THREE PHASE 3-LEVEL T-Type ISOLATED BIDIRECTIONAL AC-DC CONVERTER FOR EV CHARGING

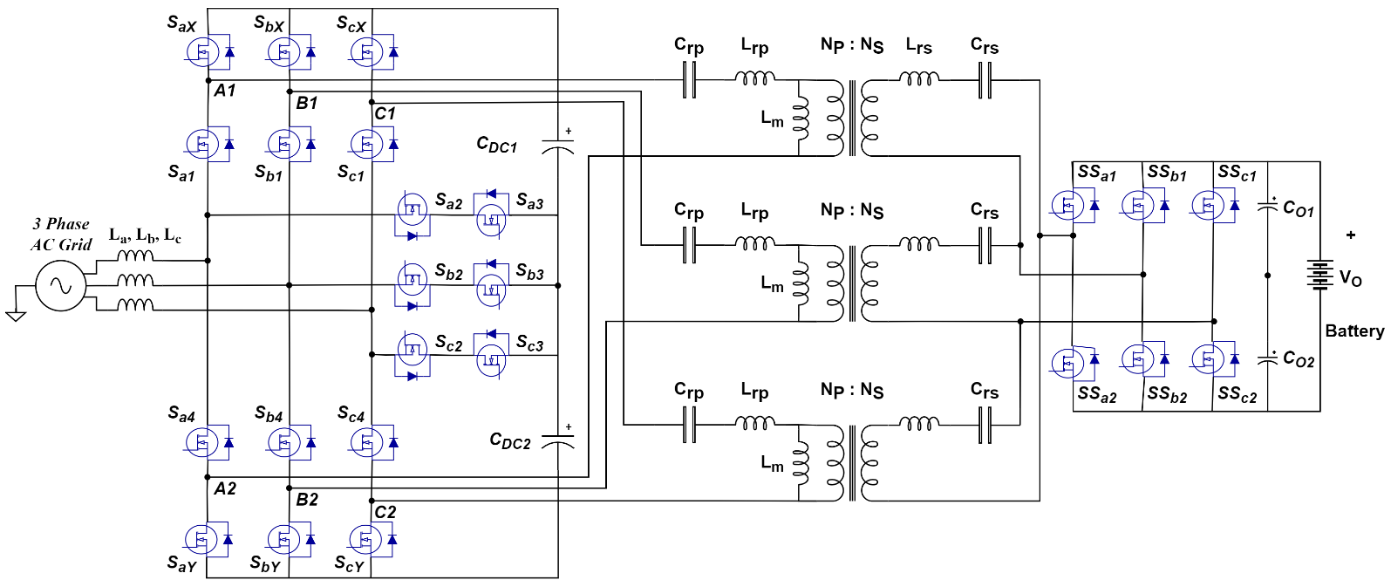


Fig.1 Three Phase 3-level T-TYPE Isolated Bidirectional Converter

PARAMETERS

PARAMETERS	SPECIFICATIONS
Peak Power Rating	6.6 kW
Switching Frequency	120 kHz(AC to DC)
Input AC Voltages	300-415 V, 50 Hz
DC Link Voltages	900-1100 V
Battery Voltages	600-800V
Primary side bridge duty ratio	0.6
Secondary side bridge duty ratio	0.5
Input AC Inductances	0.8 mH
Turns Ratio	55:80
HF Transformer magnetizing inductance	103.5 µH
Primary and Secondary Side Resonant Inductance	78.8 µH
Primary and Secondary Side Resonant Capacitance	32.145 nF
Split DC Link Capacitances	660 µF
Output Split DC Capacitances	440 µF
d-Current Controller	5 + 1000/s
q-Current Controller	5 + 1000/s
DC-link Voltage Controller	0.1 + 10/s

Output Current Controller	0.05 + 10/s

MODULATION INDEX OF THE UPPER SWITCH

$$V_{AB1} = 0.707m_a(m-1)E$$

Where $V_{AB1,MAX} = input\ rms\ line\ voltage$

$m_a = modulation\ index$

$m = number\ of\ voltage\ levels$

$E = voltage\ of\ each\ level$

$$V_{AB1} = 415\ V$$

$$m = 3$$

$$E = \frac{V_{DC}}{2} = 450\ to\ 550V$$

This implies that

$$m_a = 0.53\ to\ 0.65$$

SWITCHING FREQUENCY

●Switching frequency is selected between 100 kHz to 150 kHz.

●Most off-line AC/DC applications require a switching frequency below 150 kHz for normal operation, and usually between 100 and 150 kHz as a rule of thumb.

●This is usually because conducting EMI testing starts at 150 kHz. Maintaining the switching frequency below the EMI test's lower boundary helps the application pass the test.

●At high frequencies, the parameter of the resonant inductor and capacitor will be lower.

FILTER INDUCTOR

$$\Delta I_{rip\_max} = \frac{V_{DC}}{2(N-1)^2 f_S L_1}$$

Where N is the number of voltage levels.

f_S is switching frequency.

L_1 is filter inductance.

V_{DC} is DC Link Voltage.

ΔI_{rip_max} is the maximum ripple in the input line current.

ΔI_{rip_max} is taken as 10% of the rated peak current.

This implies that,

$$L_1 = 882\ \mu H$$

CAPACITOR CALCULATION

$$C_O \geq \frac{P_{OUT}}{4\pi f V_O \Delta V_O}$$

●ΔV_O is the Voltage ripple taken as 10% of DC Voltage.

●f is the line frequency.

This implies,

$$C_{DC} \geq 129.68\ \mu F$$

$$C_O \geq 291.78\ \mu F$$

We took,

$$C_{DC} = 292.5\ \mu F$$

$$C_O = 390\ \mu F$$

The rms ripple current passing through the capacitor is given by

$$I_{cap(rms)} = I_{ph(rms)} \sqrt{\left[2M\left\{\frac{\sqrt{3}}{4\pi} + \left(\frac{\sqrt{3}}{\pi} - \frac{9M}{16}\right)cos^2\emptyset\right\}\right]}$$

For DC Link Capacitor,

$$I_{cap(rms)} = 5.9421\ A$$

RESONANT CONVERTER PARAMETERS

The primary side and secondary side bridge voltages are given by

$$V_{ph} = \frac{V_{DC}[j\sin(2\pi h D_i) + (1 - \cos(2\pi D_i))]}{\sqrt{2}h\pi}$$

$$V_{sh} = \frac{V_{bst}\left[-\sin\left(2\pi h\left(D_o+\frac{1}{3}\right)\right)+\sin\left(2\pi h\left(\frac{1}{3}\right)\right)+1-\cos(2\pi h D_o)+\cos\left(2\pi h\left(D_o+\frac{1}{3}\right)\right)-\cos\left(2\pi h\left(\frac{1}{3}\right)\right)+j\sin(2\pi h D_o)\right]}{\sqrt{2}h\pi}$$

The final expressions for primary- and secondary-side bridge voltages can be drawn as

$$V_p(h) = V_{ph}, \qquad V_s(h) = V_{sh}e^{jh\gamma}, \qquad \gamma = \lambda + \phi, \qquad \lambda = \angle V_{p1} - \angle V_{s1}$$

MODULATION SCHEME

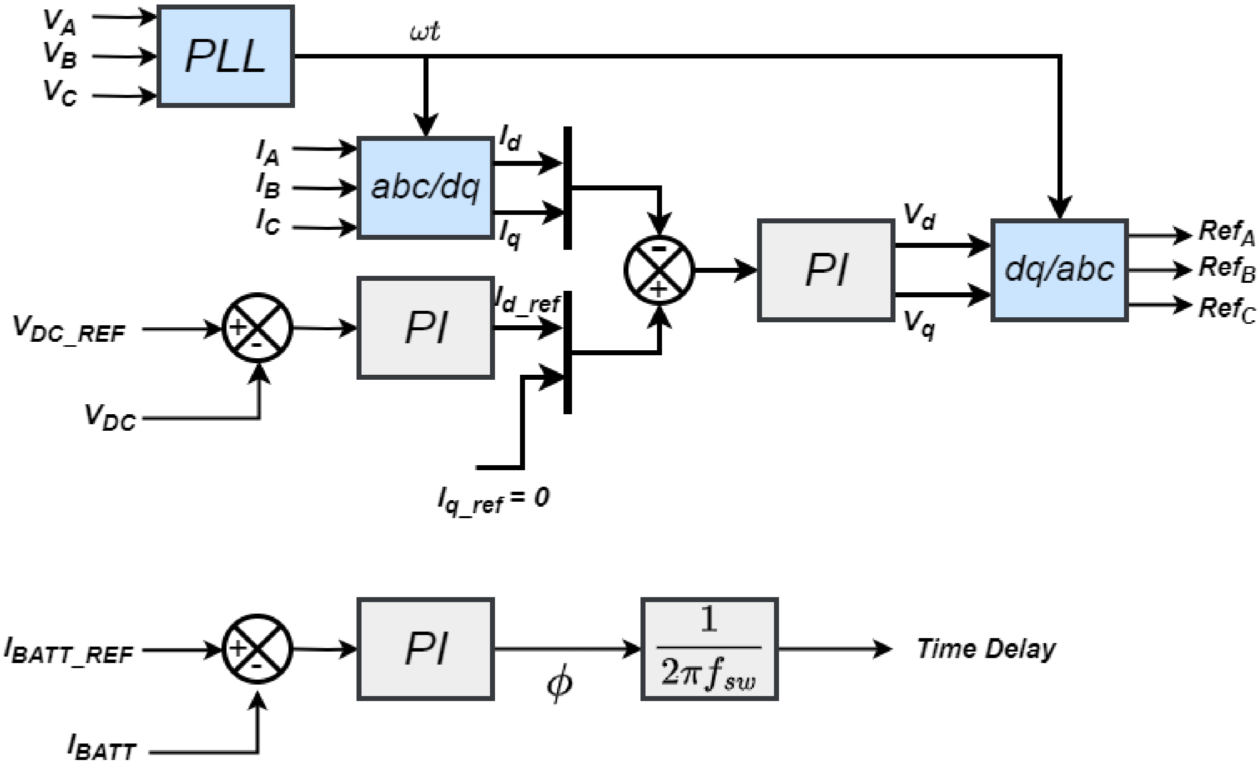
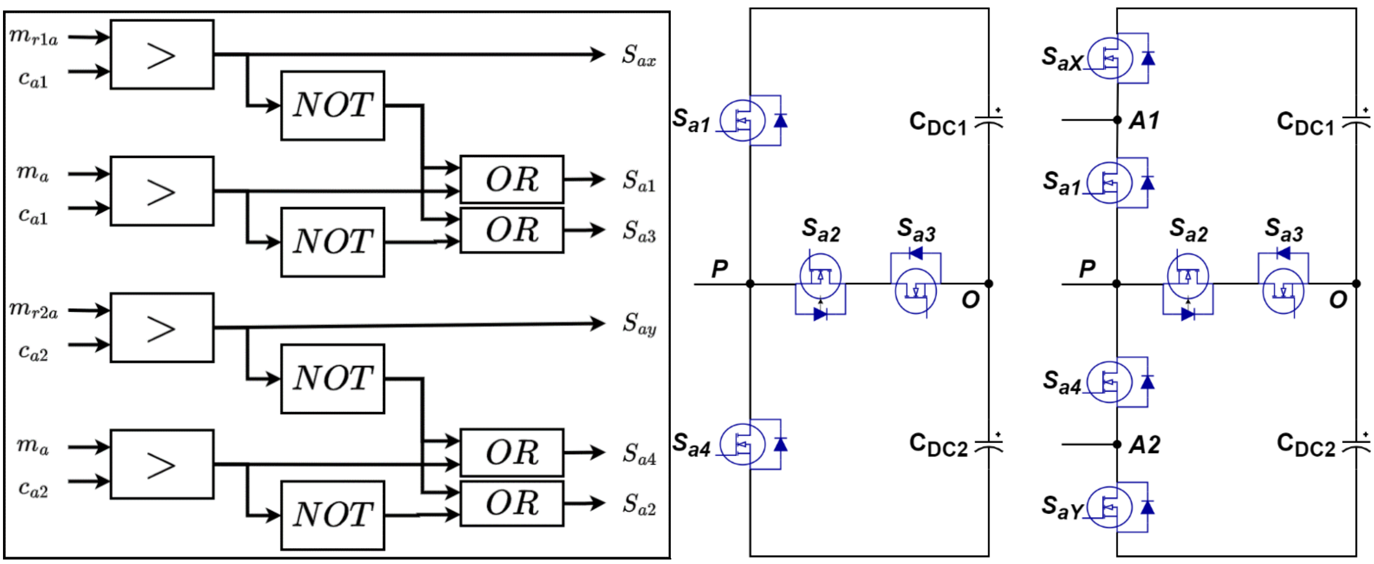
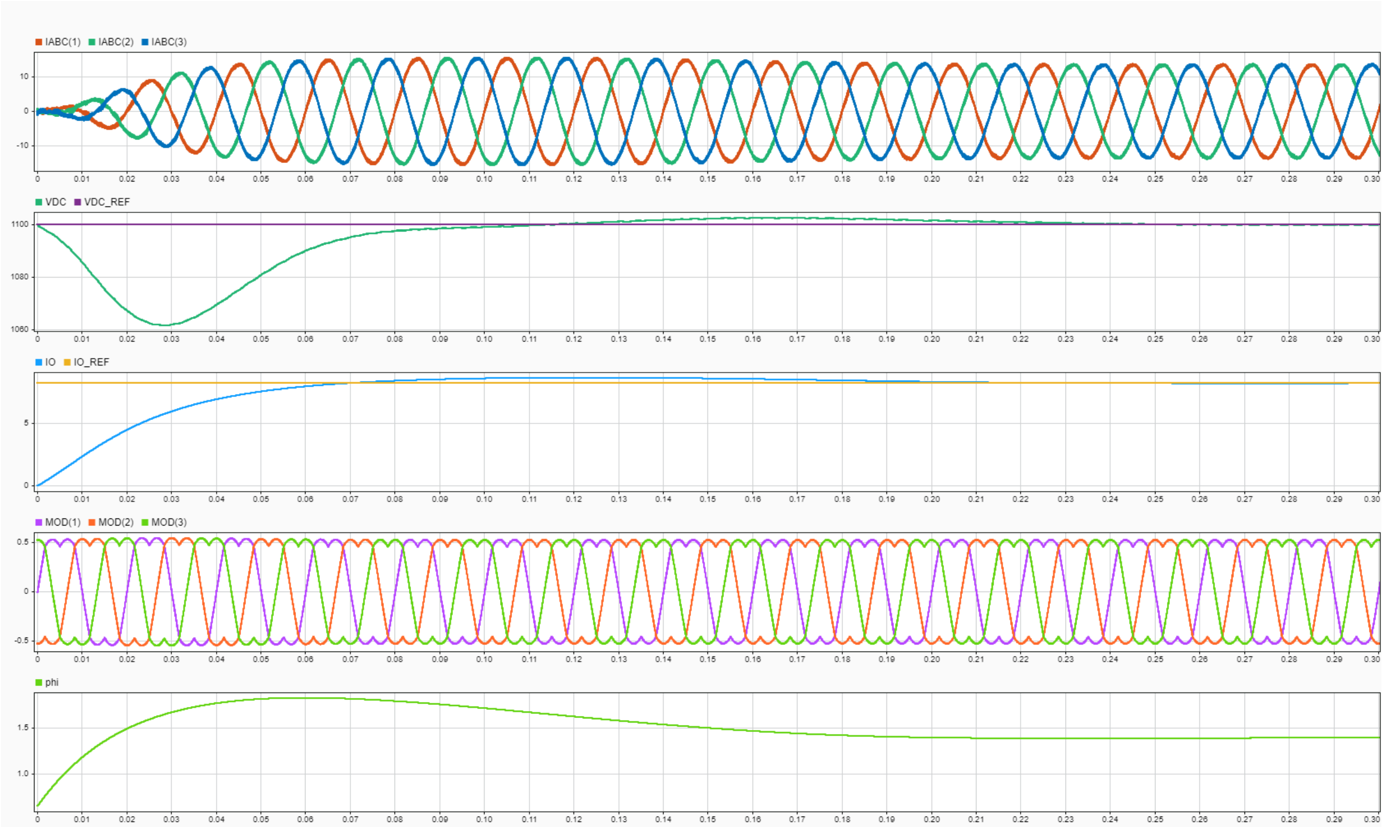
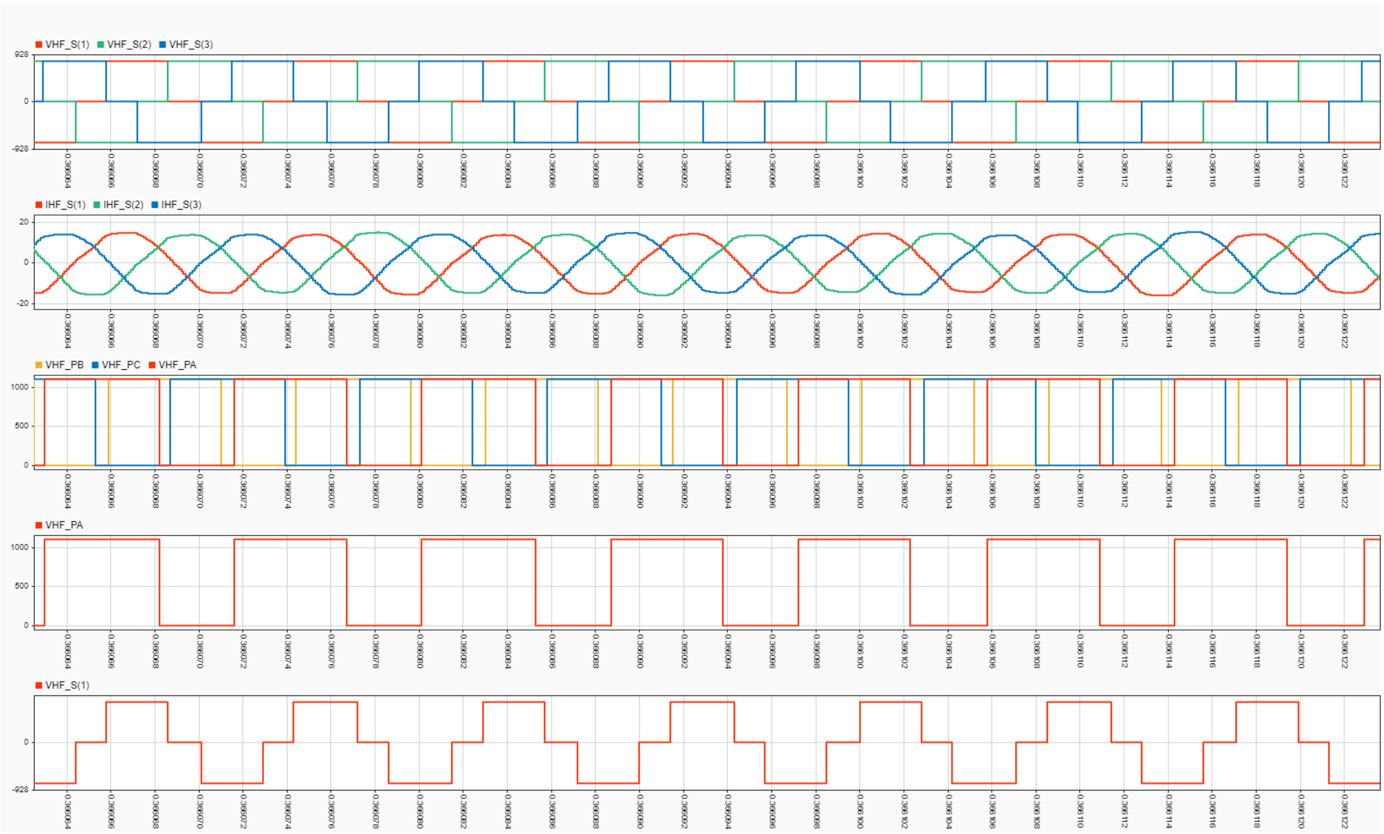


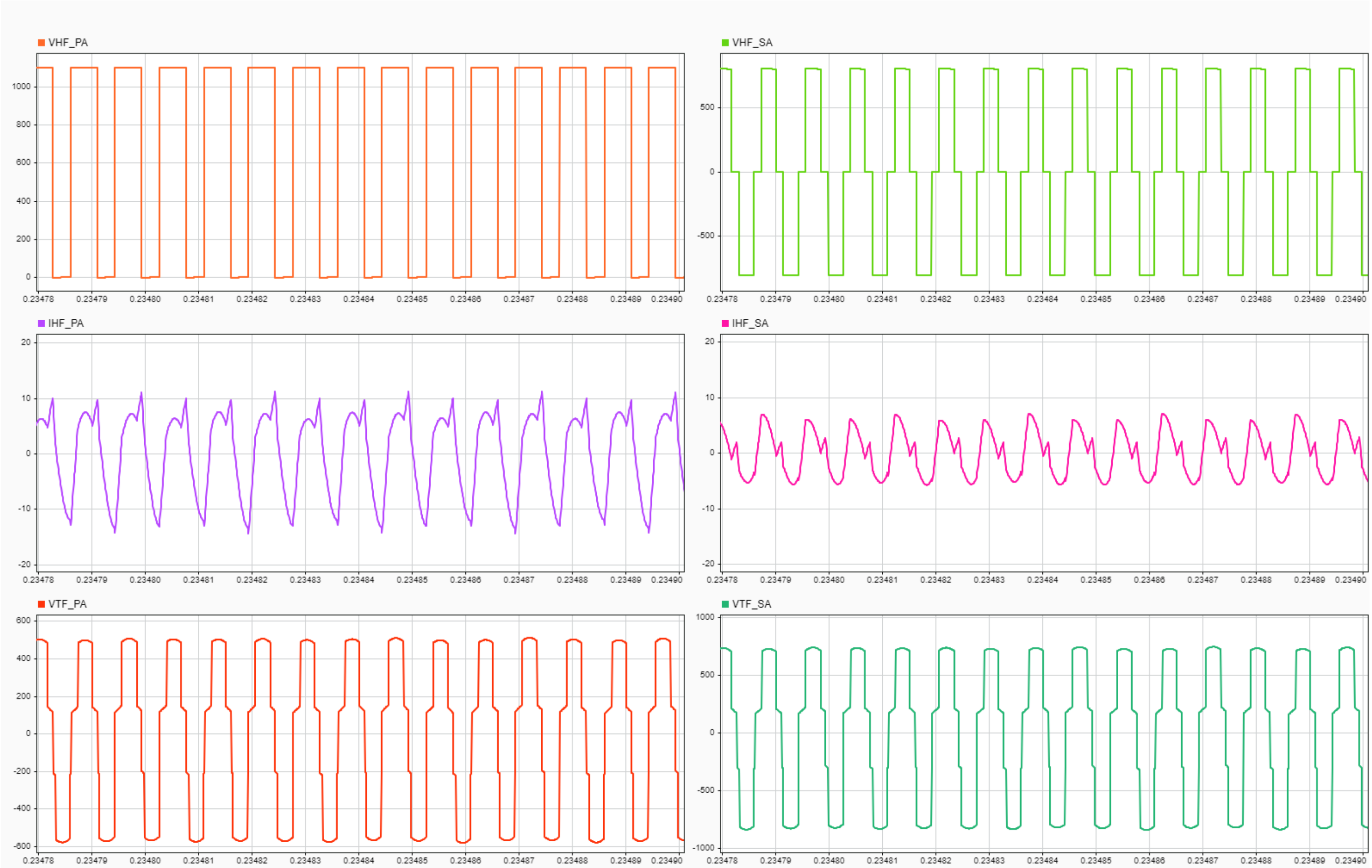
FIG. : CLOSED-LOOP CONTROL BLOCK DIAGRAM



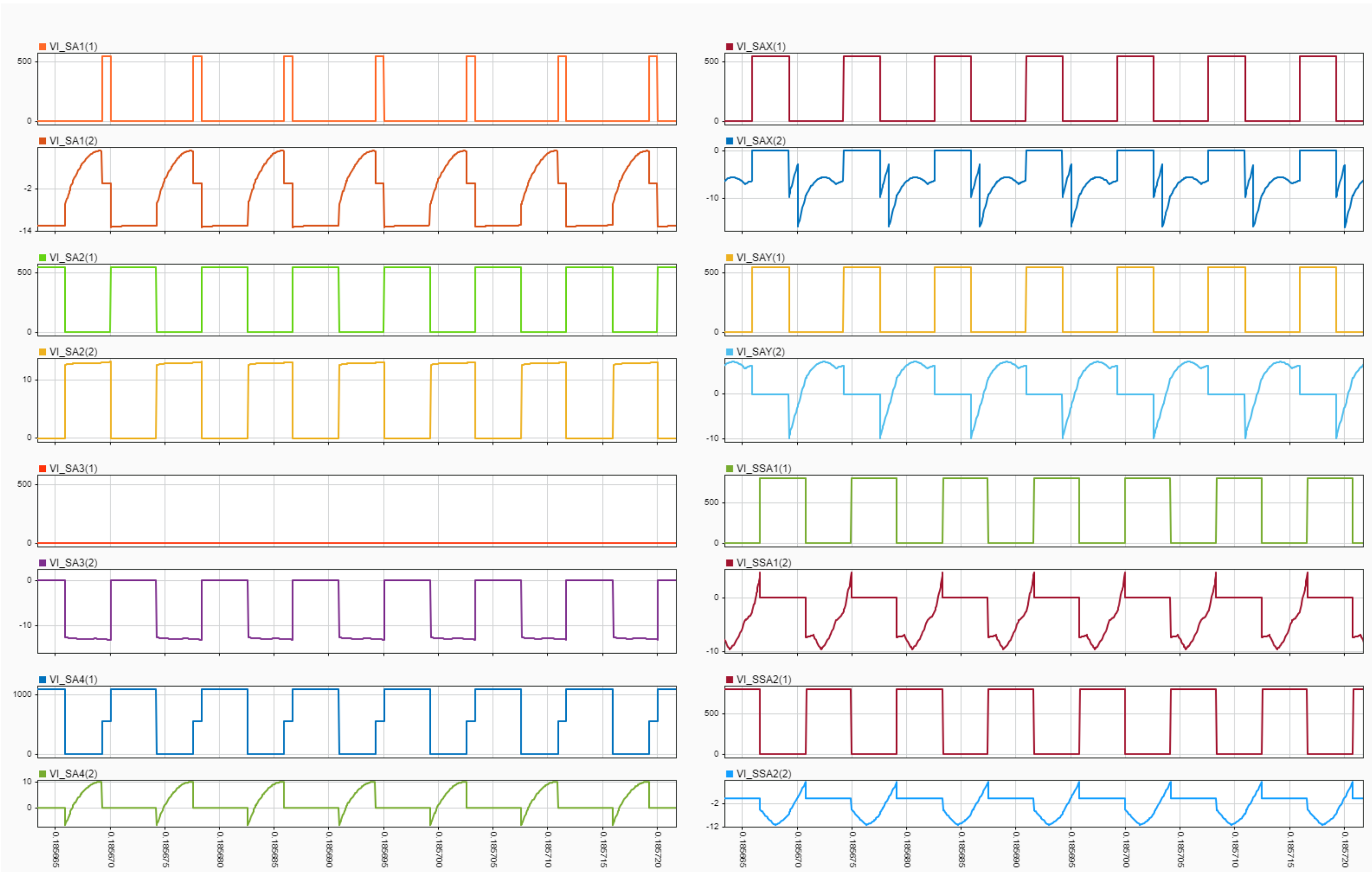
SIMULATION RESULTS







VHF_PA
1000
800
600
400
200
0
VHF_SA
500
0
-500
IHF_PA
20
10
0
-10
-20
IHF_SA
20
10
0
-10
-20
VTF_PA
600
400
200
0
-200
-400
-600
VTF_SA
1000
500
0
-500
-1000
0.23478 0.23479 0.23480 0.23481 0.23482 0.23483 0.23484 0.23485 0.23486 0.23487 0.23488 0.23489 0.23490



VI_SA1(1)
VI_SA1(2)
VI_SA2(1)
VI_SA2(2)
VI_SA3(1)
VI_SA3(2)
VI_SA4(1)
VI_SA4(2)
VI_SAX(1)
VI_SAX(2)
VI_SAY(1)
VI_SAY(2)
VI_SSA1(1)
VI_SSA1(2)
VI_SSA2(1)
VI_SSA2(2)
0.185665 0.185670 0.185675 0.185680 0.185685 0.185690 0.185695 0.185700 0.185705 0.185710 0.185715 0.185720

SWITCH SELECTION

FORMULA USED FOR CALCULATION OF CONDUCTION AND SWITCHING LOSS:

MOSFET conduction losses:

$$P_{CM} = R_{DSon} \cdot I_{Drms}^2 = R_{DSon} \cdot I_o^2 \cdot (\frac{1}{8} + \frac{m_a \cdot \cos\phi 1}{3 \cdot \pi})$$

Diode Conduction losses:

$$P_{CD} = u_{D0} \cdot I_{Fav} + R_D \cdot I_{Frms}^2 = u_{D0} \cdot I_o \cdot (\frac{1}{2 \cdot \pi} - \frac{m_a \cdot \cos\phi 1}{8}) + R_D \cdot I_o^2 \cdot (\frac{1}{8} - \frac{m_a \cdot \cos\phi 1}{3 \cdot \pi})$$

Ud0= Vsd (source to drain voltage) when drain current is zero

Io = Peak value of current

Ma =modulation index

Rdson= drain to source resistance

Rd= diode resistance

cos Ø1= power factor

MOSFET switching losses:

$$P_{sw,T} = \frac{1}{\pi}(E_{on,T} + E_{off,T})\frac{V_{DC}}{V_{DC,test}}\frac{I_p}{I_{test}}f_{sw}$$

DIODE switching losses:

$$P_{sw,D} \approx E_{on,D}f_{sw} = \frac{1}{4}Q_{rr}V_{DC}f_{sw}$$

Eon= turn on loss

Eoff=turn off loss

Vdc= input voltage

Ip= input current

Qrr= reverse recovery charge

Switch Model Number	Manufacturer	Conduction Loss (IN Watt)	Switching Loss (in Watt)	Total Loss (in Watt)
G3R40MT12K	GENESIC	3.733 W	8.3071 W	12.041 W
IMZA120R040M1H	INFINEON	4.357 W	11.47 W	15.825 W
IMZ1Z0R030M1H	INFINEON	5.048 W	16.5 W	21.548 W
NVH4L030N120M3S	ONSEMI	6.71 W	11.835 W	18.545 W
SCT4036KRHR	ROHM	5.605 W	11.63	17.235

SWITCH SELECTED: G3R40MT12K

GATE DRIVER

ACPL W346 is selected as it is suitable for SiC MOSFET and the recommended gate voltage of the switch.

$$R_{DS(ON)} = 40\ m\Omega$$

$$R_g \geq \frac{(V_{CC} - V_{EE})}{I_{OLPEAK}} - R_{DSON}$$

Where $V_{EE} = -5\ V, V_{CC} = 15\ V, I_{OLPEAK} = 2.5\ A.$

$$R_g \geq 7.96\ \Omega$$

POWER SUPPLY GATE DRIVER

MGJ2D051505BSC with 2W power and output voltage of 15/-5V is selected.

DC LINK and OUTPUT CAPACITOR

$$C_O \geq \frac{P_{OUT}}{4\pi f V_O \Delta V_O}$$

- ΔV_O is the Voltage ripple taken as 10% of DC Voltage.
- f is the line frequency.

This implies,

$$C_{DC} \geq 129.68\ \mu F$$

$$C_O \geq 291.78\ \mu F$$

We took,

$$C_{DC} = 315\ \mu F$$

$$C_O = 420\ \mu F$$

$$I_{cap(rms)} = I_{ph(rms)} \sqrt{\left[2M\left\{\frac{\sqrt{3}}{4\pi} + \left(\frac{\sqrt{3}}{\pi} - \frac{9M}{16}\right) cos^2\emptyset\right\}\right]}$$

For DC Link Capacitor,

$$I_{cap(rms)} = 5.9421\ A$$

The capacitor taken is an Aluminium Electrolytic Capacitor with a value of 420uF and a current rating of 2.96 A with 420V. The series combination of 4 capacitors with 3 parallel lines will give the suitable capacitance.

The capacitor selected is EKHJ421VSN421MR51M.

Similarly, series combination of 3 capacitors and 3 parallel lines will give suitable capacitance for the output capacitor.

SNUBBER CAPACITOR

R53BI31505000K WITH 0.15uF.

RESONANT CAPACITANCE

Cr1=32.145nF, 1000V

R76UN233050H4J is selected for the purpose. Its rating is 33nF and 1000V. The combination of 2 series and 4 parallel lines for each terminal will give equivalent Cr1. The current rating of each capacitor is 4.6 A. So, it is suitable for the resonant current.

R76QI218050H4J is selected for the purpose. Its rating is 18nF and 1000V. The combination of 2 series and 4 parallel lines for each terminal will give equivalent Cr2. The current rating of each capacitor is 2.93 A. So, it is suitable for the resonant current.

HEAT SINK

- Power Loss in one switch is 12.041W.
- We will place 3 switches in one heat sink.
- Total power loss will be 3*12.041=36.123 W.
- Ambient temperature T_A is taken as 35°C.
- Junction temperature T_J is taken as 150°C.
- Heat flow equation is $P_{LOSS} = \frac{T_J - T_A}{R_{JA}}$
- R_{JA} is the equivalent thermal resistance between the junction and the ambient.
- We must calculate R_{JH}.
- Junction to heatsink thermal resistance R_{JH} of MOSFET is 0.66 k/w.
- Equivalent R_{JA} is 4.77535 K/W.
- Equivalent Junction to Heatsink thermal resistance R_{JH} is calculated by the equivalent parallel of all the thermal resistances of MOSFET.
- It is calculated as 0.22 K/W.
- Equivalent Heatsink to Ambient Thermal Resistance R_{HA} = 4.77535-0.22 = 4.55535 K/W.
- CR-201-75E has been selected. It has a thermal resistance of 2.6 K/W.

AC PFC INDUCTOR

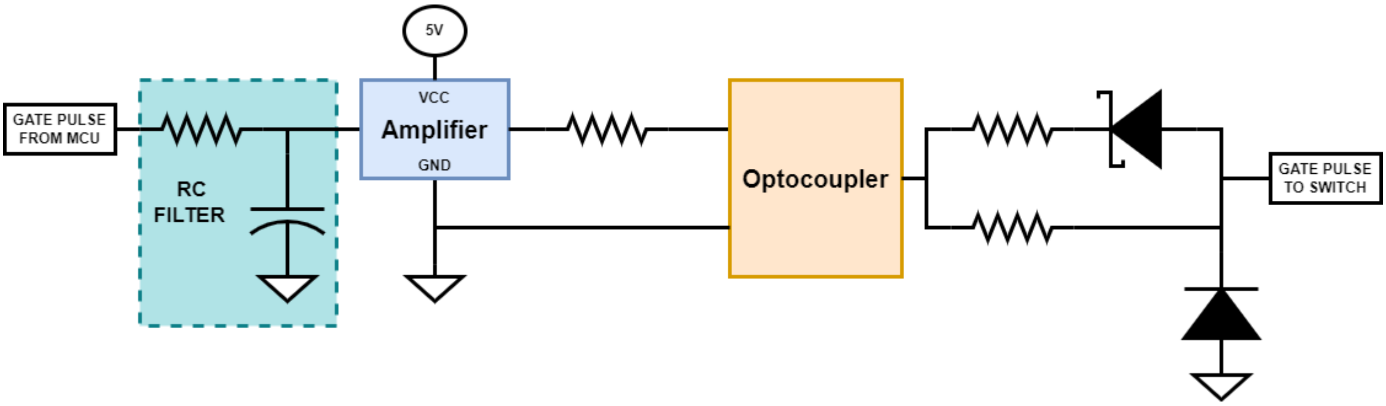
- The calculated value of inductance is 882 μH.
- The current rating should be more than 1.5 times the peak line current.
- The selected inductor is B82747S6313N061.
- It is a power line choke with 3 winding on a single toroid core.
- The rating is 950uH, 31A, 250VAC.

Point to discuss:

- Loop Inductance of Gate Signal
- Heat sink
- DC Link Capacitor

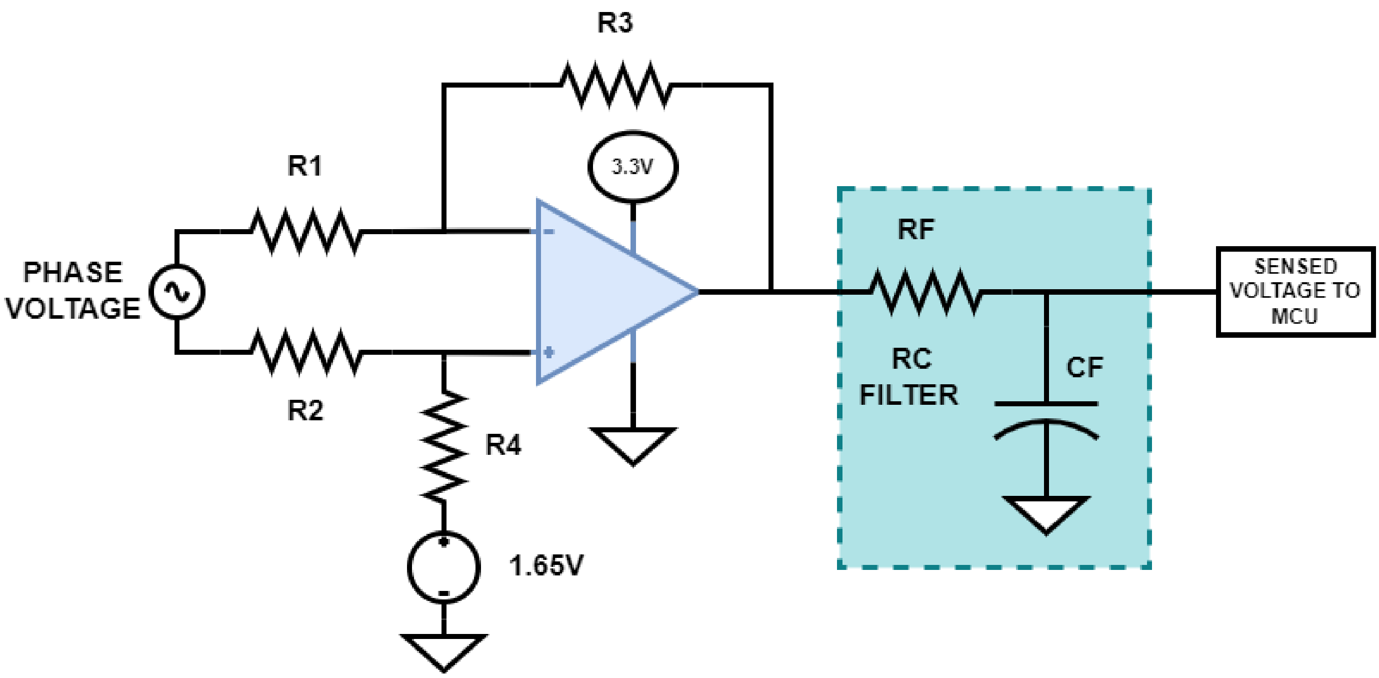
SCHEMATIC DIAGRAMS

GATE DRIVER



- Reference from Texas Instruments.
- The track length between the Optocoupler and the Gate terminal is 15 mm.
- MCU generates a Gate Pulse of 0/3V.
- RC filter is used to filter the noise.
- An amplifier generates 0/5V and is compatible with an optocoupler.
- Optocoupler ACPL-W346 is used which is compatible with SiC-MOSFET.
- Gate Resistance for the forward path is taken as 15 ohms.
- 20 ohms resistance in series with antiparallel Schottky diode is taken. It will make a net backward gate resistance of 8.57 ohms.
- An antiparallel Zener diode is connected between the gate and the ground to avoid over-voltage across the gate.
- A DC/DC converter MGJ2D051505BSC with 2W, 5V to 15V/-5V supplies the optocoupler.
- A PCB consists of 6 gate driver circuits to provide gate pulses for each leg.

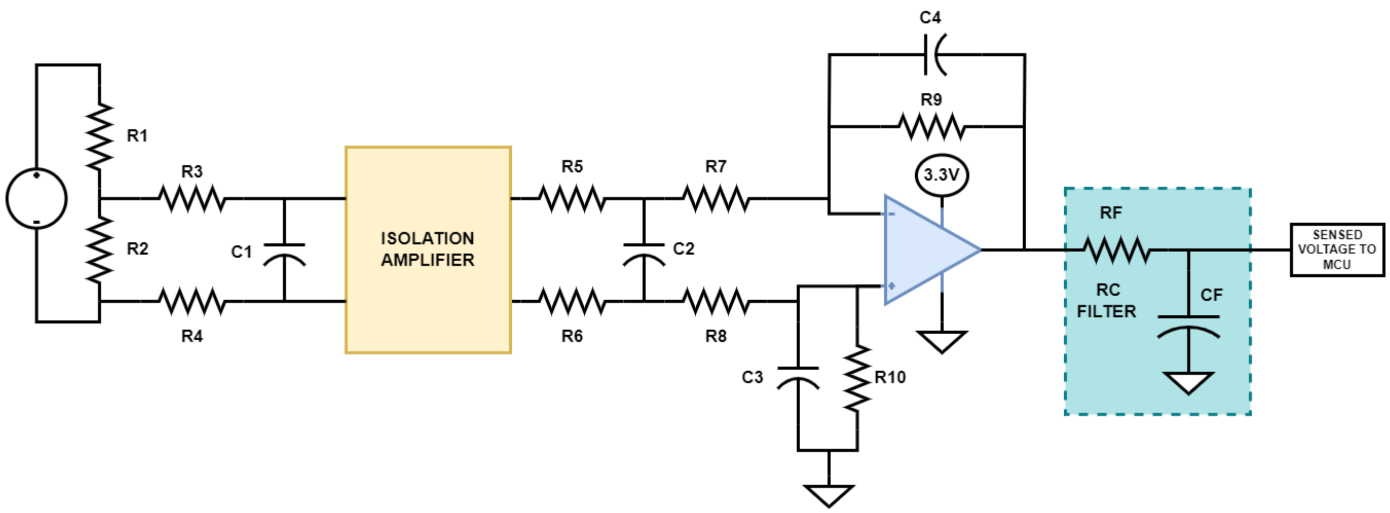
AC VOLTAGE SENSOR



- Differential Gain OPAMP Circuit is used to sense the phase voltages.
- Phase Voltage is fed to the resistor divider circuit to step down the voltage.
- A offset of 1.65V will make the voltage within the range of MCU.

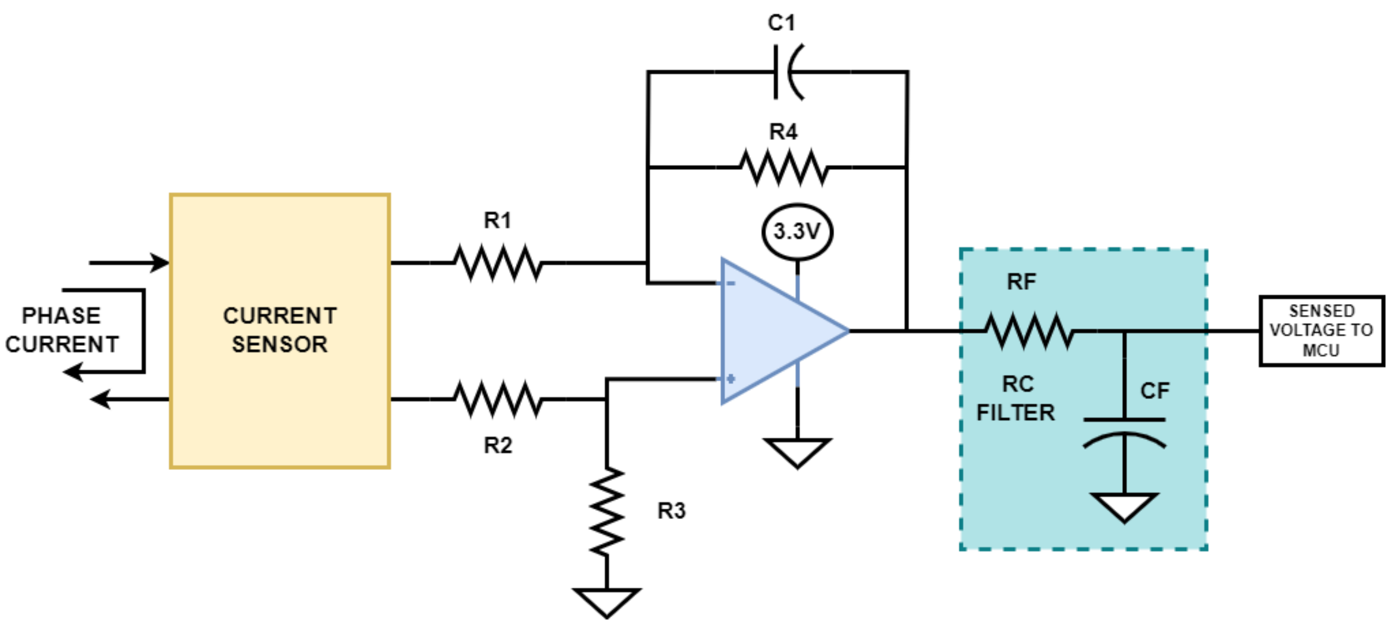
- The gain of the sensor circuit is R3/R1.
- Here, R1=R2 and R3=R4.
- A PCB will consist of sensor circuit for all three phases.
- High voltage side is placed on MAIN BOARD.
- Low voltage side is placed on AC VOLTAGE SENSOR PCB.

DC VOLTAGE SENSOR



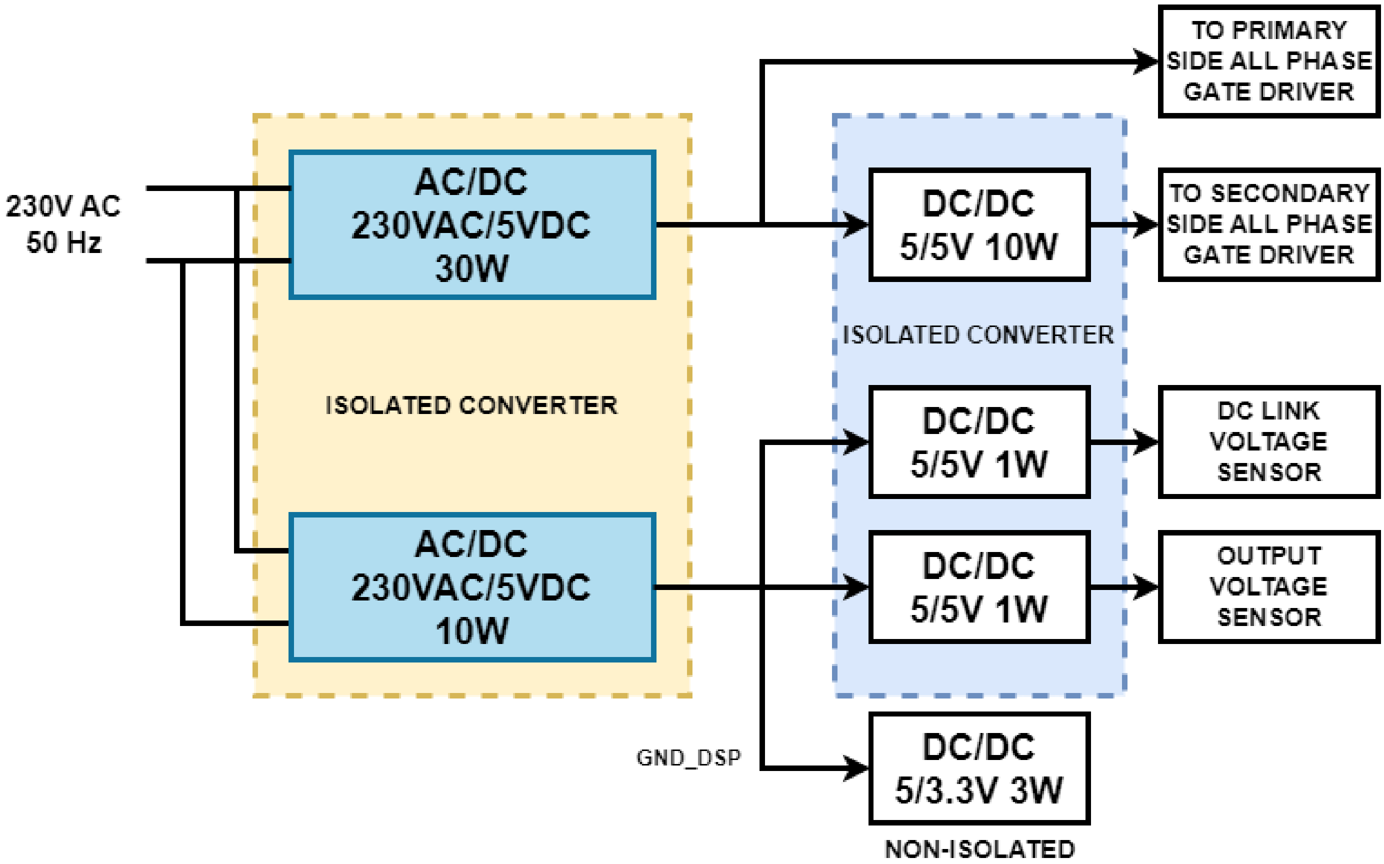
- R1 and R2 form the resistor divider circuit.
- R3, R4 and C1 forms RC filter circuit.
- An isolation amplifier AMC 1311 isolates the DC Link side from MCU ground.
- Opamp amplifies the signal to the required range of 0/3V.
- Signal is filtered using an RC circuit and fed into MCU.
- The cutoff frequency of filter 1 is 200kHz.
- The cutoff frequency of filter 2 is 1.7 kHz.
- The cutoff frequency of filter 3 is 15 kHz.

CURRENT SENSOR



- Hall effect-based Current Sensor is used.
- Sensor IC connects in series with phase track.
- The output voltage corresponds to the input current generated by the sensor.
- The voltage is filtered out and clamped up to make it in the range MCU.

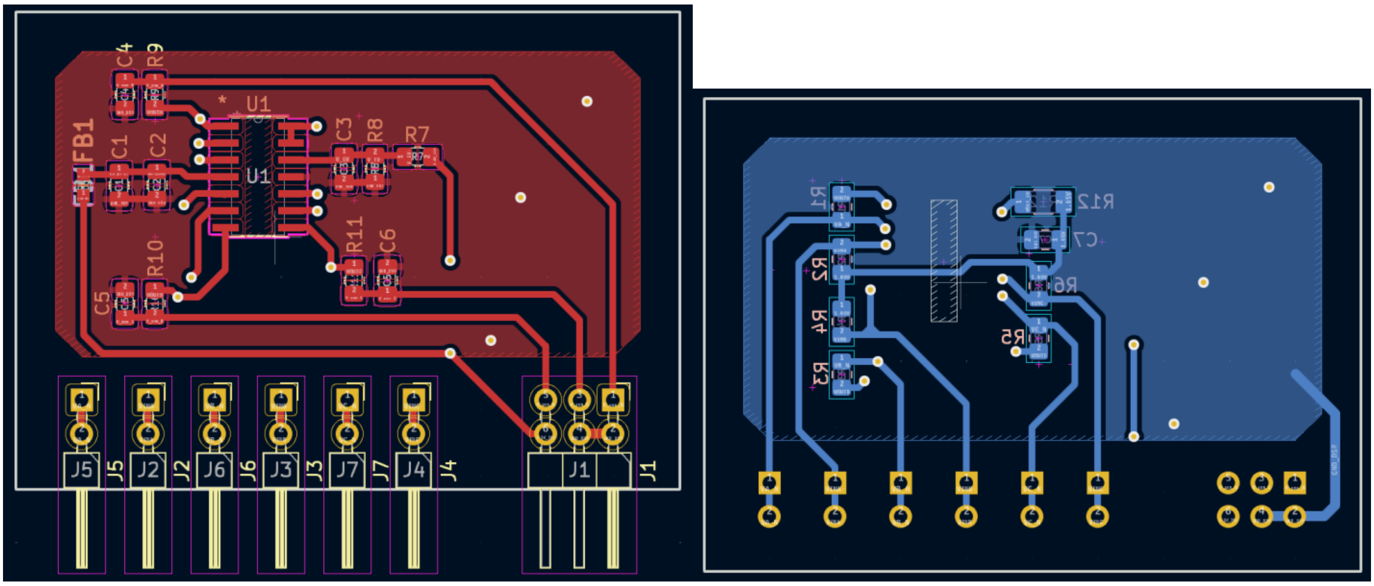
AUXILIARY POWER SUPPLY



- RACM30-055K/277W is used to provide 230VAC to 5V with 30W rating.
- RAC10E-05SK/277 is used to provide 230VAC to 5V with 10W rating.
- This 5V will supply all the sensors with respect to GND_DSP.
- A non-isolated DC/DC converter will generate the 3.3V required by the sensors.
- The 5V terminal has isolated ground and will supply every gate driver's secondary circuit.

PCB FOOTPRINT

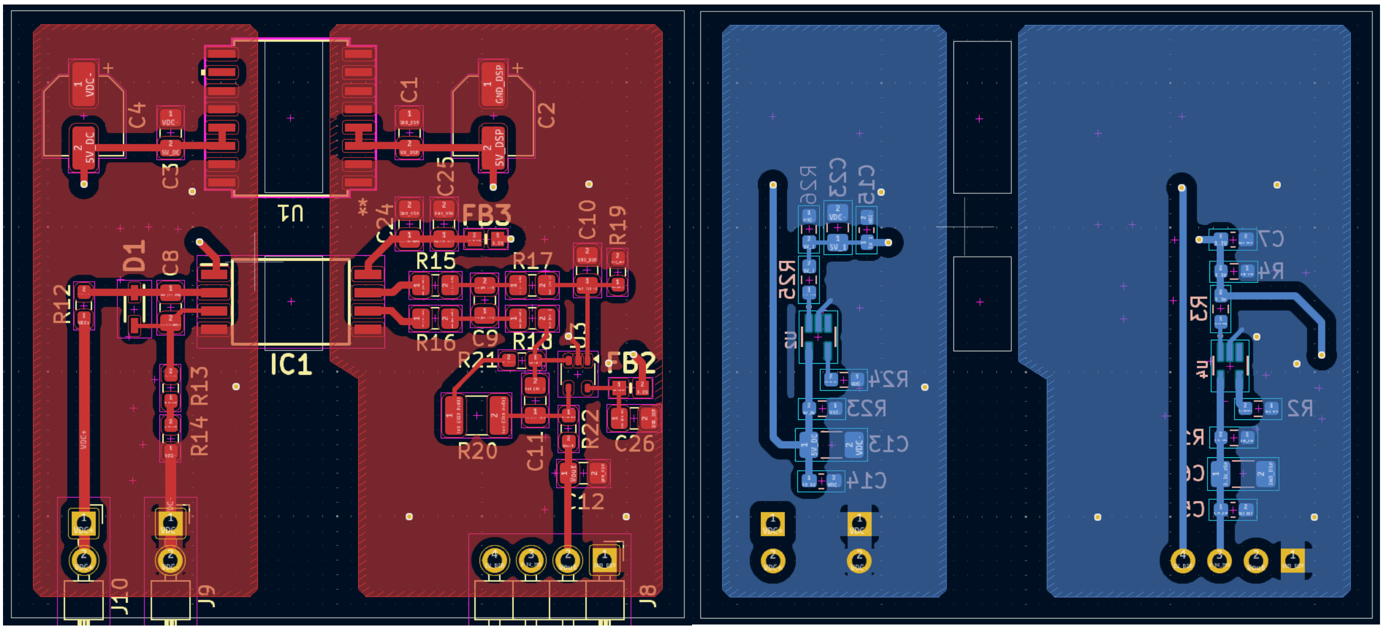
AC VOLTAGE SENSOR



DIMENSION: 50MM*36MM

TERMINAL DISTANCE: 5MM

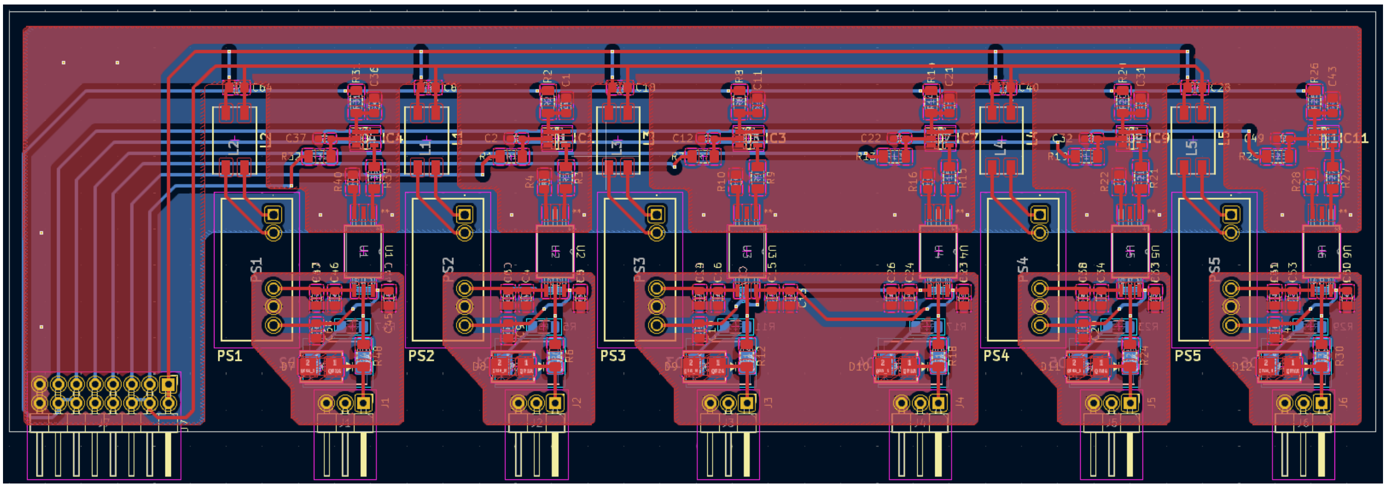
DC VOLTAGE SENSOR



DIMENSION: 49MM*52MM

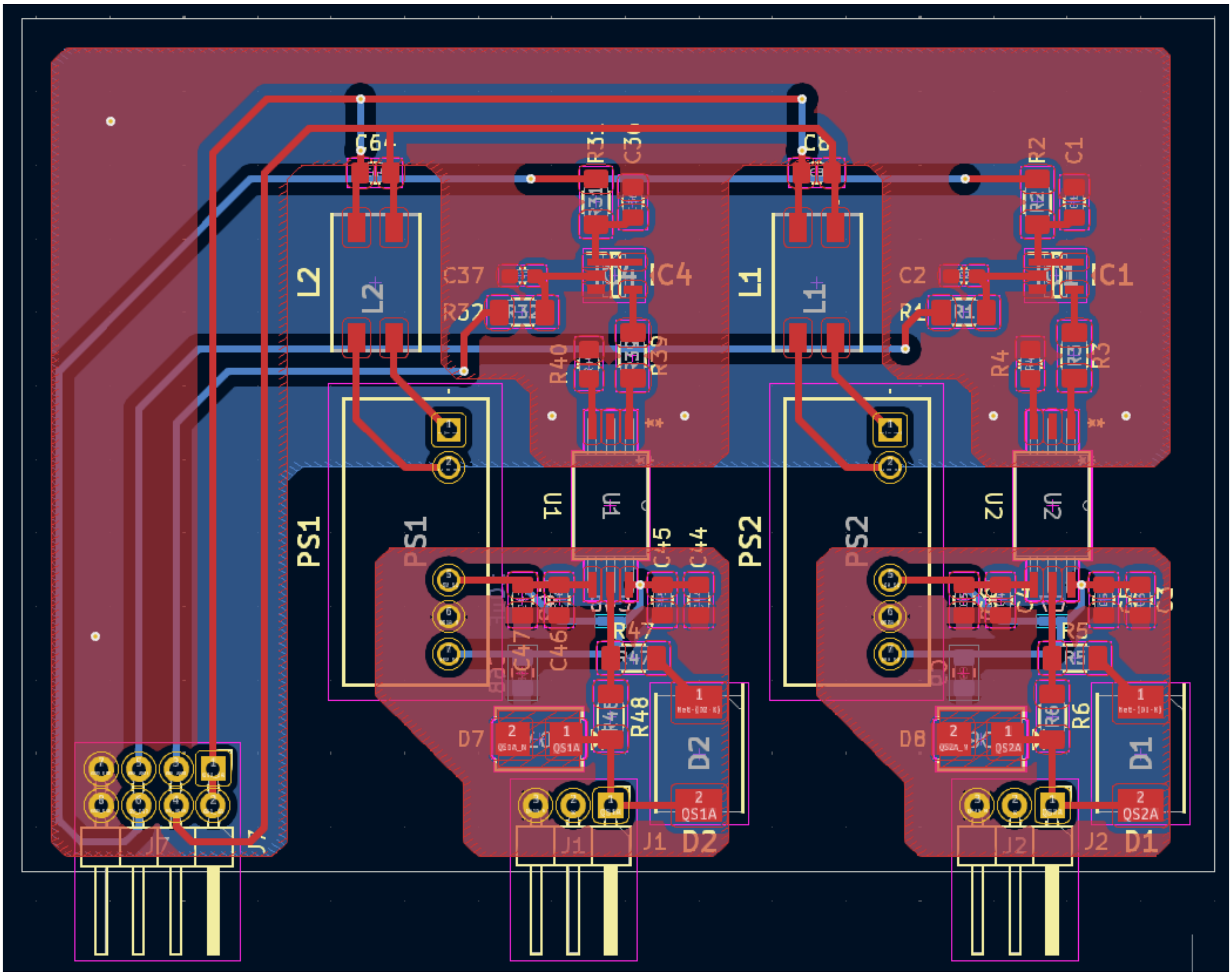
TERMINAL DISTANCE: 10MM

GATE DRIVER

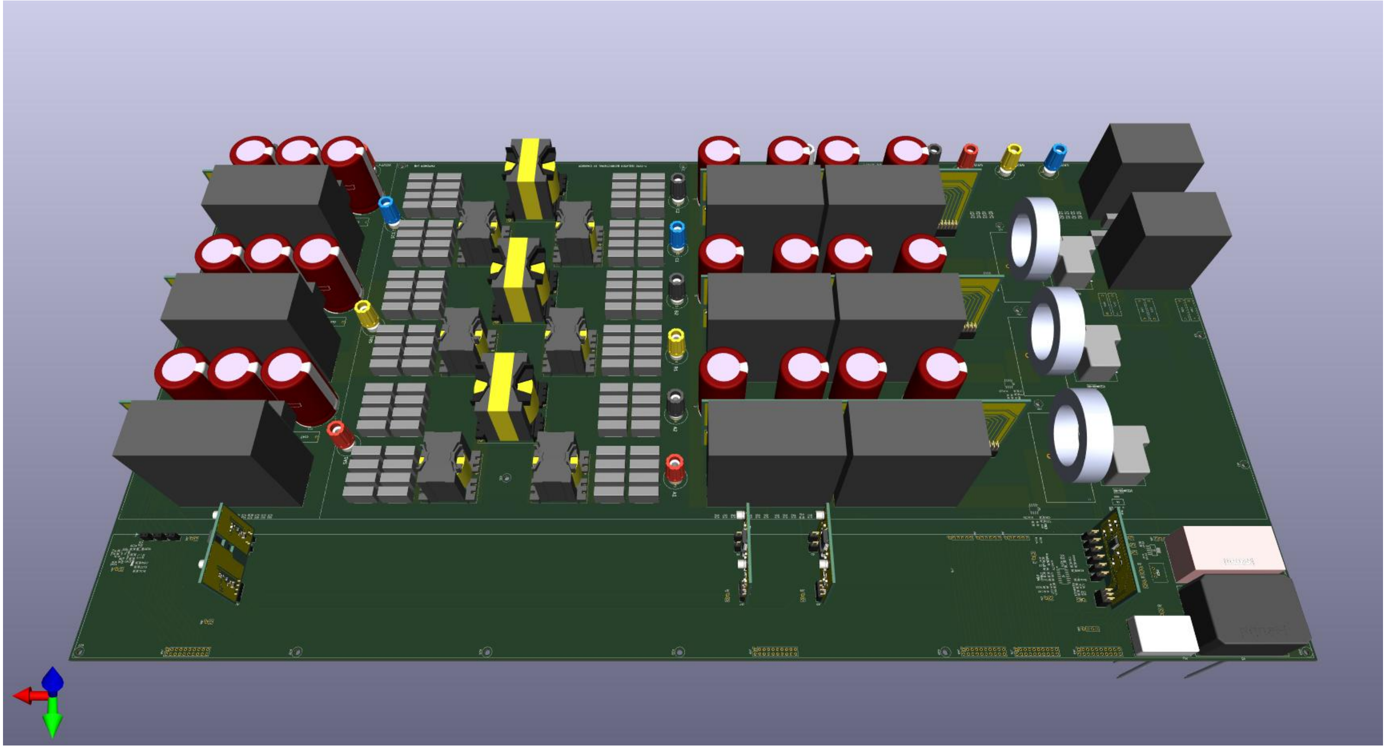


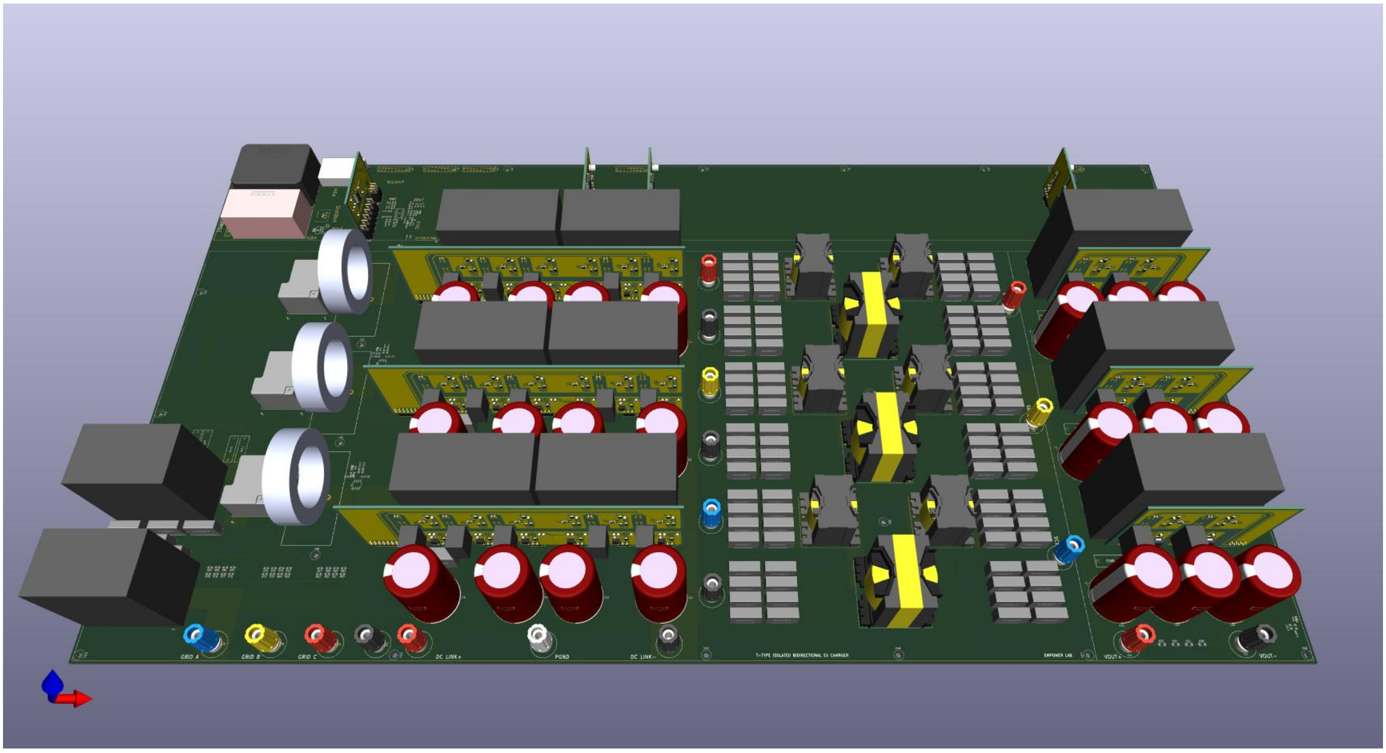
DIMENSION: 189MM*58MM

TERMINAL DISTANCE: 26.5MM



DIMENSION: 81MM*58MM




GRID A
GRID B
GRID C
DC LINK+
PGND
DC LINK-
T-TYPE ISOLATED BIDIRECTIONAL EV CHARGER
EMPOWER LAB
VOUT+
VOUT-

Discussion Points:

1. EMI filter placement on the Main Board.
2. HF transformer terminal.
3. RC filter in ADC terminal
   - Simulation done in the LTSpice.
   - Output is coming correct with the suitable RC filter.
4. FRC cable placement.
5. CCS coding.