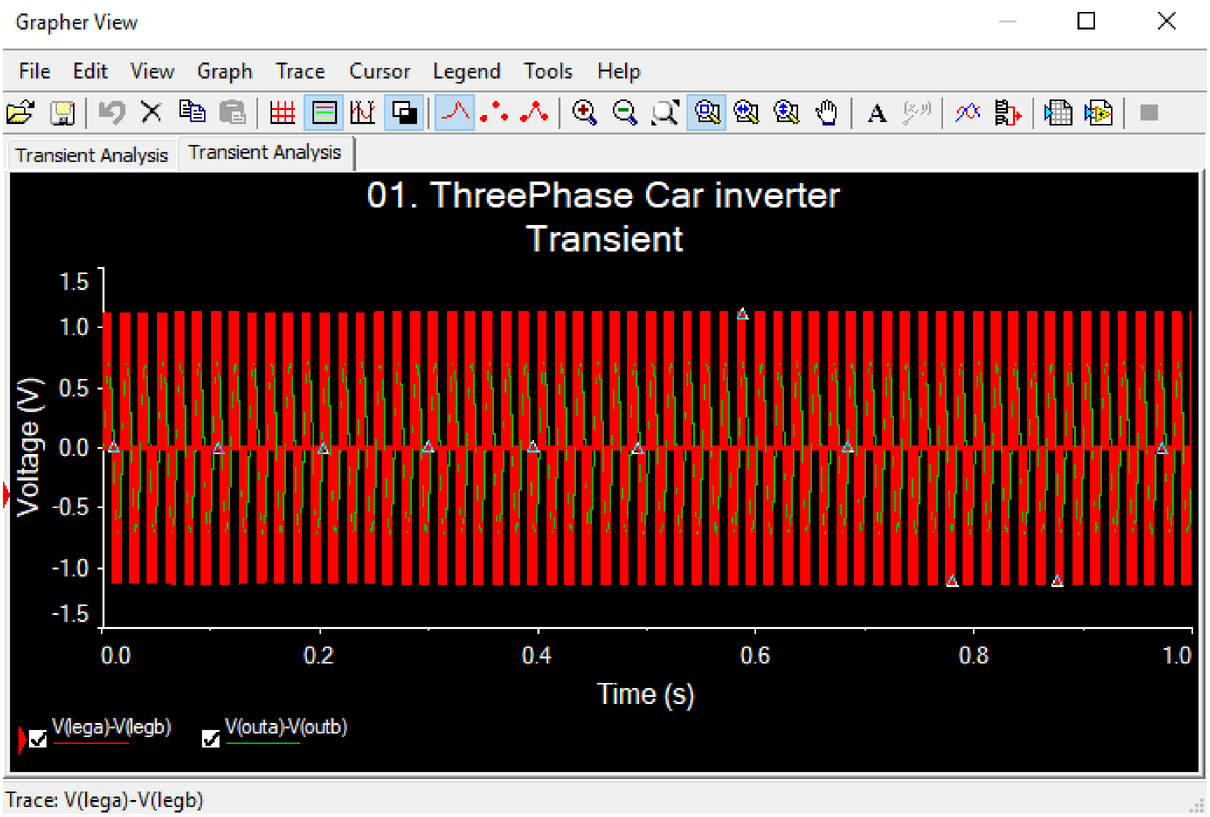
■ Maximum Ratings and Characteristics

● Absolute Maximum Ratings (T_c=25°C, V_{cc}=15V unless otherwise specified)

Items				Symbol	Min.	Max.	Units
Collector-Emitter Voltage (*1)				V_{CES}	0	600	V
Short Circuit Voltage				V_{SC}	200	400	V
Inverter	Collector Current		DC	I_C	-	200	A
			1ms	I_{CP}	-	400	A
			Duty=50.3% (*2)	$-I_C$	-	200	A
	Collector Power Dissipation		1 device (*3)	P_C	-	462	W
Brake	Collector Current		DC	I_C	-	-	A
			1ms	I_{CP}	-	-	A
	Forward Current of Diode			I_F	-	-	A
	Collector Power Dissipation		1 device (*3)	P_C	-	-	W
Supply Voltage of Pre-Driver (*4)				V_{CC}	-0.5	20	V
Input Signal Voltage (*5)				V_{in}	-0.5	V_{CC}+0.5	V
Alarm Signal Voltage (*6)				V_{ALM}	-0.5	V_{CC}	V
Alarm Signal Current (*7)				I_{ALM}	-	20	mA
Junction Temperature				T_j	-	150	°C
Operating Case Temperature				T_{opr}	-20	110	°C
Storage Temperature				T_{stg}	-40	125	°C
Solder Temperature (*8)				T_{sol}	-	260	°C
Isolating Voltage (*9)				V_{iso}	-	AC2500	Vrms
Screw Torque			Terminal (M4)	-	-	1.7	Nm
			Mounting (M4)				

Note *1: V_{CES} shall be applied to the input voltage between terminal P-(U,V, W) and (U,V, W, B)-N.
Note *2: Duty=125°C/$R_{th(j-c)D}$ /(I_F×V_F Max.)×100
Note *3: P_C=125°C/$R_{th(j-c)Q}$ (Inverter & Brake)
Note *4: V_{CC} shall be applied to the input voltage between terminal No.4 and 1, 8 and 5, 12 and 9, 14 and 13.
Note *5: V_{in} shall be applied to the input voltage between terminal No.3 and 1, 7 and 5, 11 and 9, 15~18 and 13.
Note *6: V_{ALM} shall be applied to the voltage between terminal No.2 and 1, 6 and 5, 10 and 9, 19 and 13.
Note *7: I_{ALM} shall be applied to the input current to terminal No.2,6,10 and 19.
Note *8: Immersion time 10±1sec. 1time.
Note *9: Terminal to base, 50/60Hz sine wave 1min. All terminals should be connected together during the test.

Using the above data, the multisim model is run for the simulations to obtain the following results shown below.

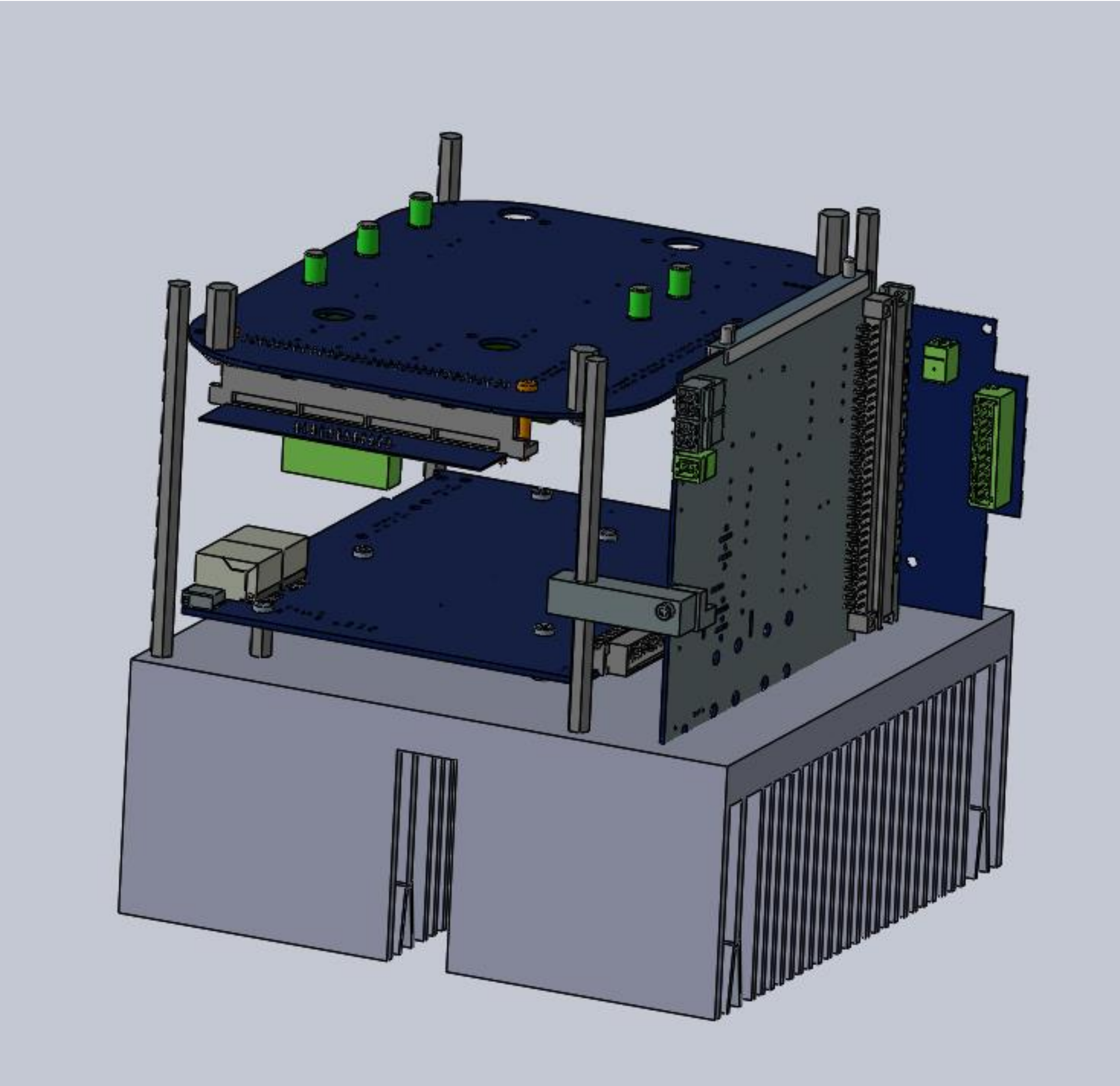


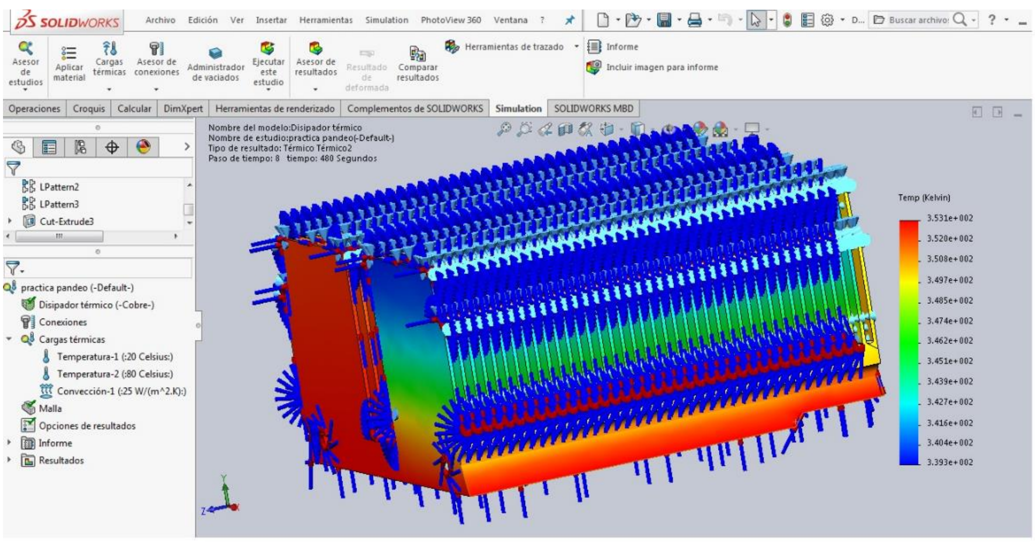
Packaging and Assembling

Designed inverter needs to be packaged. In a formula type car it is desired to have the components packed as tightly as possible. The packaging is represented in the figure below using the CAD software Solidworks. In the cad shown here only one inverter and heatsink is represented, however, since the vehicle has four individual motors for all the four wheels, therefore four inverter packs would be required, one for each motor.

Ideally, it is required to have water cooling, but for the scope of this project and also because of budget cap, an air cooled, heatsink is demonstrated. Water cooling gives advantage with the weight, and also provides more control over the module temperature. However, it is more complex to design and would cost more as well.

With the heatsink, it is important that there is direct air interaction with the heatsink itself in order to cool down the module. This has been verified by conducting thermal analysis of the heatsink. This is also represented below with the appropriate results and input parameters.





Thermal analysis of the heatsink is shown in the above image. The analysis is conducted in Solidworks and is believed to be 98 percent accurate. Air speed of 10 m/s, ambient temperature of 50 deg C is used as boundary conditions. The channels and number of rows are modified accordingly with accordance to the first few simulations.

Conclusion

Energy storage-inverter-motor system design is completed. While the Energy storage design was touched upon in previous document, this document primarily deals with the investigation of IGBT and inverter design, along with modulation techniques, feedback circuits and thermal analysis. The project, more importantly deals with the type of motor used and the switches and power circuits used in three phase full bridge Inverter.

The document is well compiled and is in tandem with previous work. Energy Storage System has not been changed, neither is anything else. The structure of the vehicle was planned well in advance and the work done in this project justifies that.

Future work would include, designing of the shutdown circuit, required for these types of formula cars, and implementing the current work in test bench using the necessary tools.

References

I. Nxp.com. (2019). [online] Available at: https://www.nxp.com/files-static/training/doc/dwf/DWF13_AMF_AUT_T0144.pdf [Accessed 29 Apr. 2019].

II. Ecee.colorado.edu. (2019). [online] Available at: http://ecee.colorado.edu/~ecen4827/supplement/34_feedback1 [Accessed 29 Apr. 2019].

III. Kalmakov, V., Andreev, A. and Salimonenko, G. (2016). Development of Formula Student Electric Car Battery Design Procedure. *Procedia Engineering*, 150, pp.1391-1395.