IFEC 22

SMART, EFFICIENT AND LIGHT SOLAR MICROGRID INVERTER

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University of Moratuwa, Sri Lanka

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Team UOM

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PROJECT INTRODUCTION

SMART, EFFICIENT AND LIGHT SOLAR MICROGRID INVERTER

IMPLEMENTATION PROGRESS

PROGRESS

Phase 1
Literature Review and Simulation

Phase 2
Detailed Design

Phase 3
Low voltage low power hardware implementation

NEXT STEPS

Phase 4
High voltage low power testing

Phase 5
High voltage high power testing

Phase 6
Final design

PROGRESS UP TO NOW

Phase 1

Literature review and simulation

- Literature review on achieving goals
- Deciding on topologies and design aspects
- Simulating the inverter design (Spice software)
- Evaluating the performance and doing the required changes
- Finalizing the design

Phase 2

Detailed design

- Delegating work among team members
- Identifying components for physical implementation
- Research and obtaining ideas on circuit function, control algorithm and circuit behaviour
- Implementation of the detailed design

Phase 3

Low voltage low power hardware implementation

- Research and components selection
- Finalizing schematics and design PCBs for low voltage low power testing
- Sending the PCB for manufacturing
- Converting the simulated control algorithmm for the c2000 eval board
- Soldering and assembling PCBs
- Testing and combining all the modules

SPECIFICATIONS

Parameter	Specification	Realization in Simulation
Input Voltage	36V - 60V DC (48 V Nominal)	36V - 60V DC (48 V Nominal)
Input Current	20A with ripple <10%	20A with ripple <10%
Output Voltage	Single Phase - 120V ~ 230V AC Three Phase - 208V ~ 260V AC	Three Phase - 230V AC
Grid Frequency	40-65 Hz	57 Hz - 62 Hz
Output Power	Maximum of 1 kW	Required Active Power Delivery with frequency achieved
Total Harmonic Distortion	<2% at 1 kW	<0.1% at 1 kW
Power Factor	>0.99 at 1 kW	0.9980 at 1 kW
Efficiency	>95% at 1 kW >94% at 500 W	96.61% at 1 kW 97% at 500W

IMPLEMENTATION PROGRESS

PROGRESS

Phase 1
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Detailed design

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Low Voltage Low Power Hardware Implementation

NEXT STEPS

Phase 4
High Voltage Low Power Hardware Implementation

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High Voltage High Power Hardware Implementation

Phase 6
Final Design

NEXT STEPS

Phase 4

High voltage low power testing

- Increasing the voltage and testing the circuit behaviour
- Validating design and control changes
- Applying necessary changes

Phase 5

High voltage high power testing

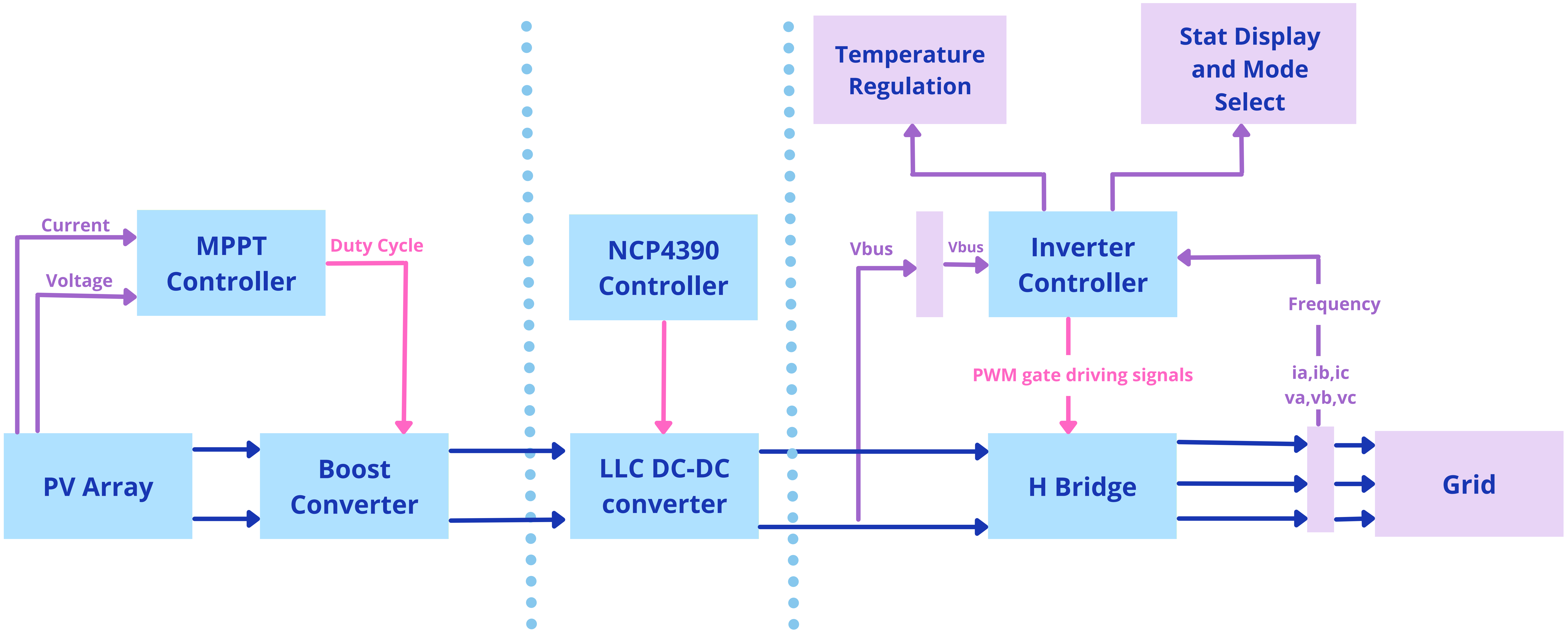
- Testing the circuit at high voltage and high power conditions
- Evaluating the performance
- Tune the system parameters to achieve necessary performance

Phase 6

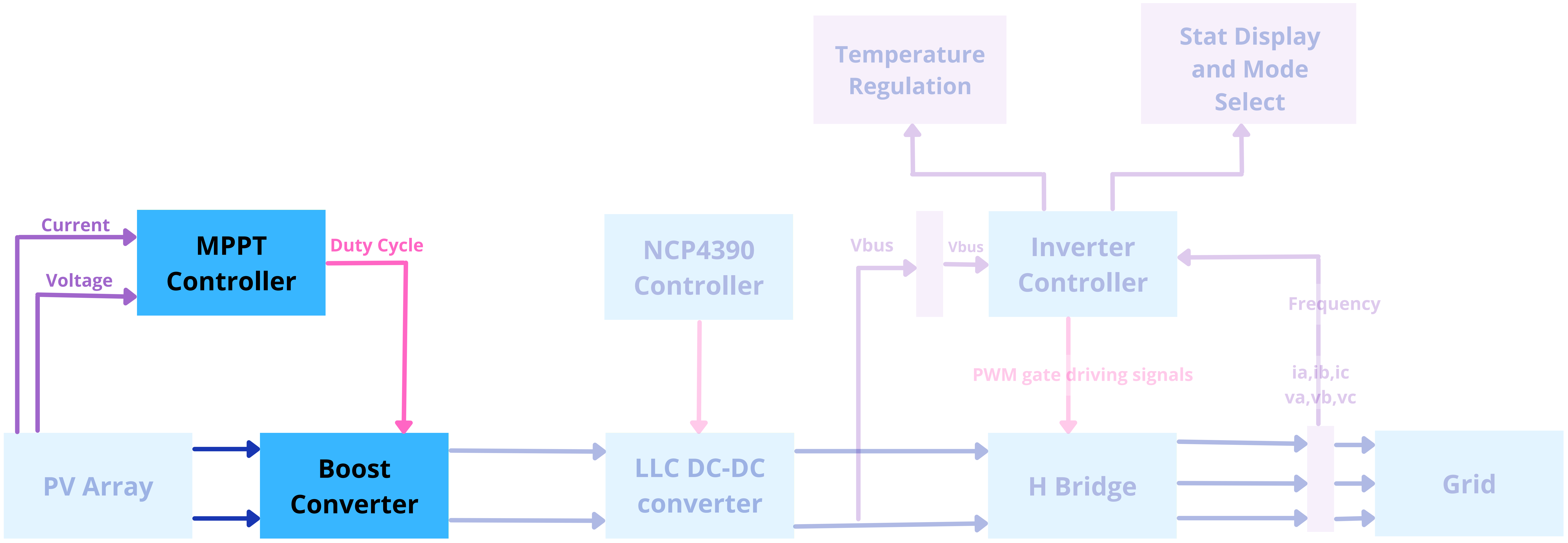
Final design

- Integrating all modules to one board
- Designing the schematics/ PCBs
- Sending the PCB for manufacturing
- Assembling the PCB
- Testing and tuning the system parameters
- Final design

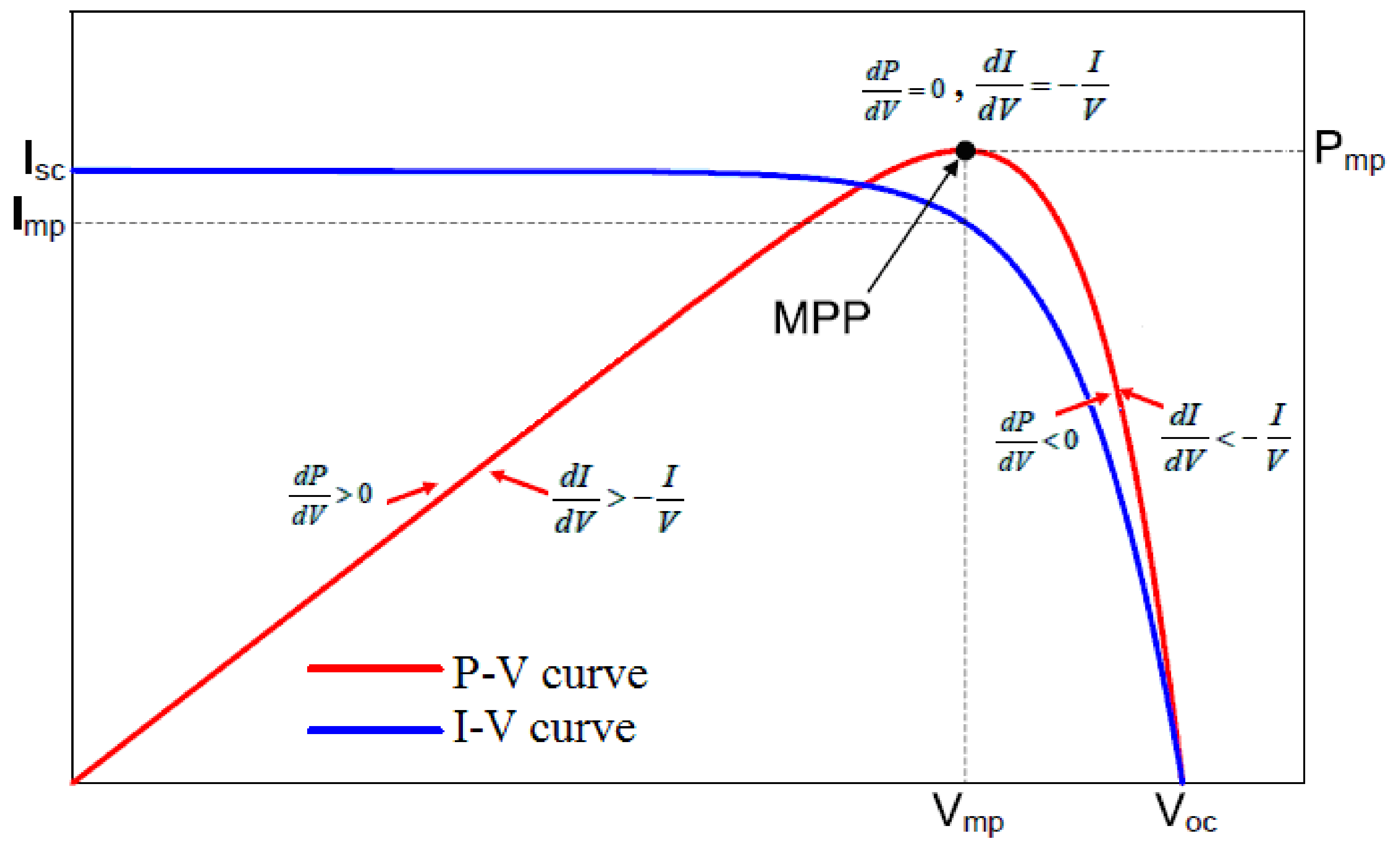
HIGH LEVEL BLOCK DIAGRAM



BOOST CONVERTER AND MPPT



MAXIMUM POWER POINT TRACKING



The voltage and current of a solar array vary with the

- Temperature
- Irradiance

of the environment.

Therefore continuous tracking of the maximum power point is needed for efficient power generation.

Incremental Conductance Algorithm is implemented on C2000 Dual-core microcontroller by Texas Instruments with reference to the following design guide.

Incremental conductance algorithm is proposed to track the MPP for a PV module under a fast-changing solar irradiation level.

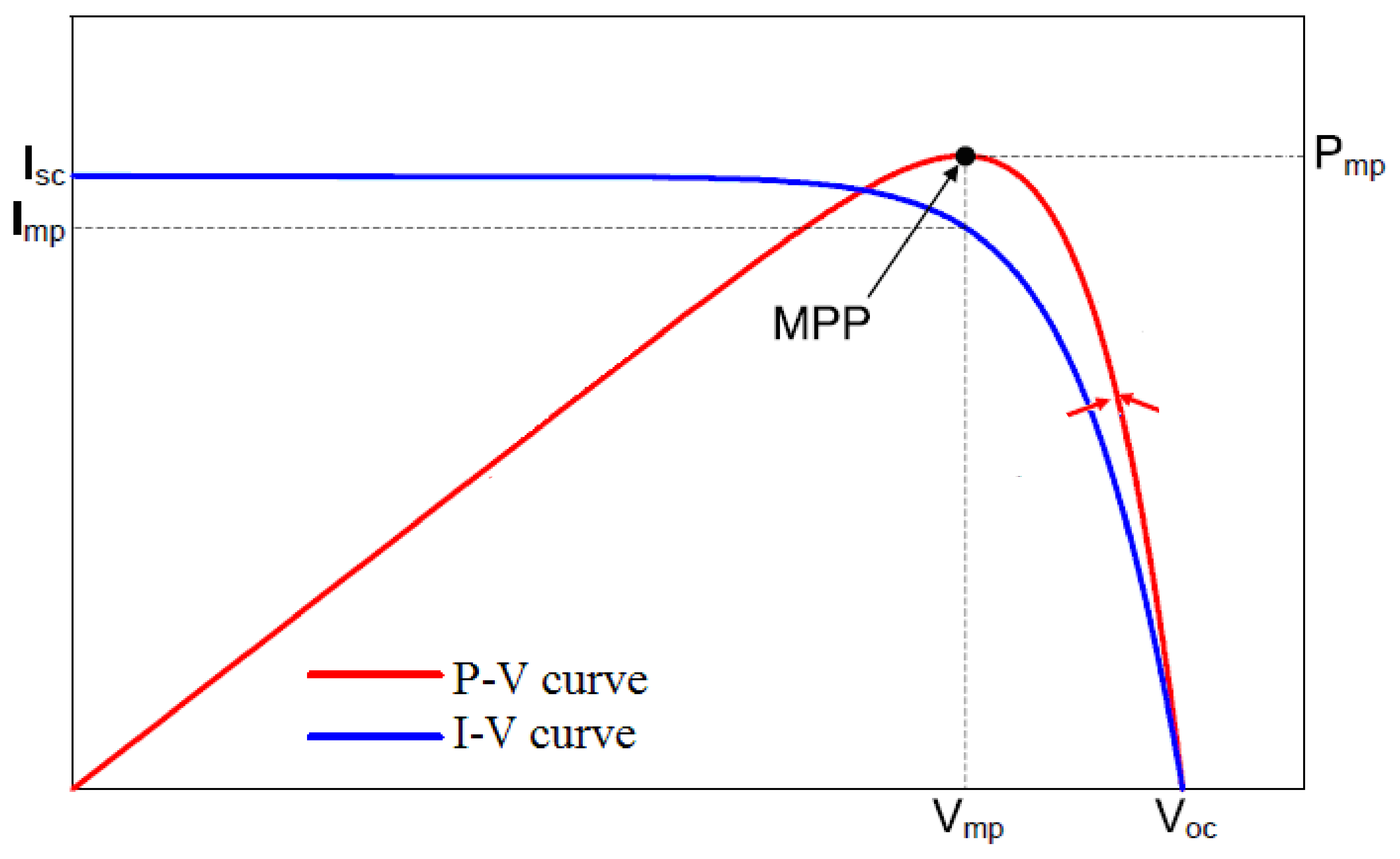
Shang, L., Guo, H. & Zhu, W. An improved MPPT control strategy based on incremental conductance algorithm. Prot Control Mod Power Syst 5, 14 (2020).

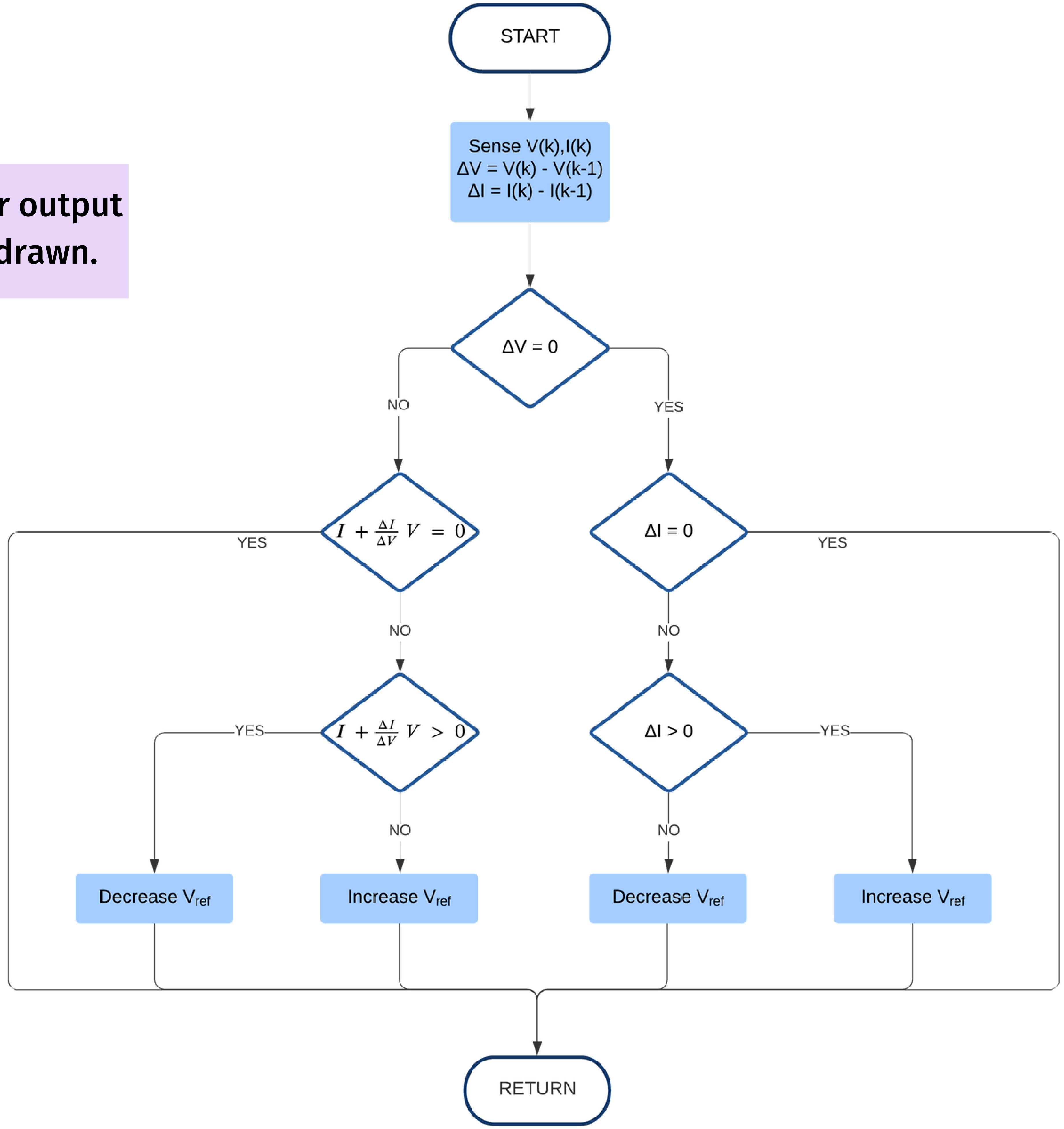
INC ALGORITHM

Analyzes the power output with the voltage drawn.

$$P = VI$$

$$\frac{\Delta P}{\Delta V} = I + V\frac{\Delta I}{\Delta V}$$





INC ALGORITHM

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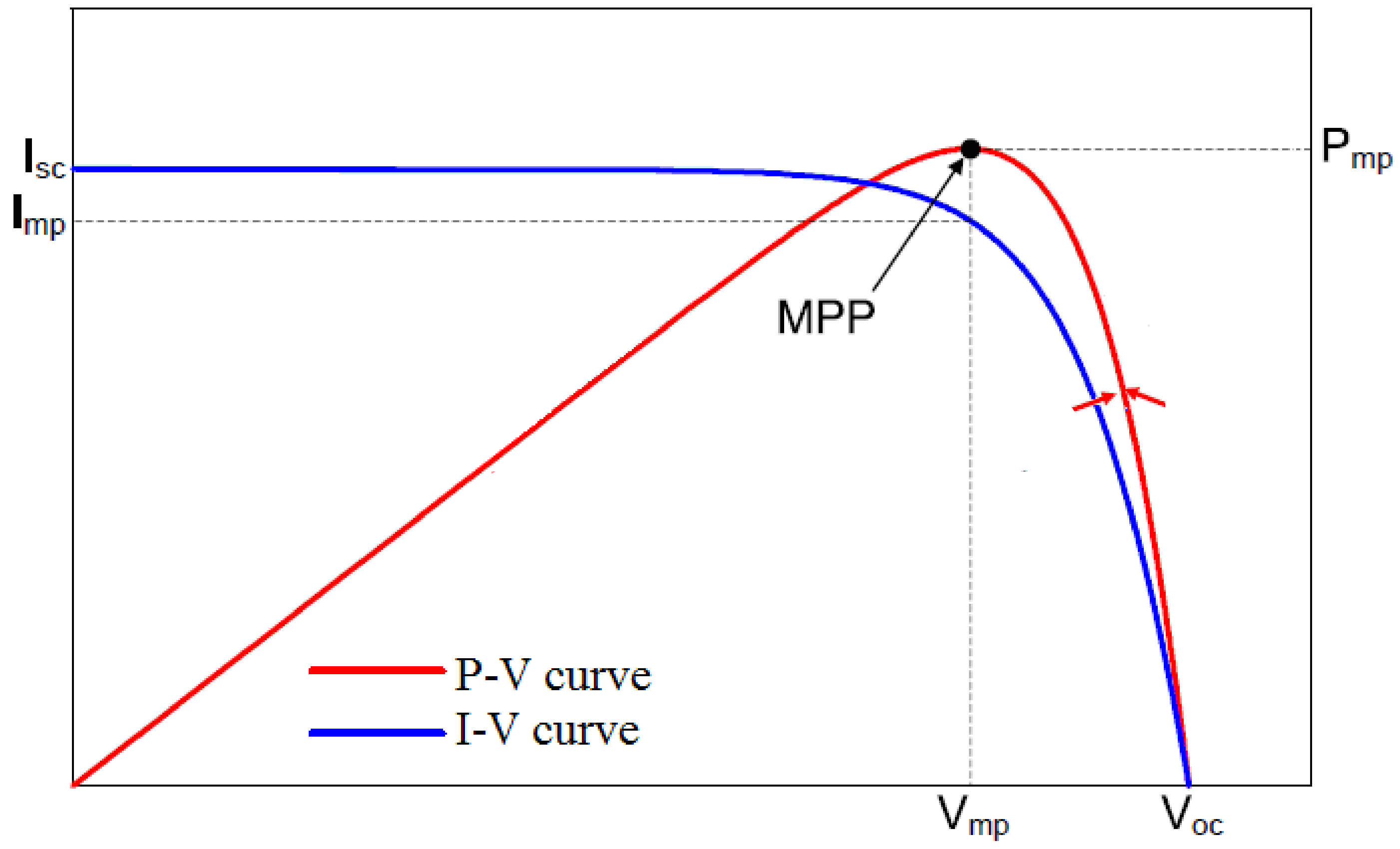
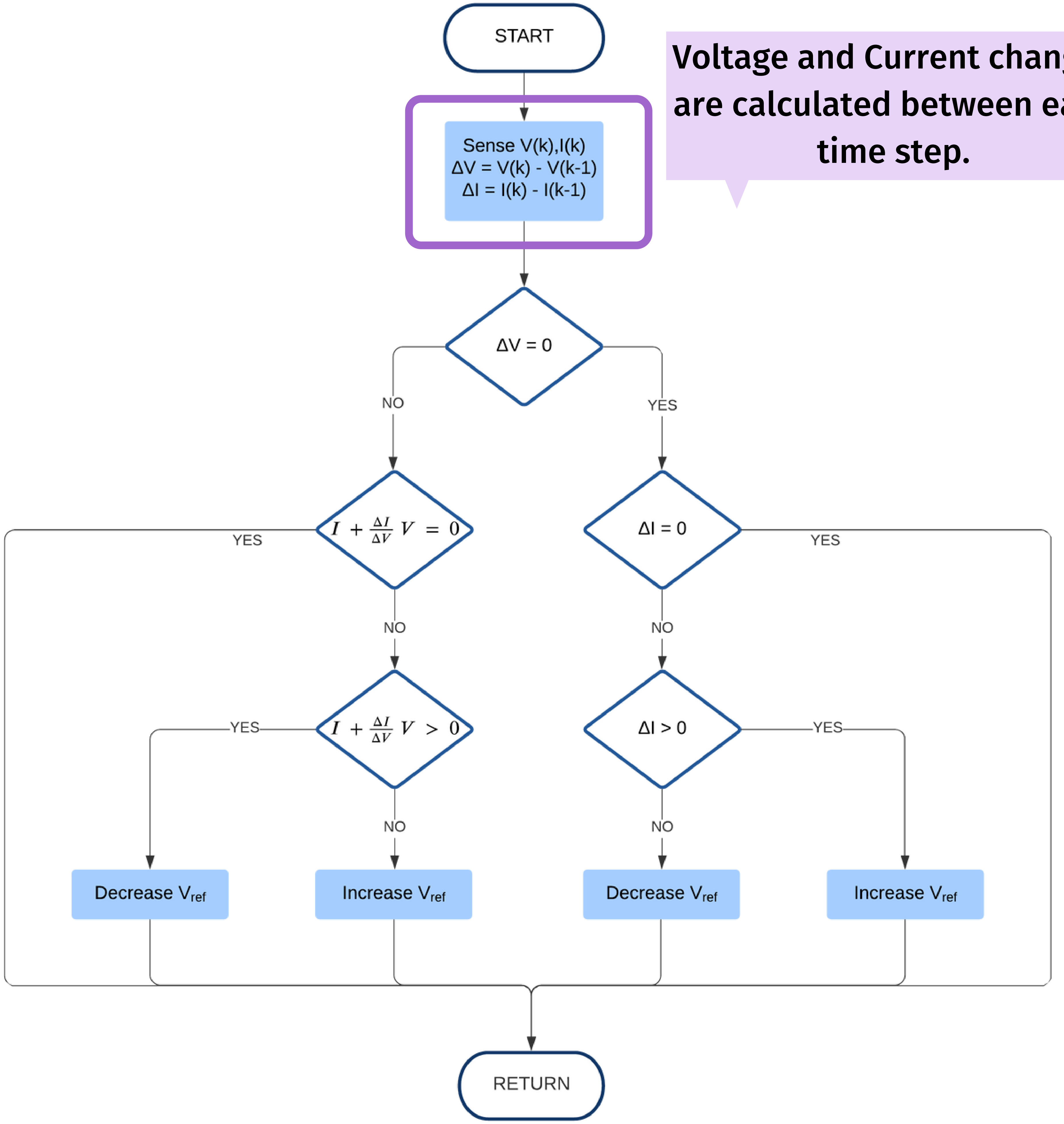


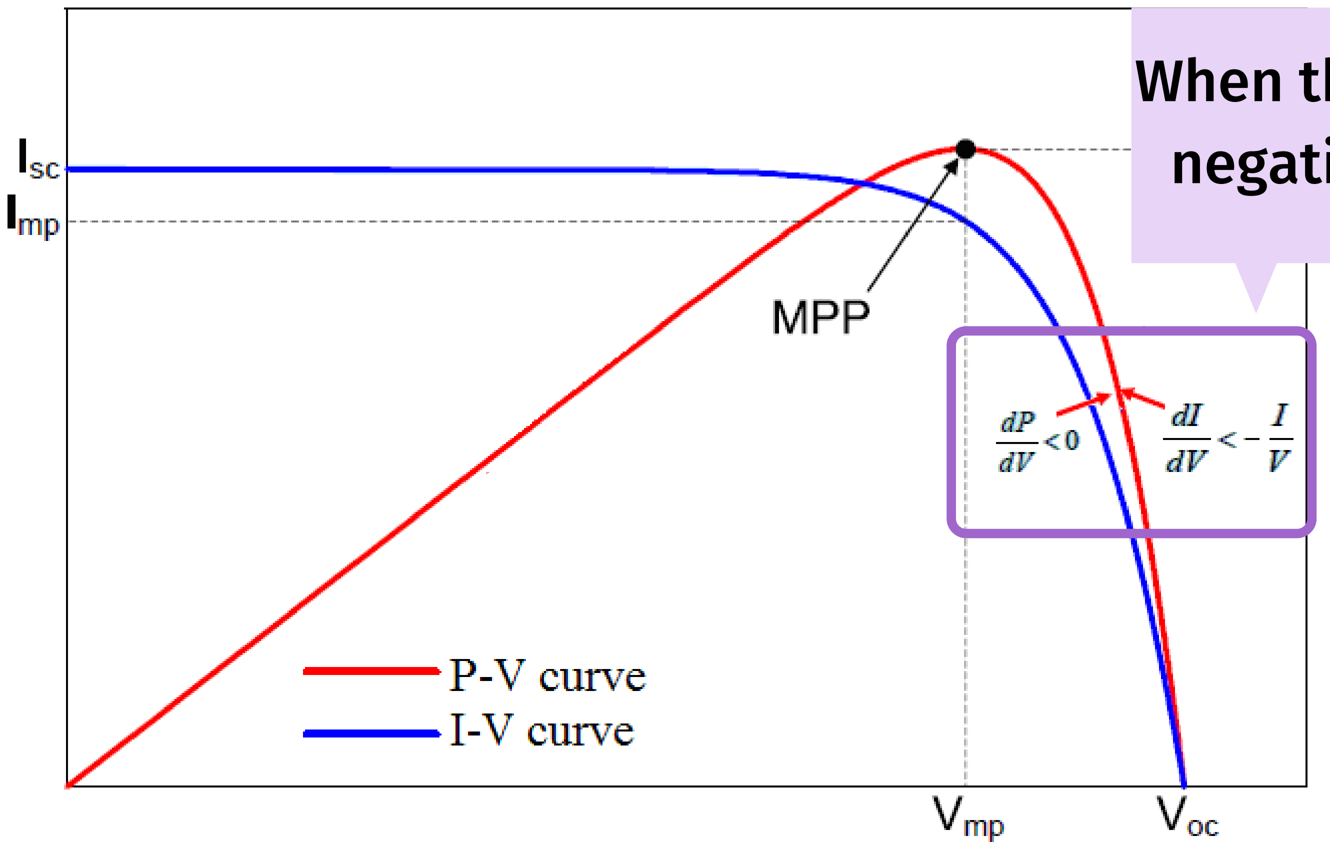


Voltage and Current changes are calculated between each time step.

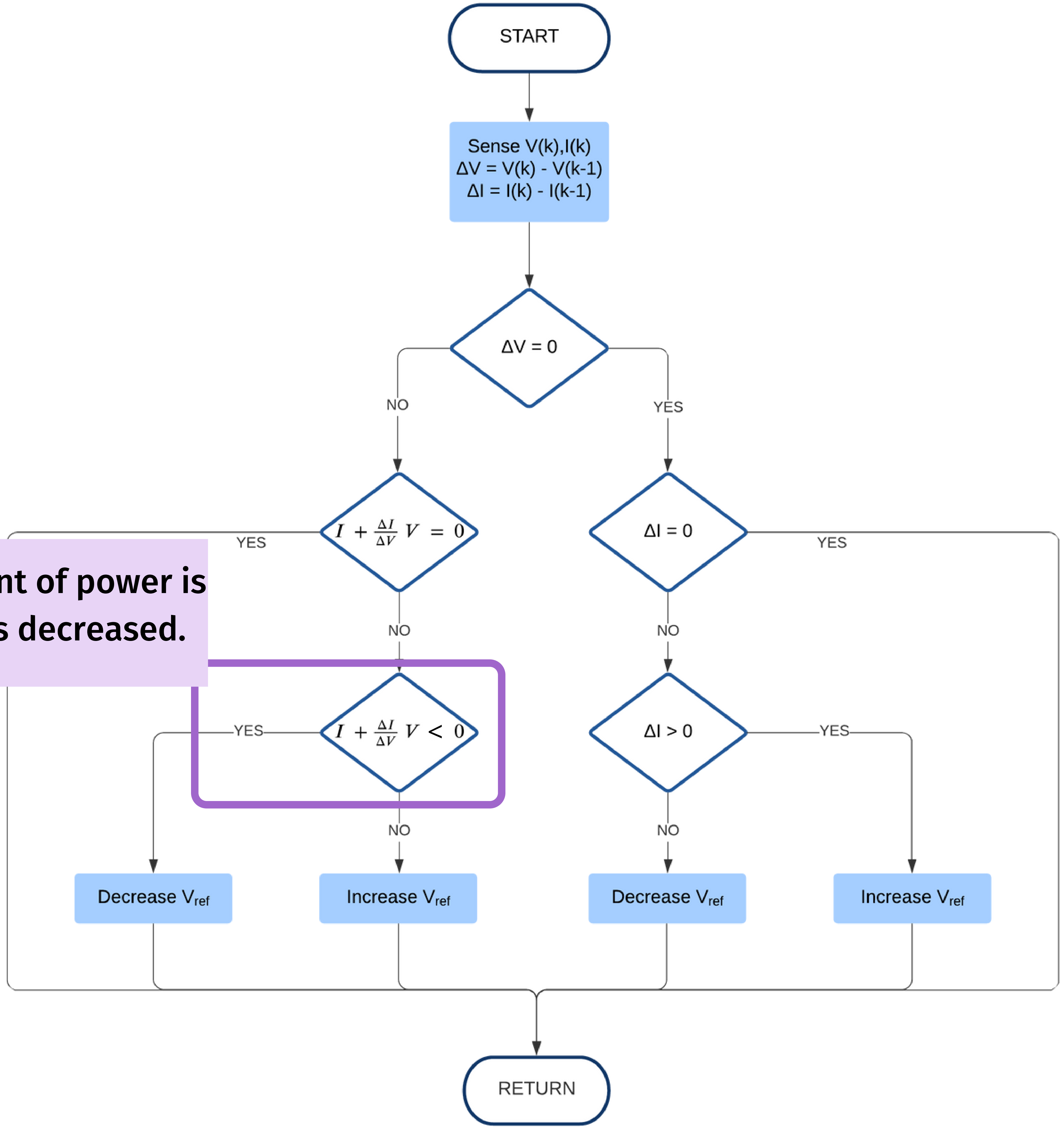
INC ALGORITHM

$$P = VI$$

$$\frac{\Delta P}{\Delta V} = I + V\frac{\Delta I}{\Delta V}$$



When the gradient of power is negative, Vref is decreased.

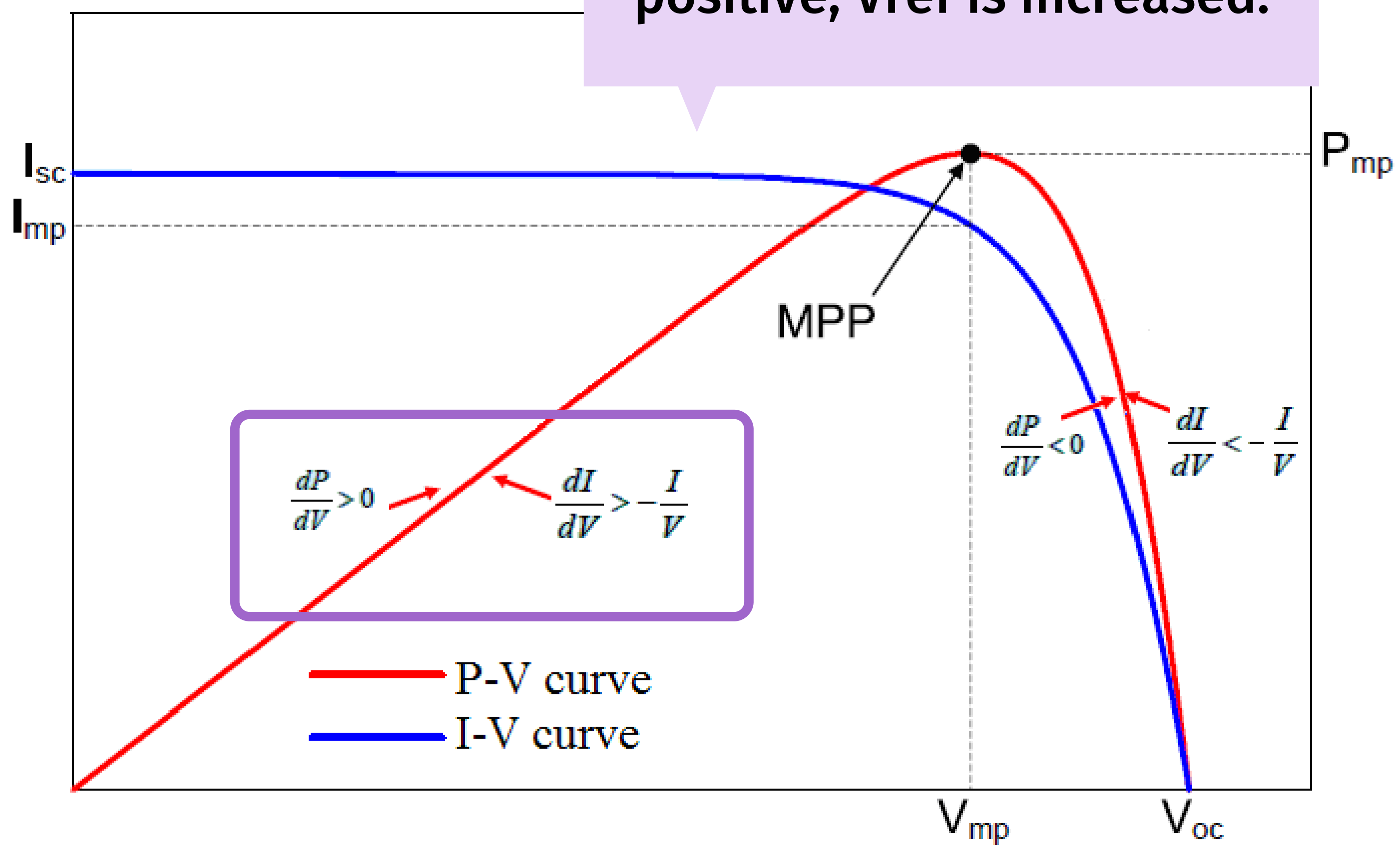


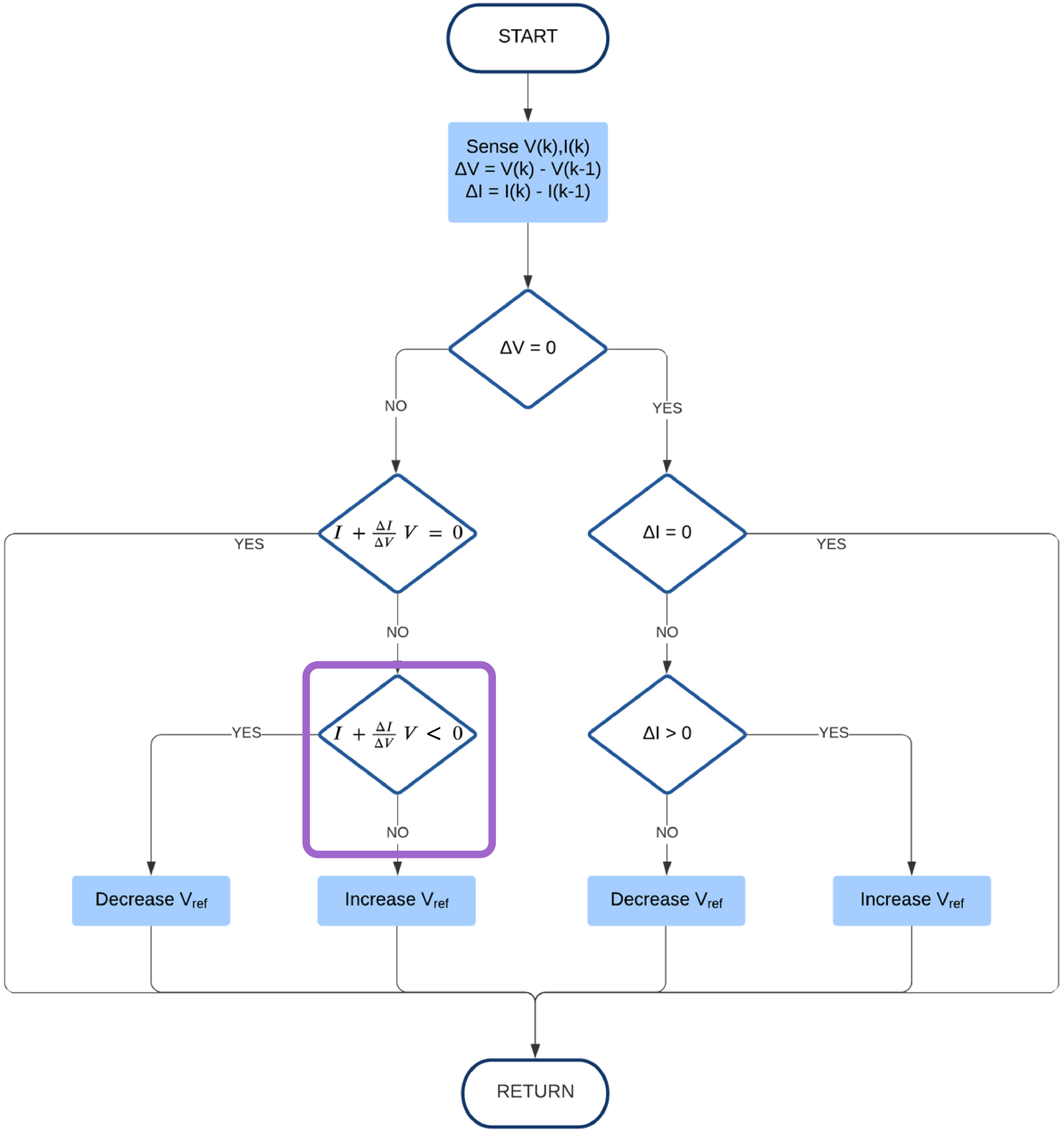
INC ALGORITHM

$$P = VI$$

$$\frac{\Delta P}{\Delta V} = I + V\frac{\Delta I}{\Delta V}$$

When the gradient of power is positive, Vref is increased.



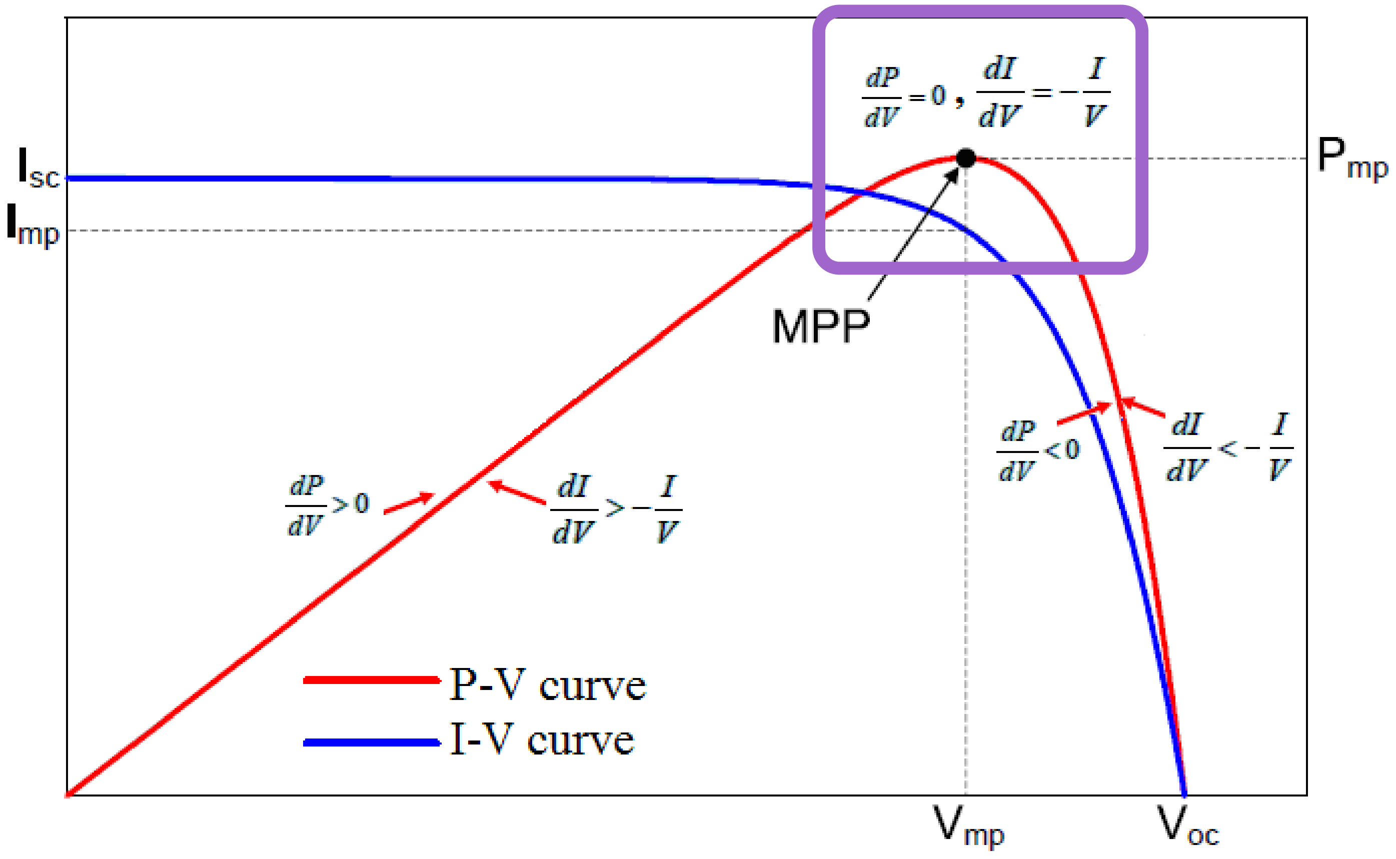


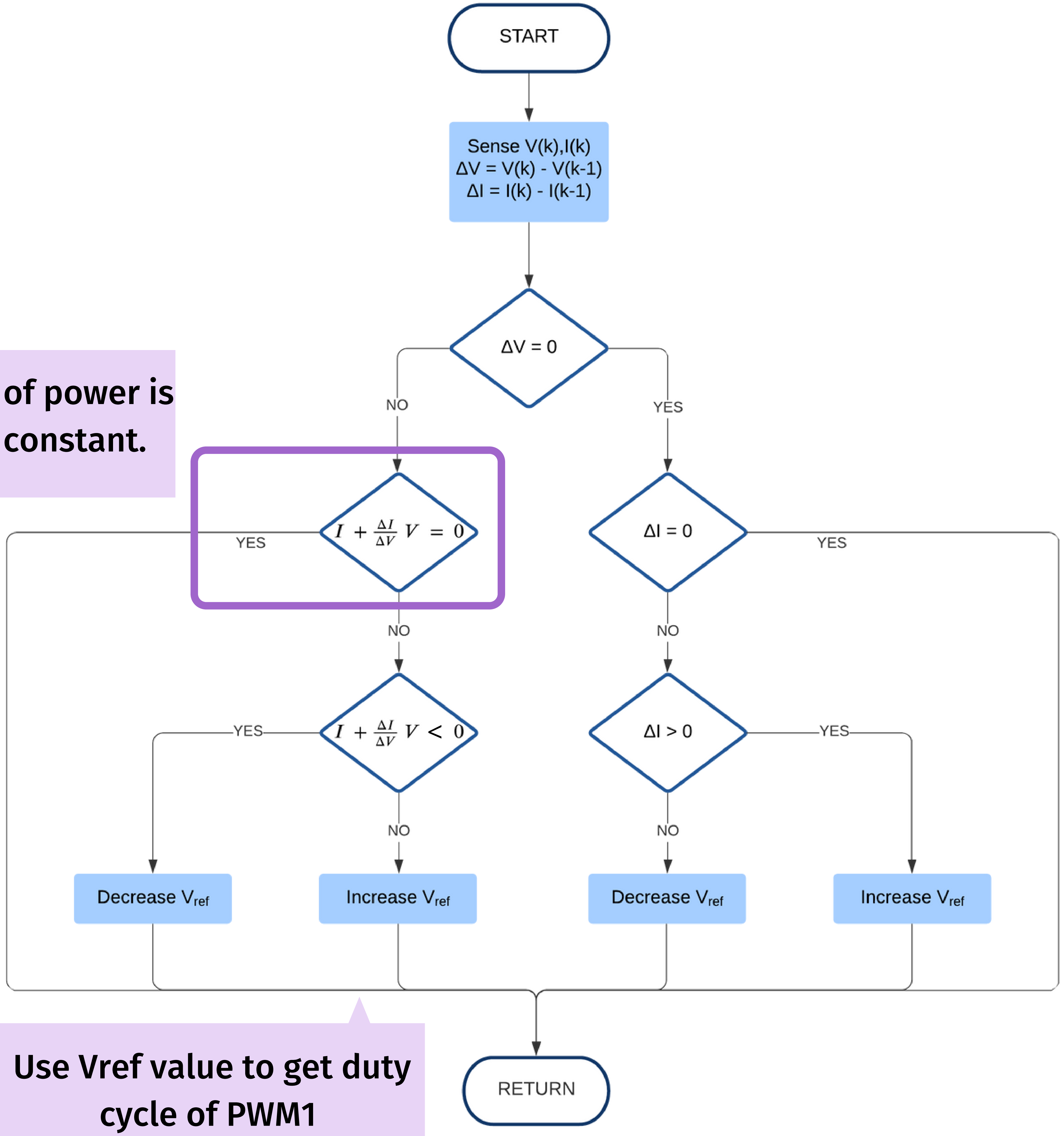
INC ALOGORITHM

$$P = VI$$

$$\frac{\Delta P}{\Delta V} = I + V\frac{\Delta I}{\Delta V}$$

When the gradient of power is zero, Vref is held constant.





Use Vref value to get duty cycle of PWM1

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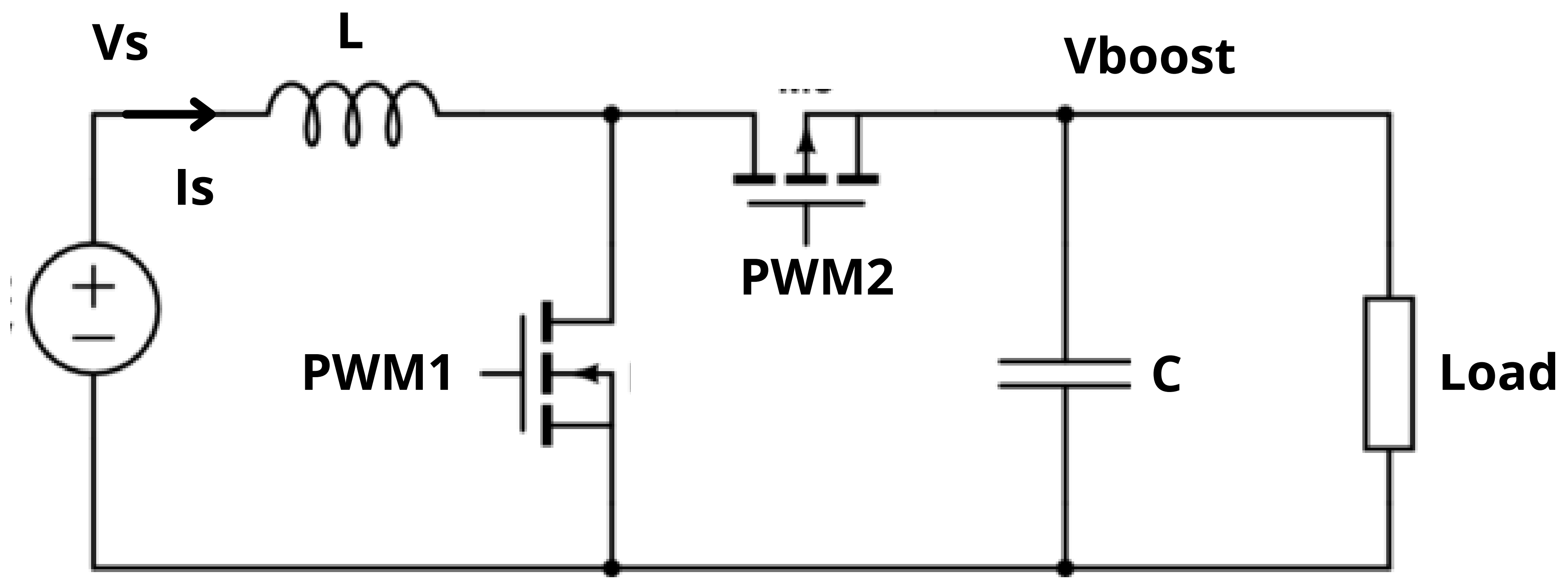
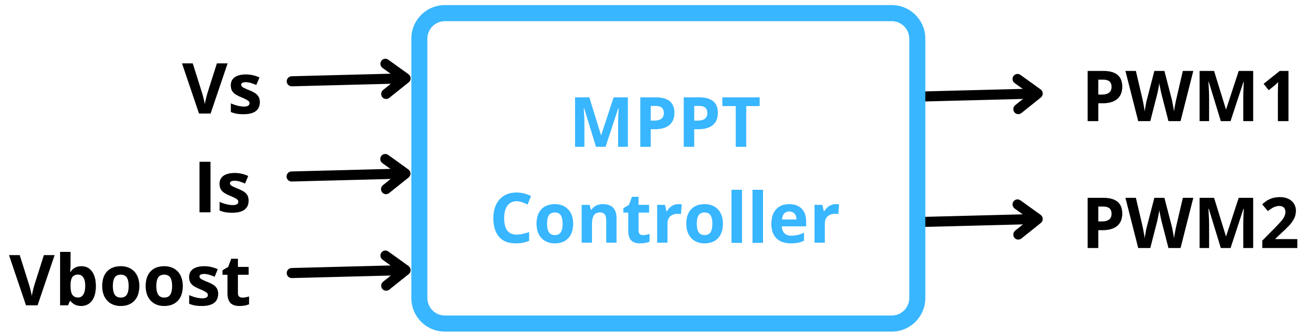
SYNCHRONOUS BOOST CONVERTER





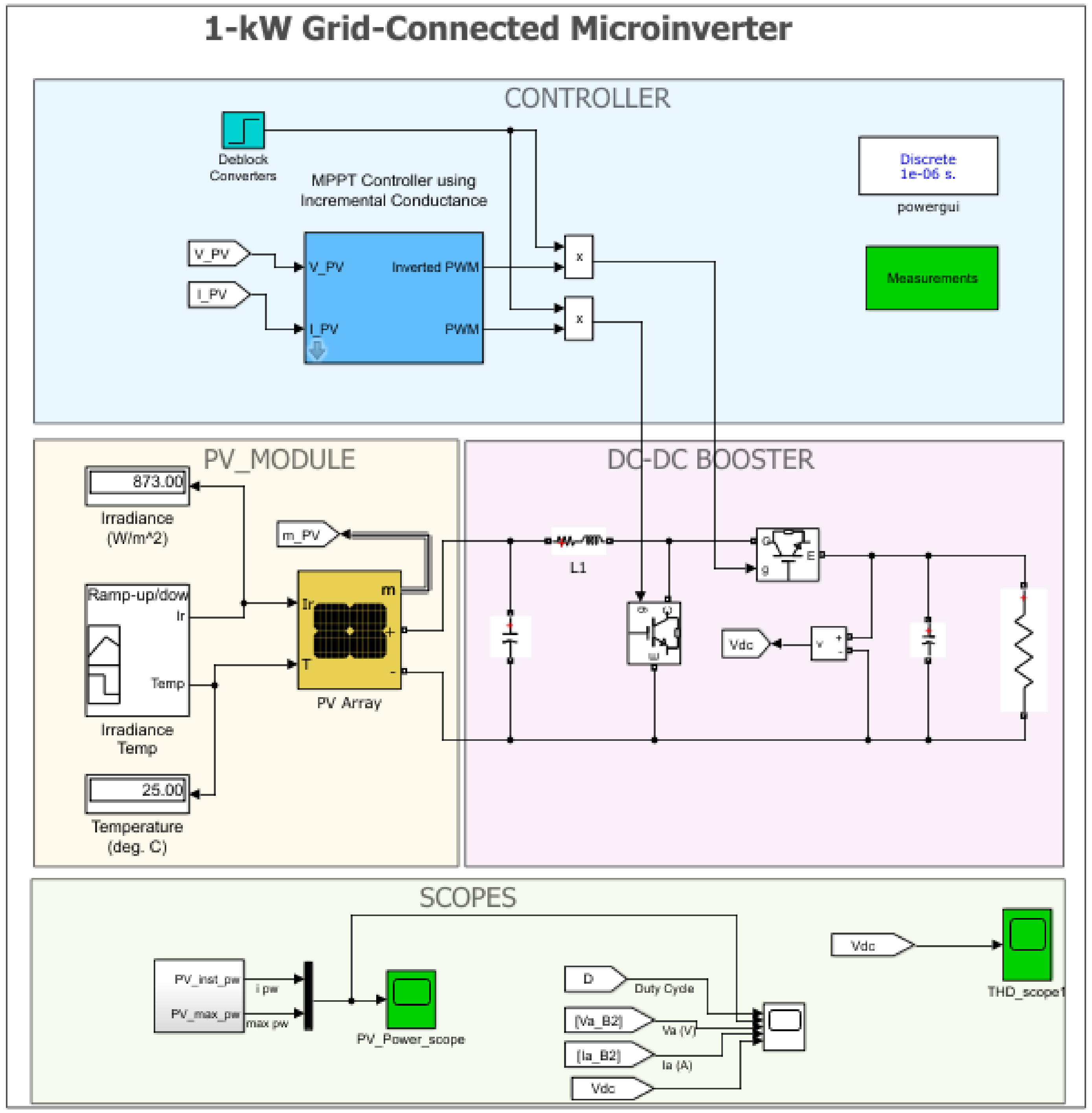
Functionality

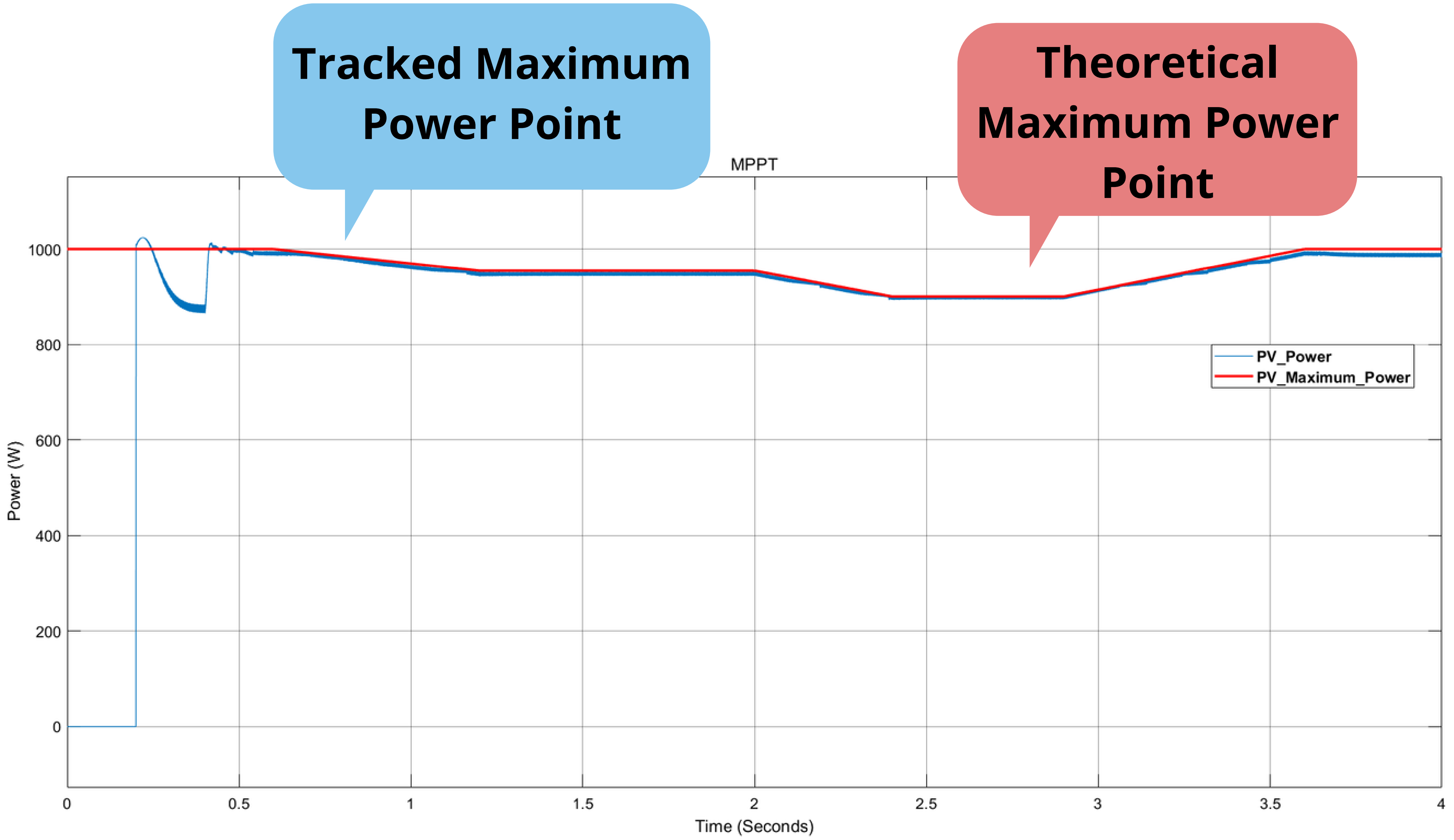
- The maximum power point is tracked by varying impedance seen by PV cells.
- Voltage and current sensors are used to monitor Vs, Vboost, and Is
- Inc algorithm runs on the MPPT controller adjusts the duty cycle of the PWM1 signal to track the MPPT.
- PWM2 is an inverted signal of PWM1.
- The stability of output voltage is maintained using the Vboost value.

Digitally Controlled HV Solar MPPT DC-DC Converter User Guide by Texas Instruments

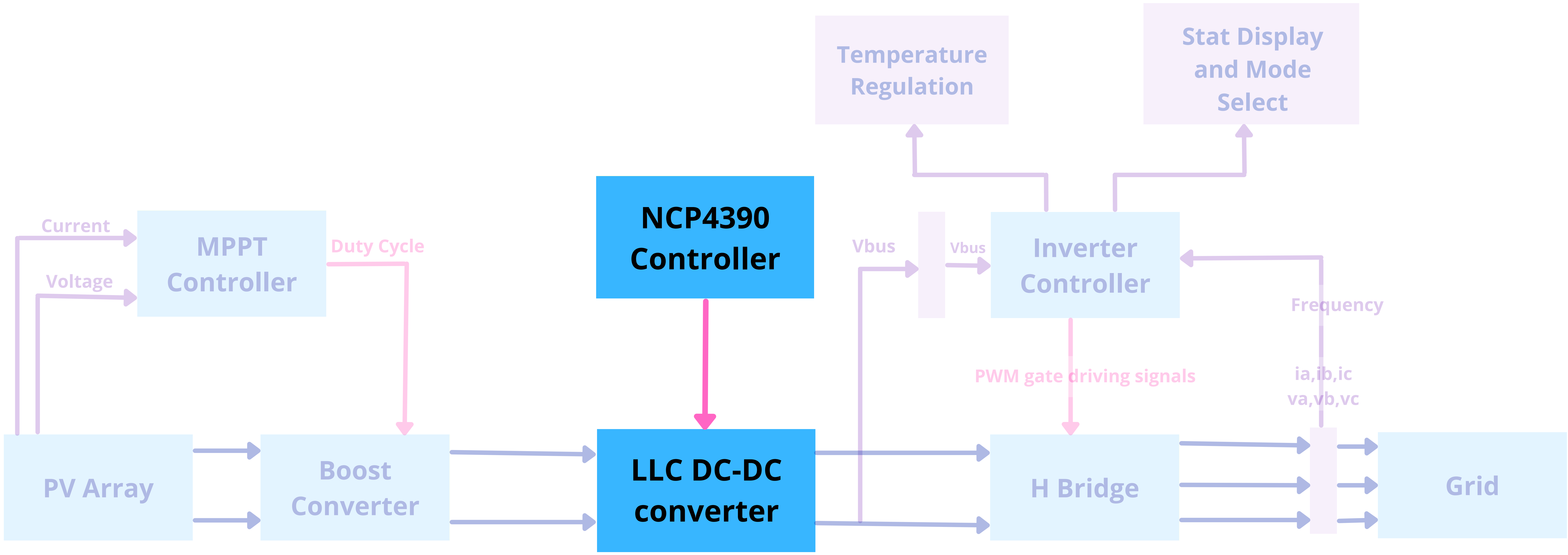
https://www.ti.com/lit/ug/tidu404/tidu404.pdf

SIMULATION OF INC ALGORITHM





LLC CONVERTER



LLC RESONANT CONVERTER

Functionality

- Stepping up the DC voltage from 70-90 V up to 600 V for the inverter switching circuit. The increased DC voltage allows faster response during load changes.
- LLC and Flyback type converters provide electrical isolation without the need of a bulky 3-phase transformer at the output. The high-frequency operation allows smaller transformer and higher efficiency.
- Flyback converter has lower power handling capability than LLC converter topology. Hence, LLC topology selected.

LLC Resonant Converter is suitable for DC-DC conversions in the 100W - 500W range.
Flyback converter is not suitable for system with >100W power handling.

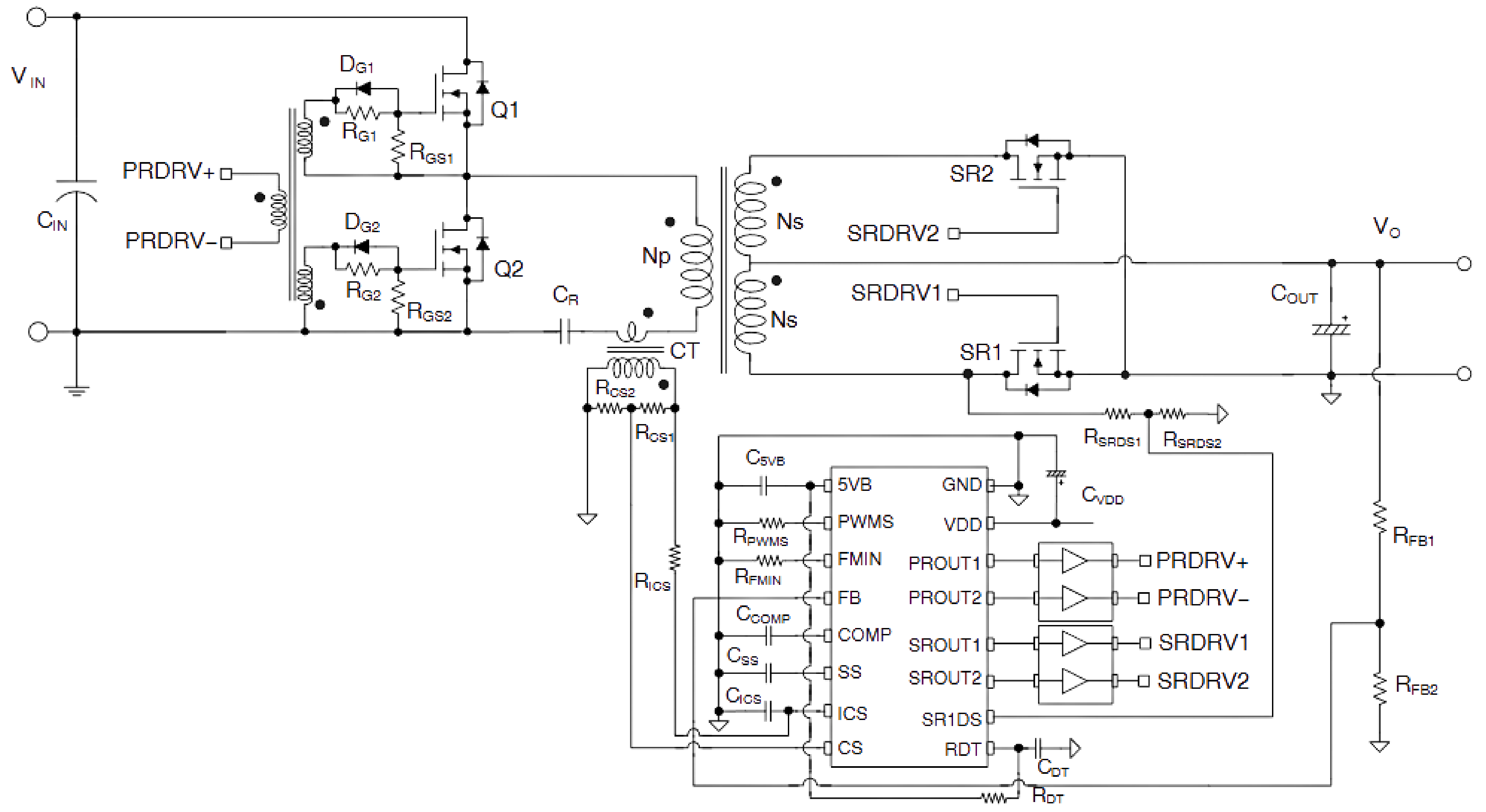
https://training.ti.com/sites/default/files/docs/Selecting%20Optimal%20Topology.pdf

Zhang et al. has designed a 1 1kW LLC resonant converter with 93.95% efficiency at 875kHz switching frequency.

Y. Zhang, D. Xu, K. Mino and K. Sasagawa, "1MHz-1kW LLC Resonant Converter with Integrated Magnetics," APEC 07 - Twenty-Second Annual IEEE Applied Power Electronics Conference and Exposition, 2007, pp. 955-961, doi: 10.1109/APEX.2007.357630.

LLC CONVERTER

- Design is based on the verified and tested design provided by Onsemi. NCP4390 LLC controller used. Following the reference design.



Reference design

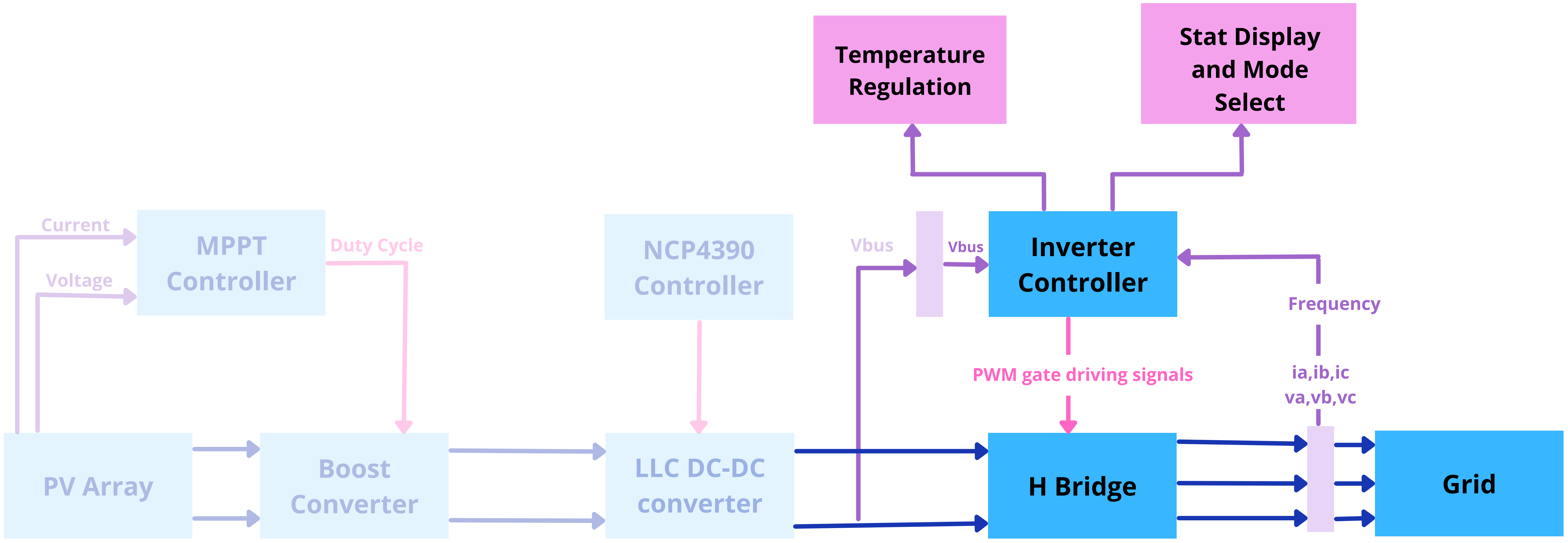
Features

- Pulse Frequency Modulation Controller
- Higher Operating Frequency
- Protection
  - Over Current Protection
  - Output Short Circuit Protection
  - Overload Protection
- Programmable dead time
- Low cost of implementation

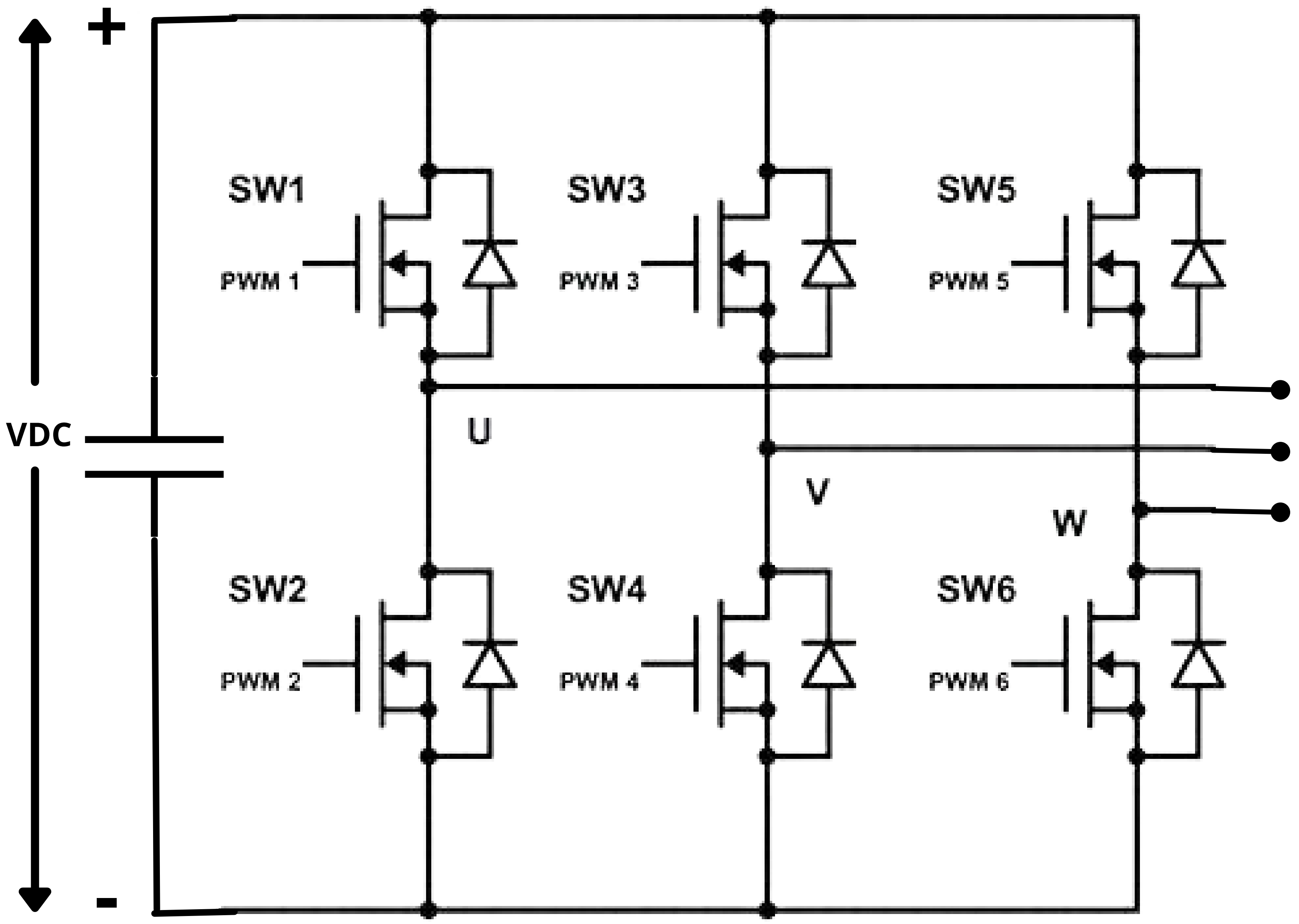
Reference Design for the LLC DC-DC Converter

https://www.onsemi.com/products/power-management/ac-dc-power-conversion/offline-controllers/ncp4390#overview

INVERTER


Temperature Regulation
Stat Display and Mode Select
Current
Voltage
MPPT Controller
Duty Cycle
NCP4390 Controller
Vbus
Vbus
Inverter Controller
Frequency
PWM gate driving signals
ia,ib,ic
va,vb,vc
PV Array
Boost Converter
LLC DC-DC converter
H Bridge
Grid

INVERTER TOPOLOGY



Two level 3 Phase H bridge

- Simple
- Higher Power Density
- Reduced Cost
- Facilitates both 3-phase and single-phase

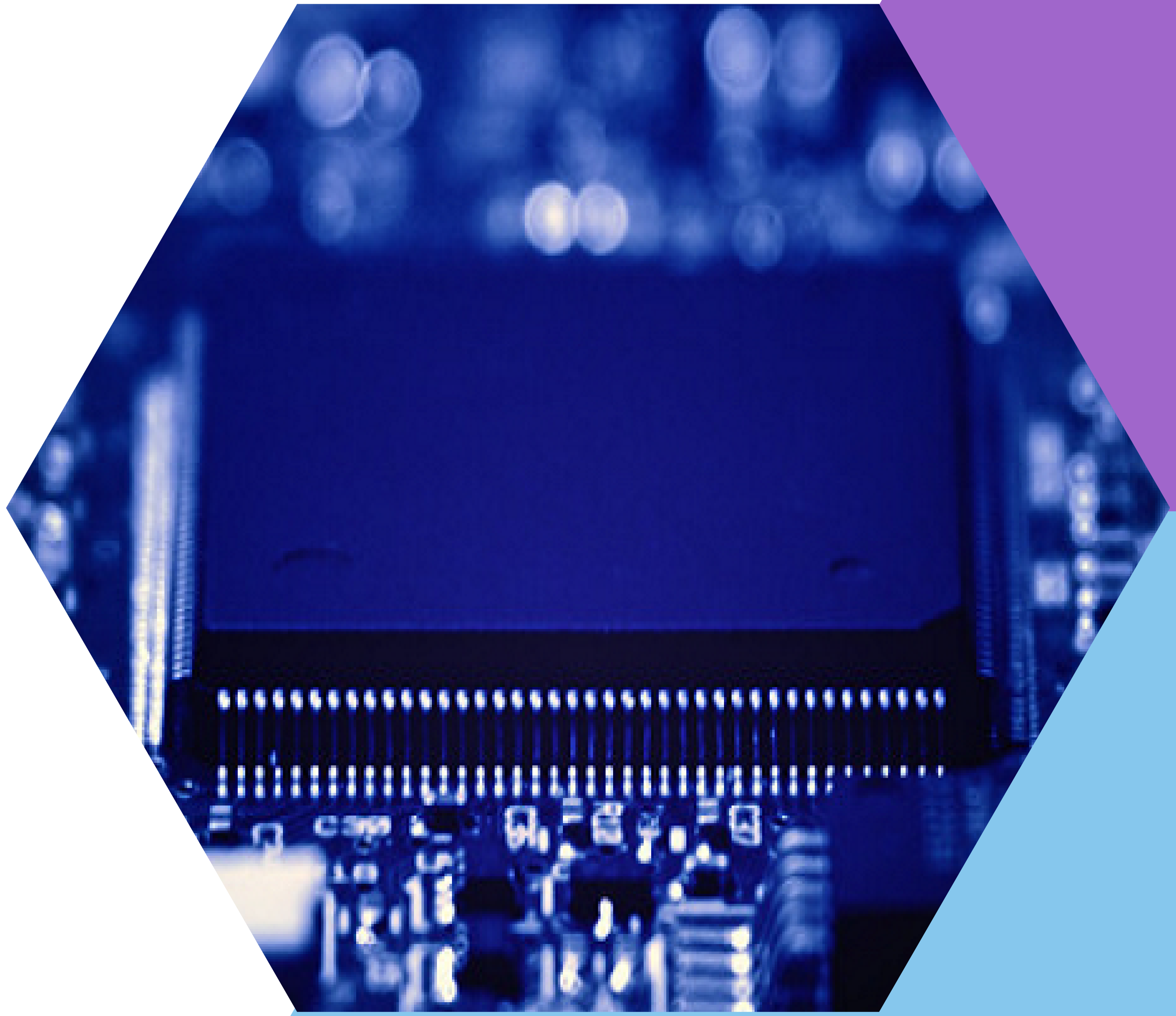
Use of wideband gap semiconductor MOSFETs

- High Frequency Switching due to higher saturation electron drift velocity
- Higher Power Density due to higher thermal conductivity
- Lower on resistance lead to low conduction losses

With SiC 1200V MOSFETs, it becomes possible to implement simple two-level (2L) structure inverter with comparable efficiency with a multilevel inverter but high potential to reduce the overall cost by nearly 10%.

Sintamarean, Nicolae-Cristian & Eni, Emanuel-Petre & Blaabjerg, F. & Teodorescu, Remus & Wang, Huai. (2014). Wide-Band Gap Devices in PV Systems -Opportunities and Challenges. 10.1109/IPEC.2014.6869846.

INVERTER CONTROLLER

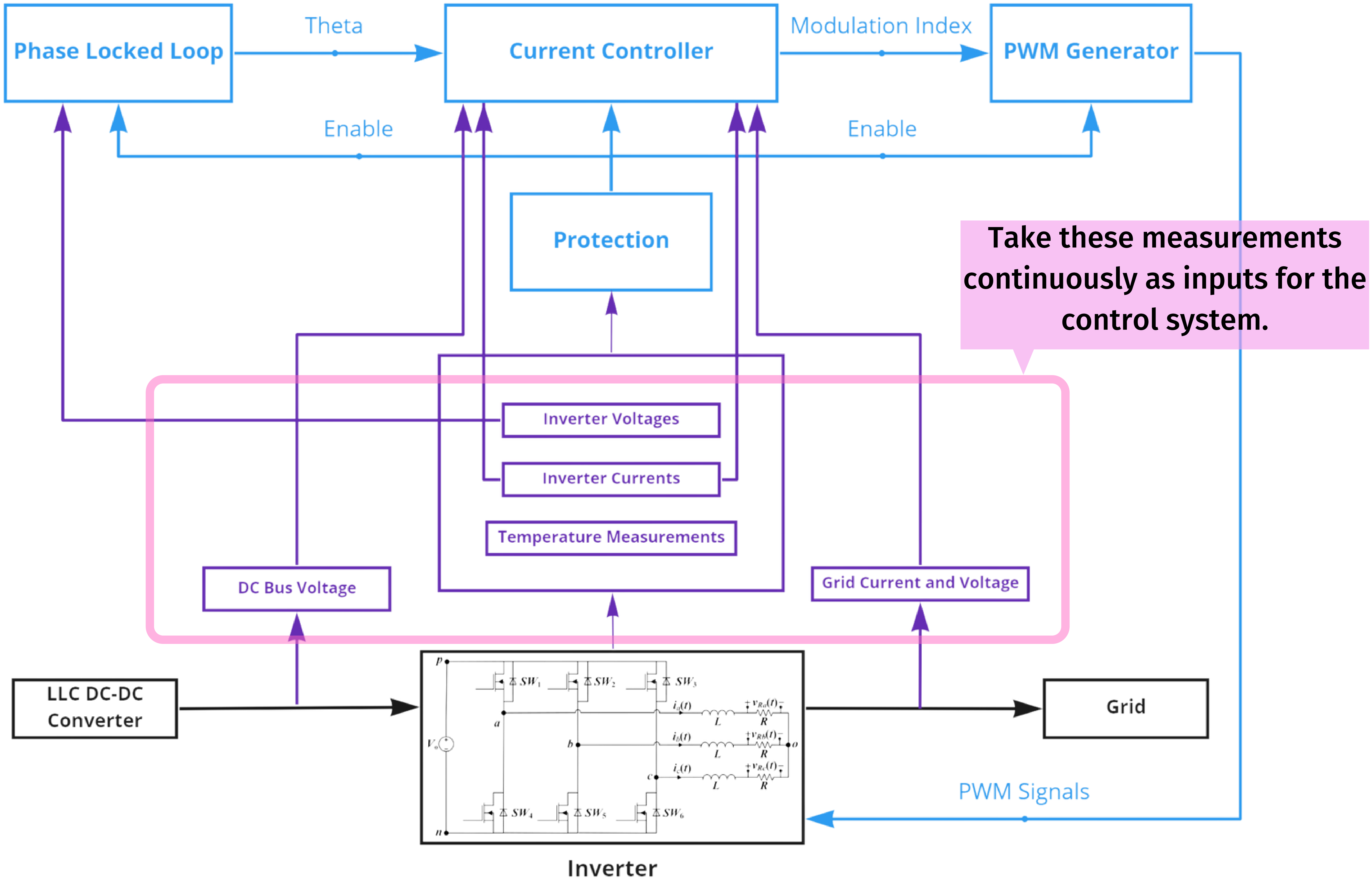


Functionality

- Sinusoidal inverter output generation
- Grid frequency synchronization
- Reactive power compensation
- Active Power Delivery
- Protection methods

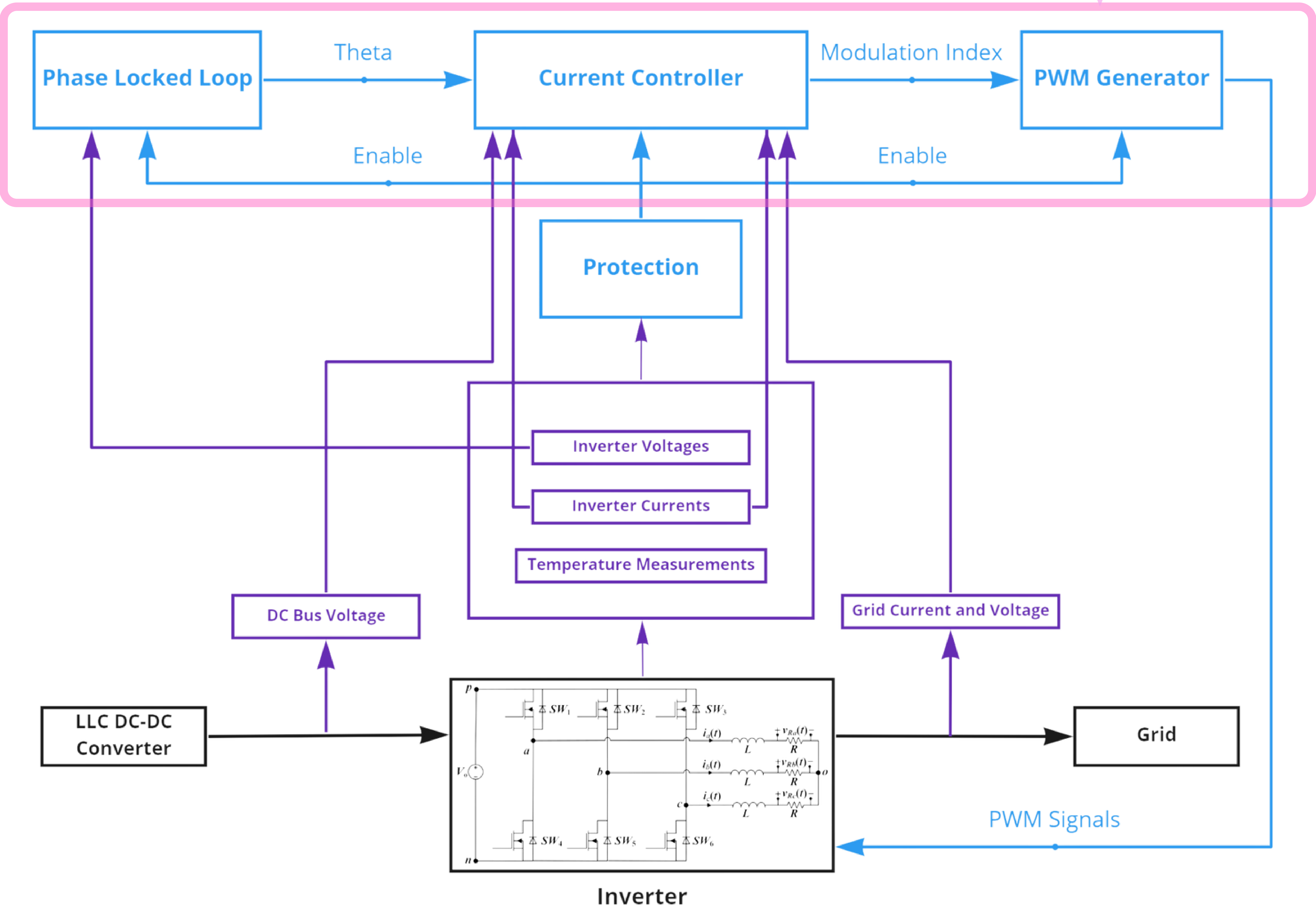
- Implemented on dual-core C2000 MCU by Texas Instruments
- Operating frequency - 100 MHz

CONTROLLER BLOCK DIAGRAM

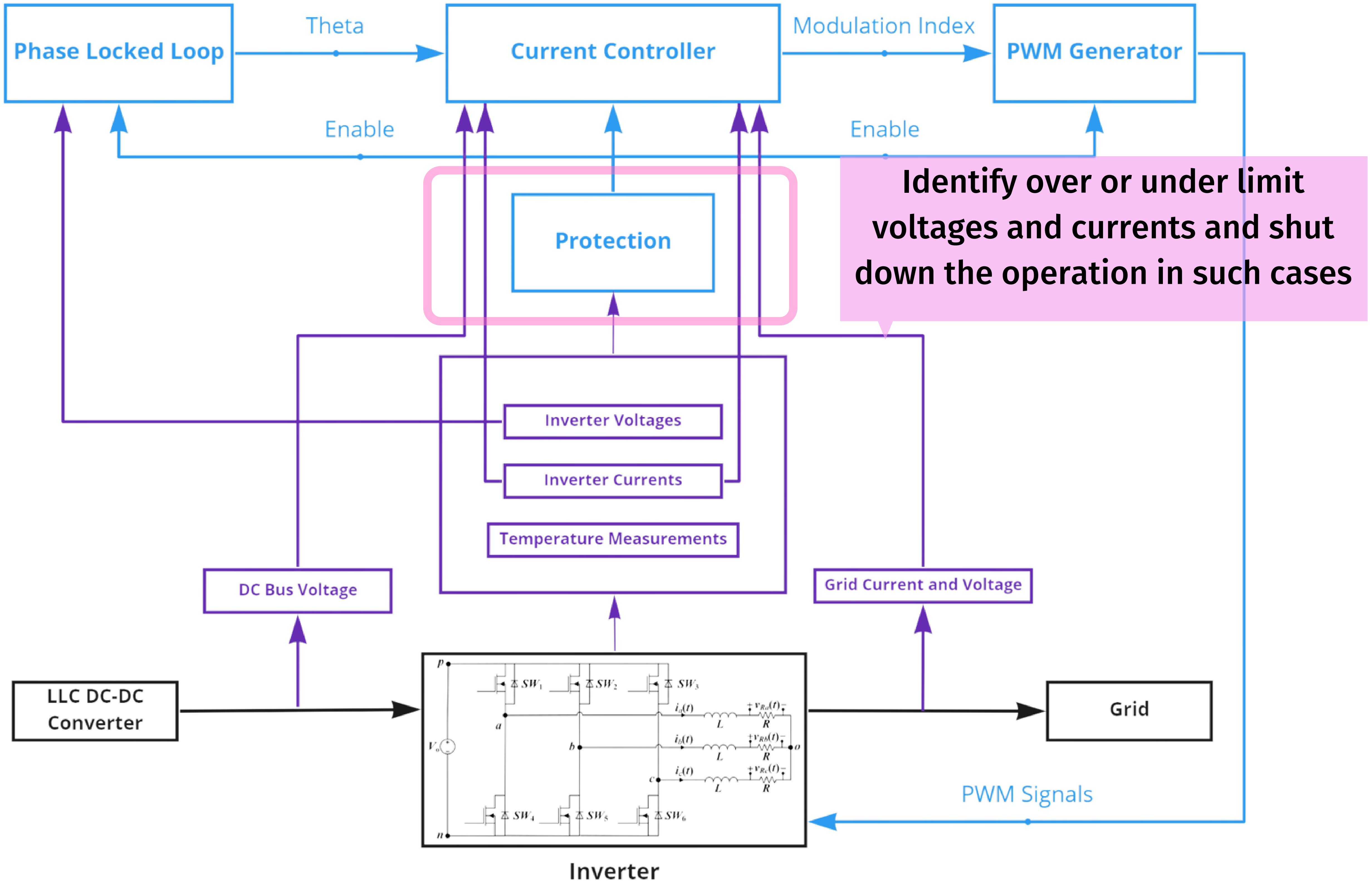


CONTROLLER BLOCK DIAGRAM

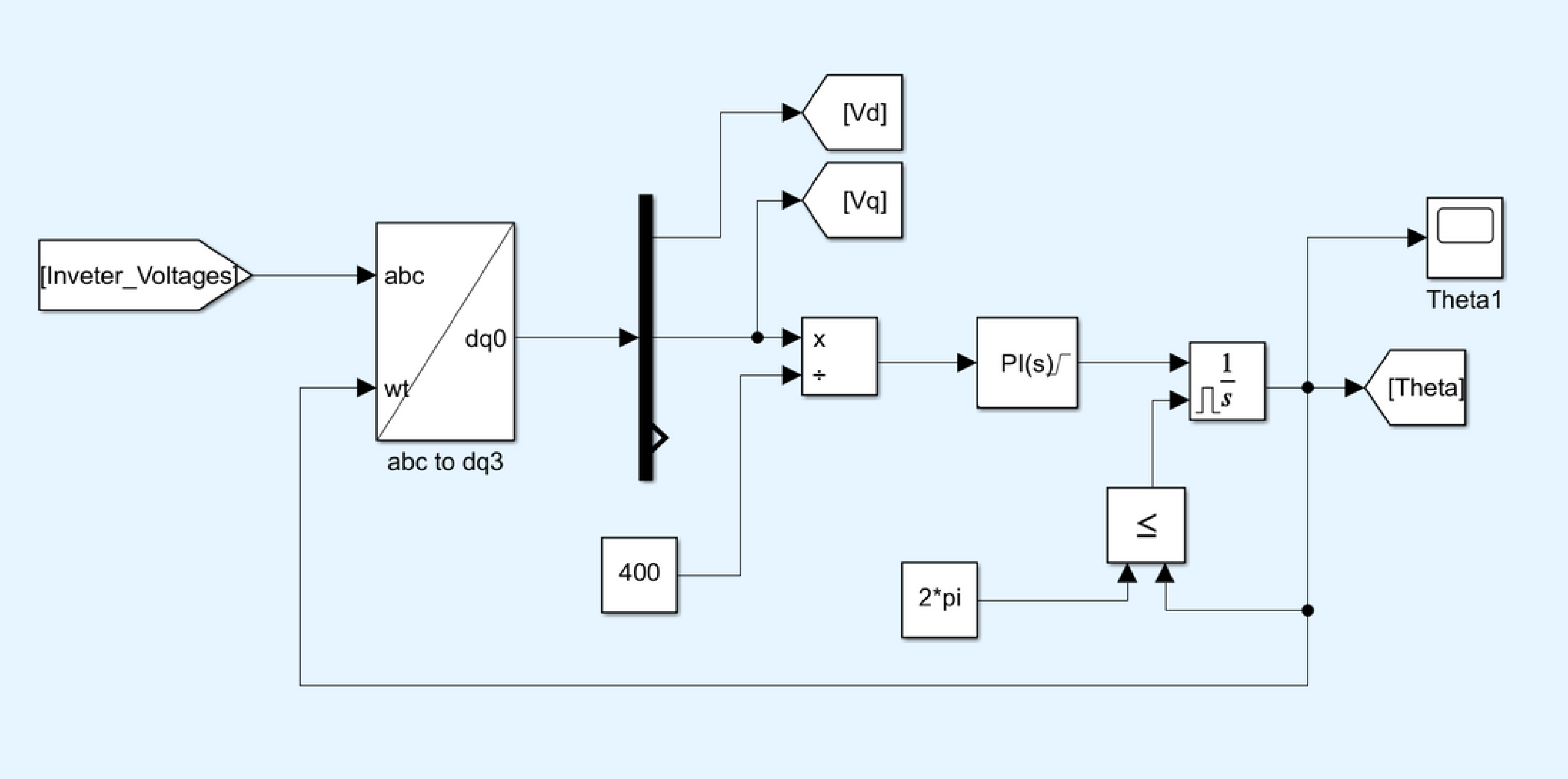
Inverter PWM Generation for the MOSFETs to facilitate the requirements



CONTROLLER BLOCK DIAGRAM



PHASE LOCKED LOOP



Functionality

- Synchronize the frequency and the phase of the inverter output voltage with the grid.

Methodology

- Perform Park transformation on the inverter voltages.
- Impose Vq = 0 using a PI Controller to synchronize the inverter voltage with the grid.

CURRENT CONTROL

Functionality

Generate sinusoidal reference waveforms for the PWM generator.

Reactive Power Compensation

Provide or absorb the reactive power required by inductive or capacitive loads to maintain a grid power factor at desired level.

Active Power Delivery

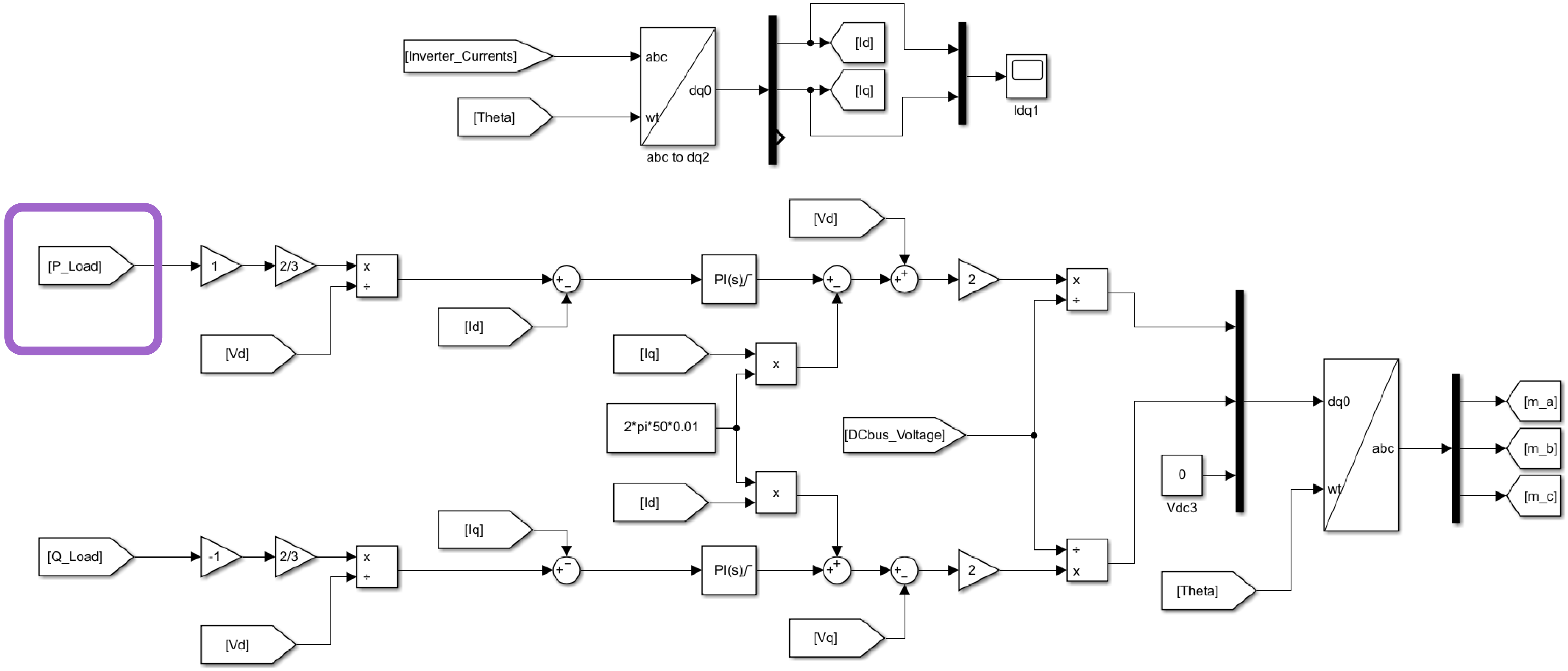
Provide the active power required according to the grid frequency.

- Convert inverter currents into DQ frame.
- Reactive Power Compensation → Iq Current
- Active Power Delivery → Id Current

CURRENT CONTROL METHODOLOGY

Reactive Power Compensation and Active Power Delivery

- The control system determines the active power based on the grid frequency.
- The control system determines the reactive power based on the grid voltage.



CURRENT CONTROL METHODOLOGY

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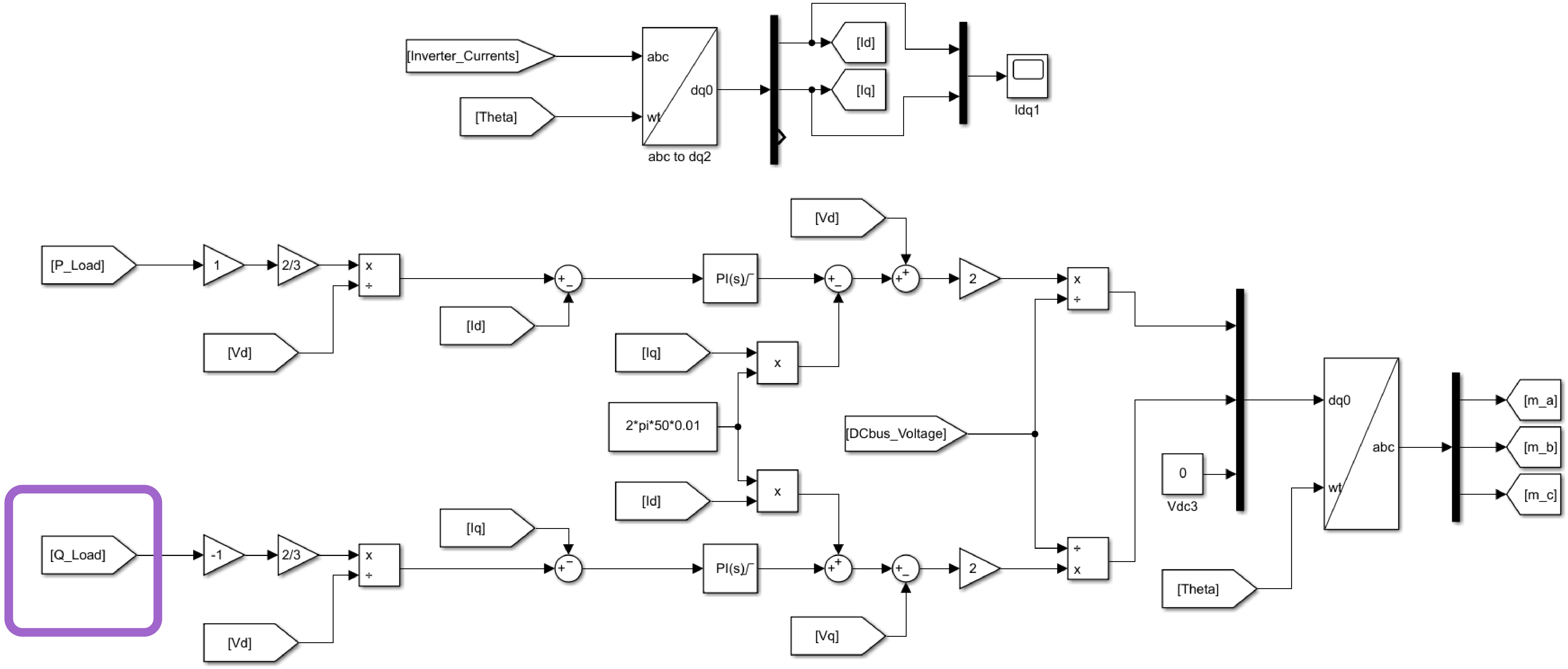
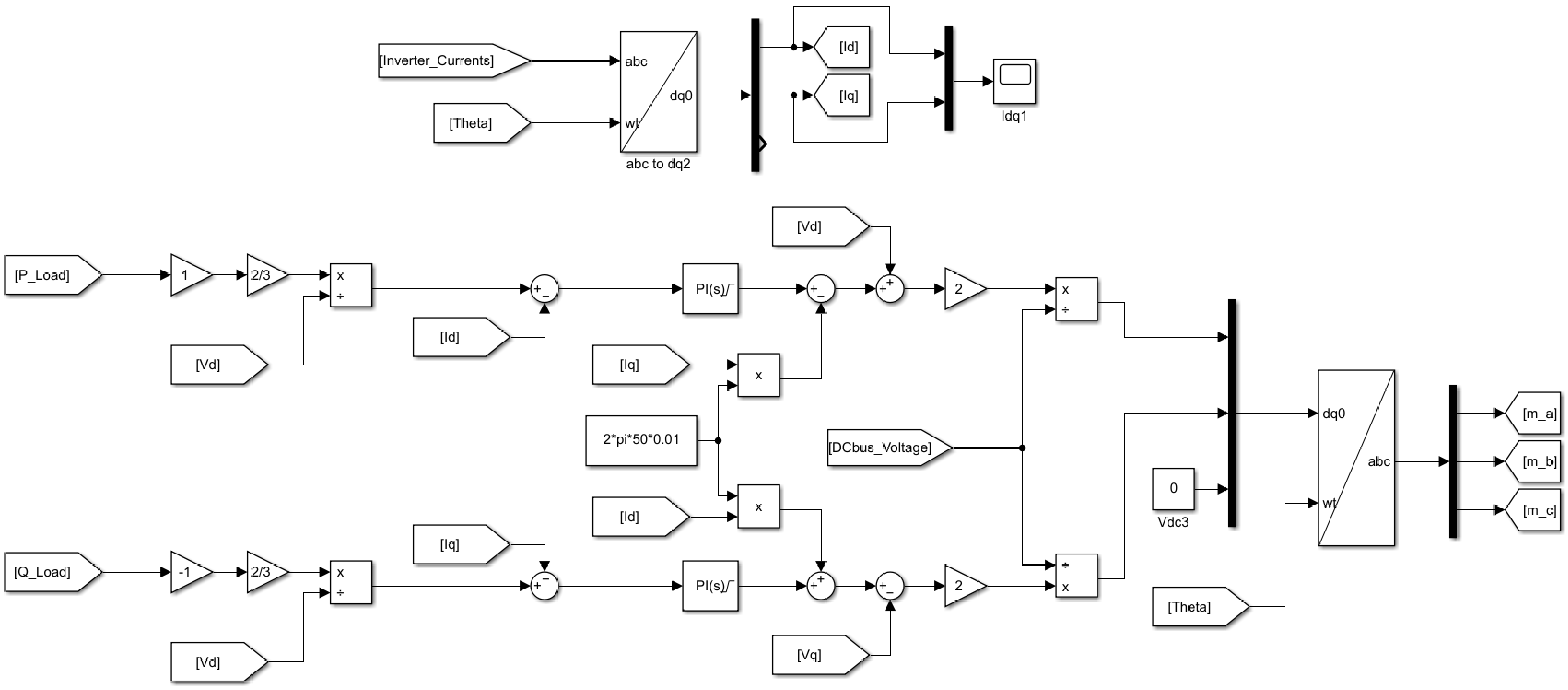


CURRENT CONTROL METHODOLOGY

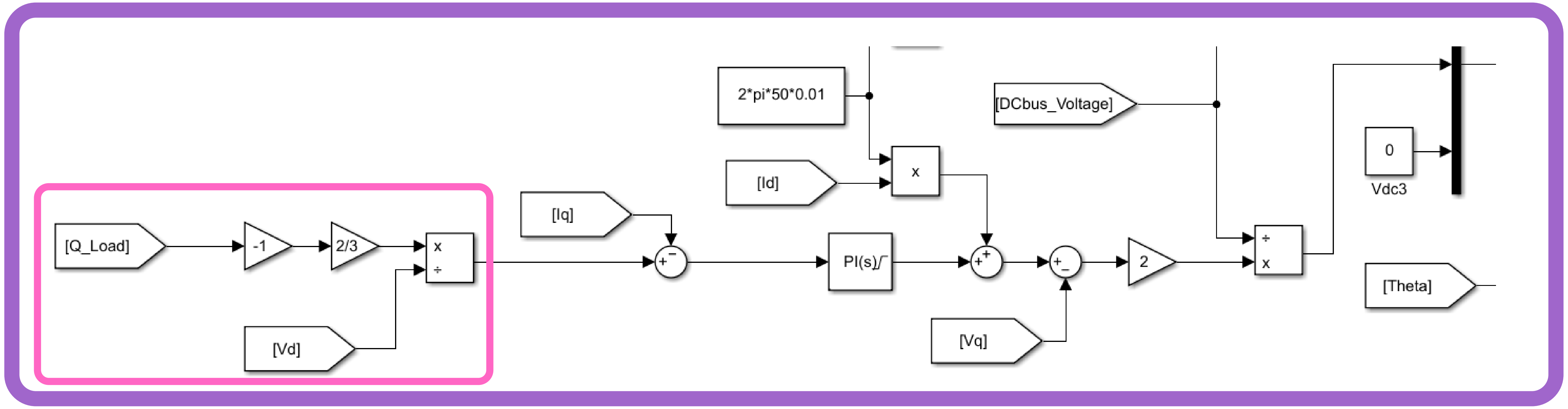
Reactive Power Compensation and Active Power Delivery

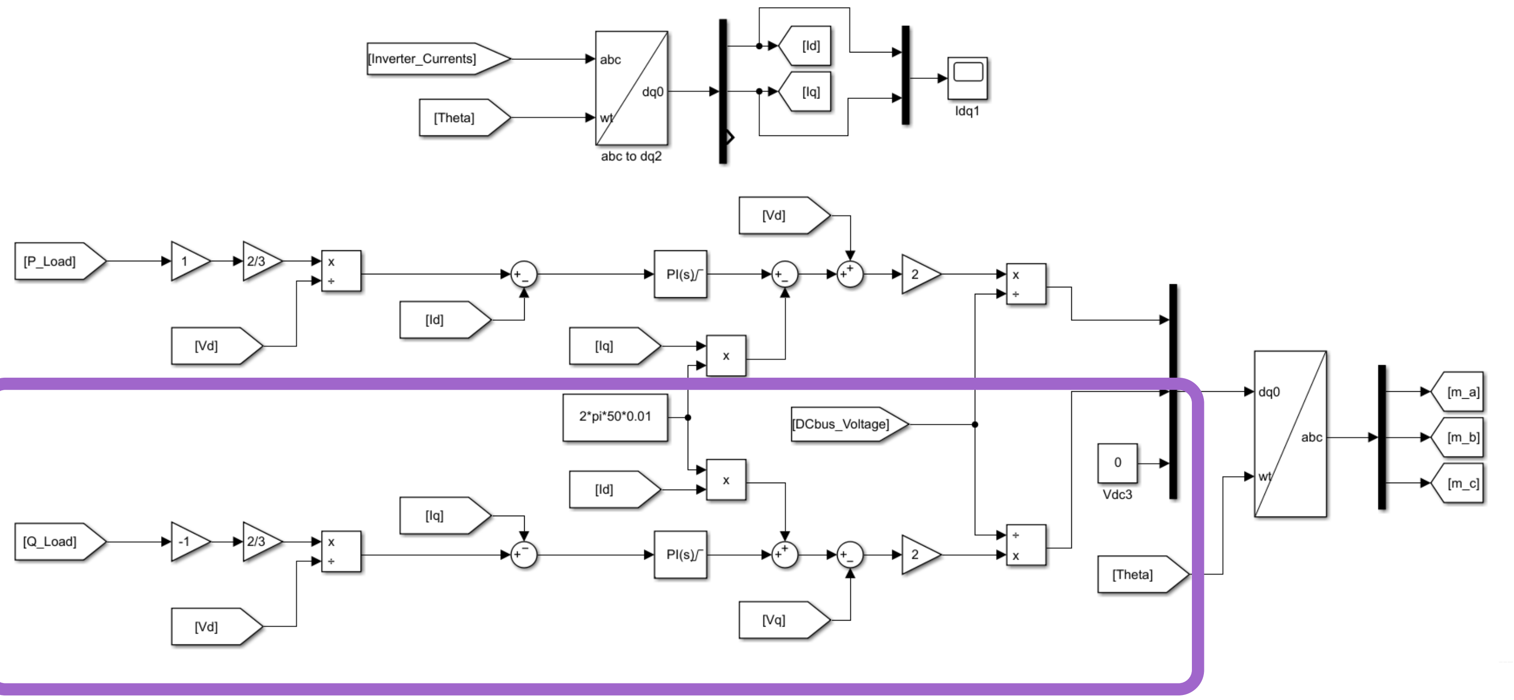
- The control system for both reactive power compensation and active power delivery are logically symmetric.



CURRENT CONTROL METHODOLOGY

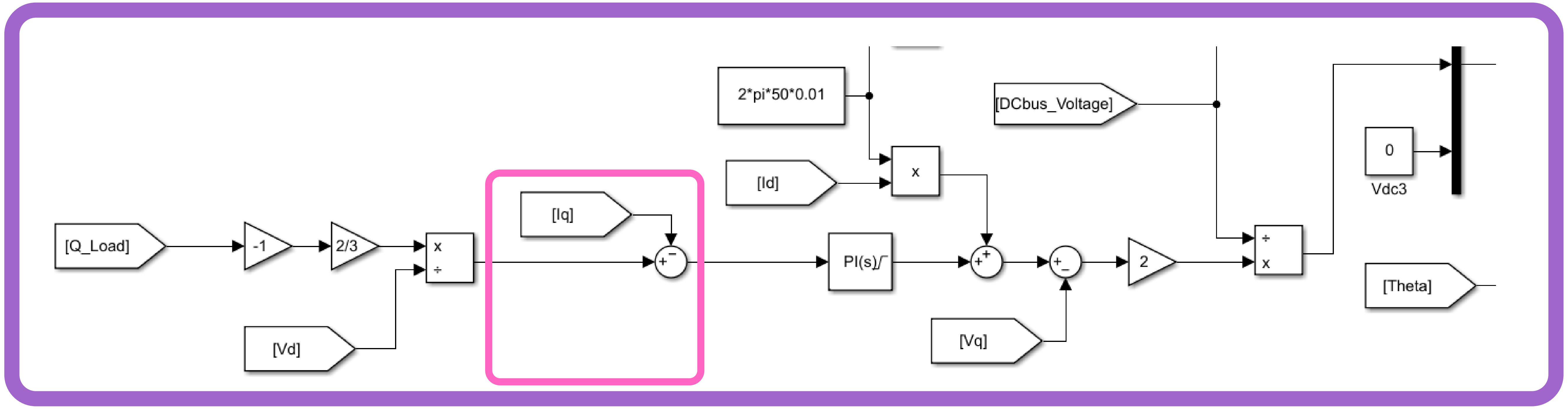
Reactive Power Compensation and Active Power Delivery

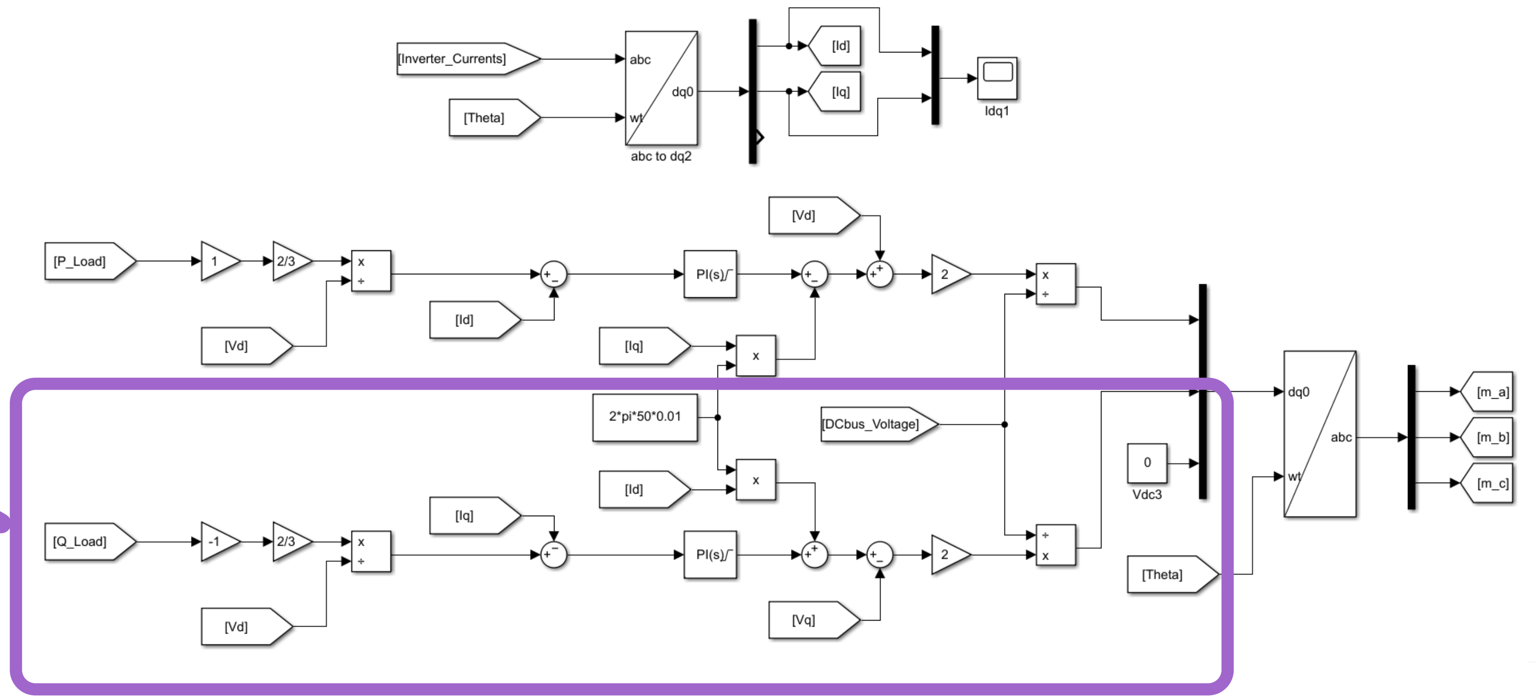




CURRENT CONTROL METHODOLOGY

Reactive Power Compensation and Active Power Delivery





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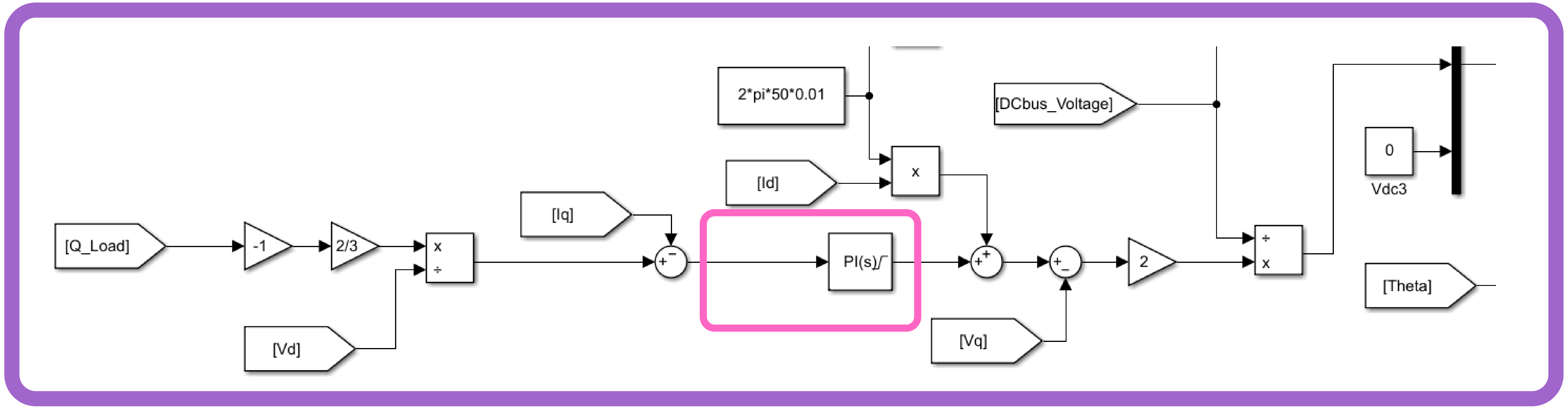
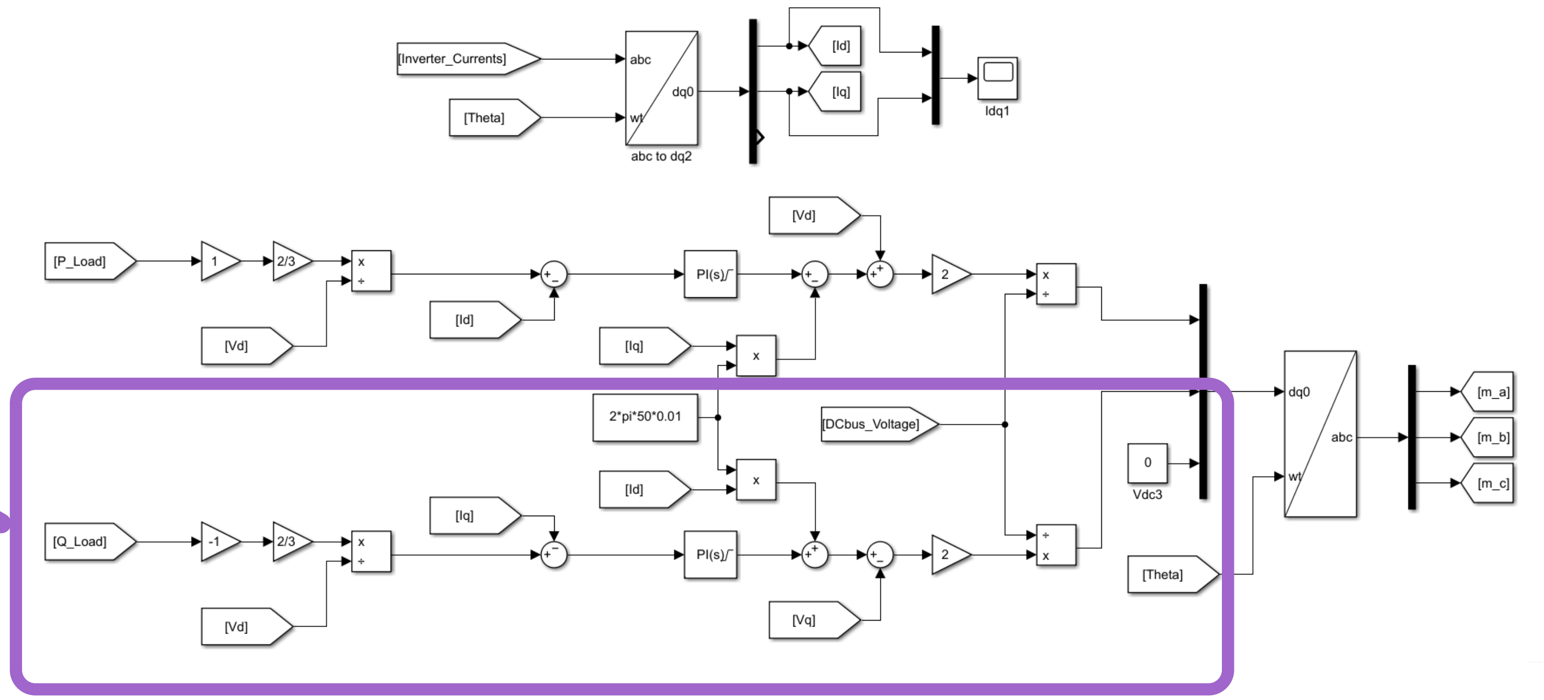
CURRENT CONTROL METHODOLOGY

Reactive Power Compensation and Active Power Delivery





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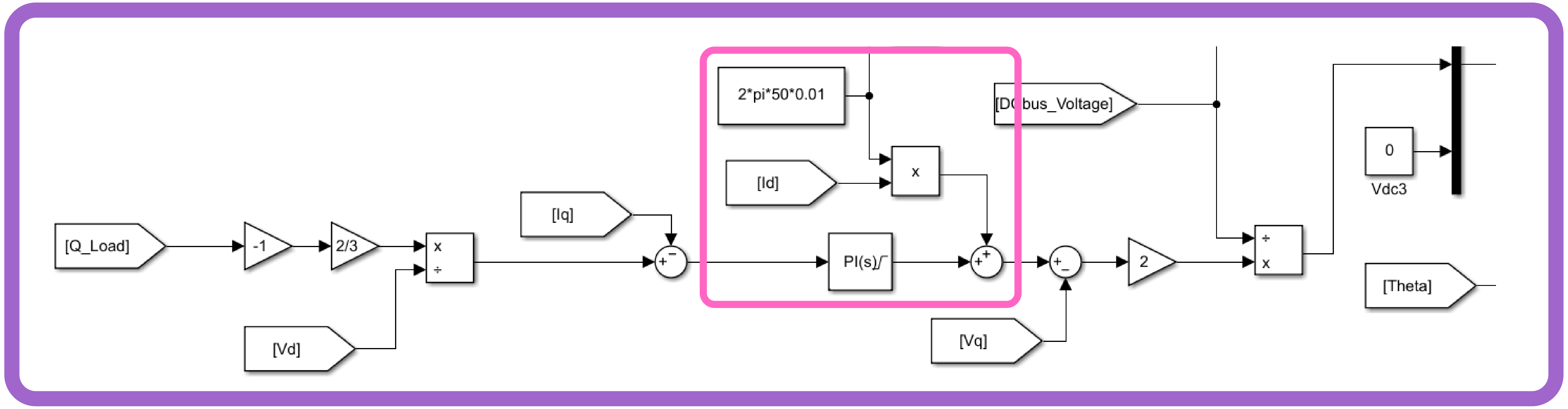
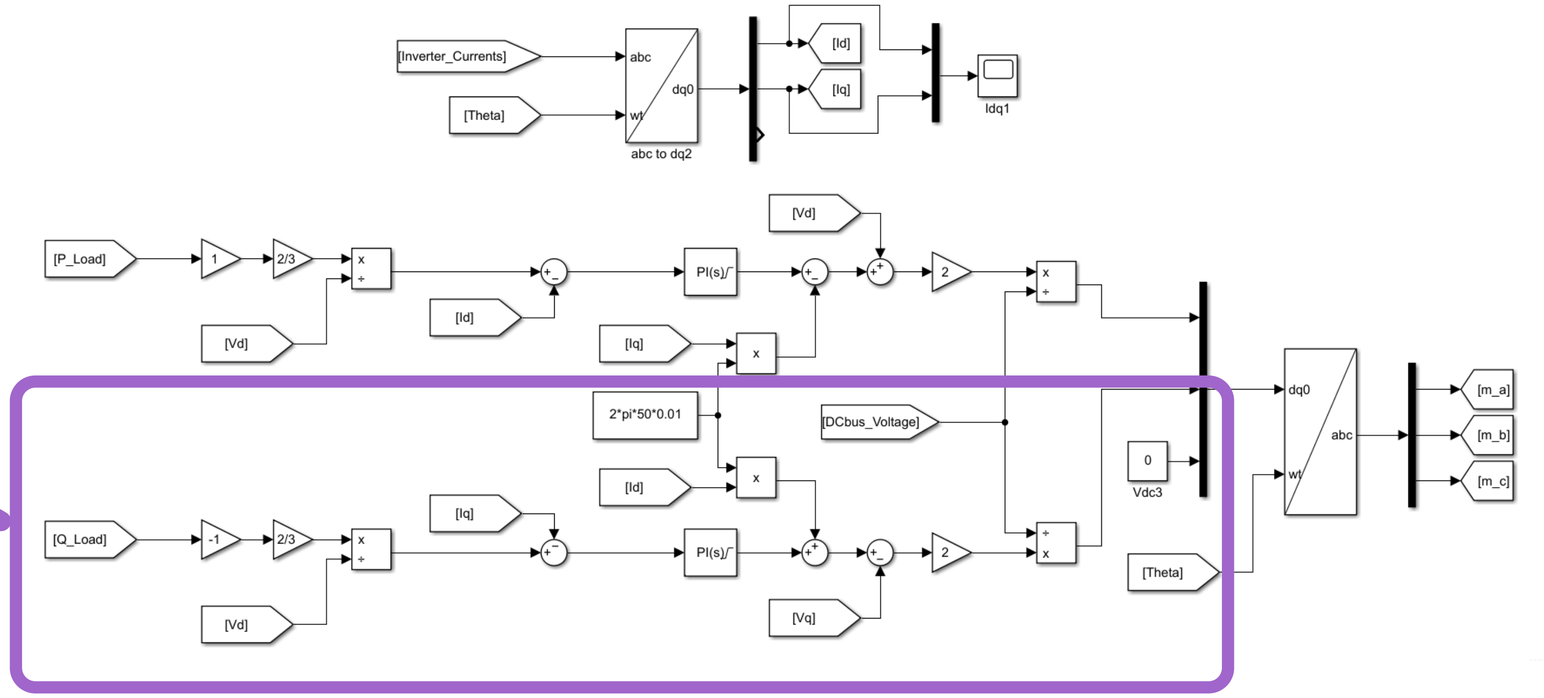
CURRENT CONTROL METHODOLOGY

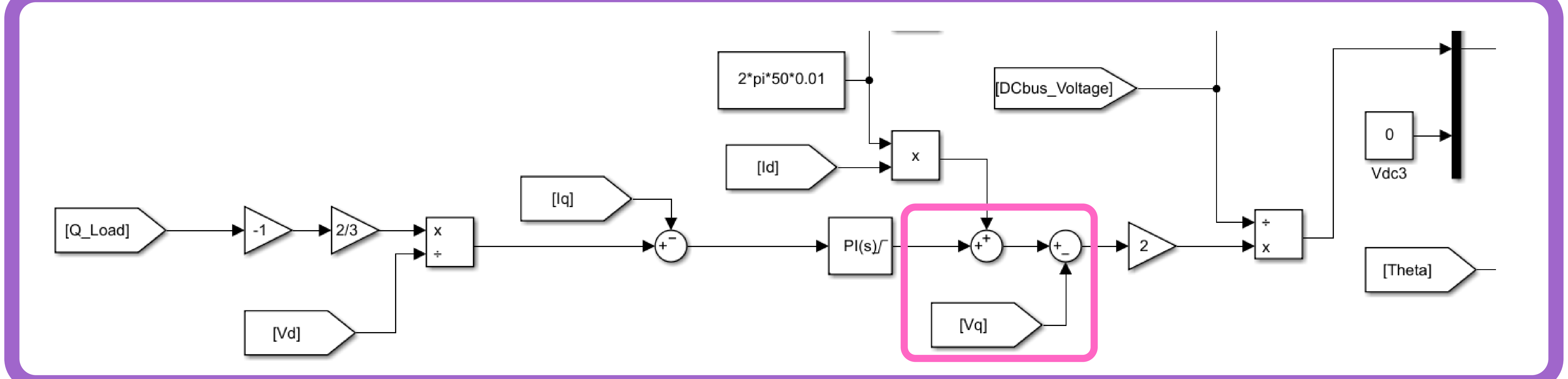
Reactive Power Compensation and Active Power Delivery

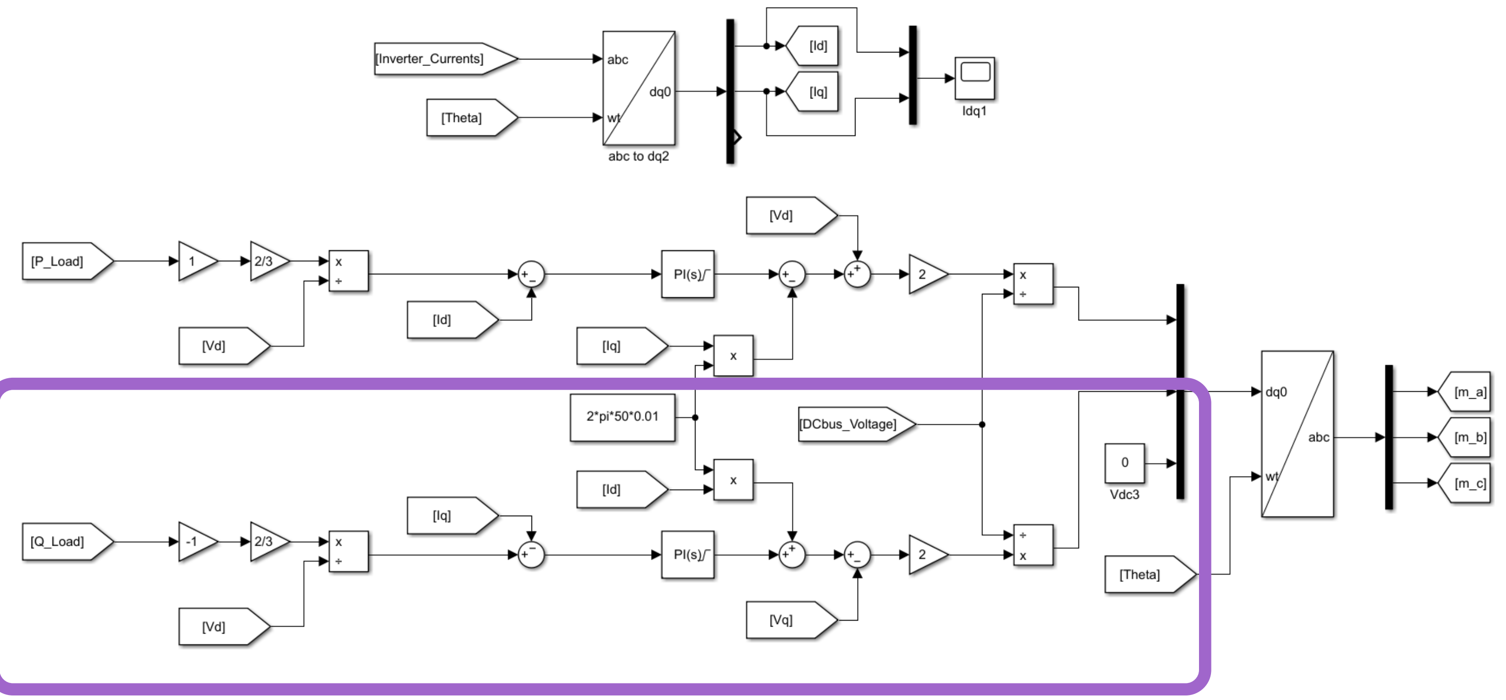




CURRENT CONTROL METHODOLOGY

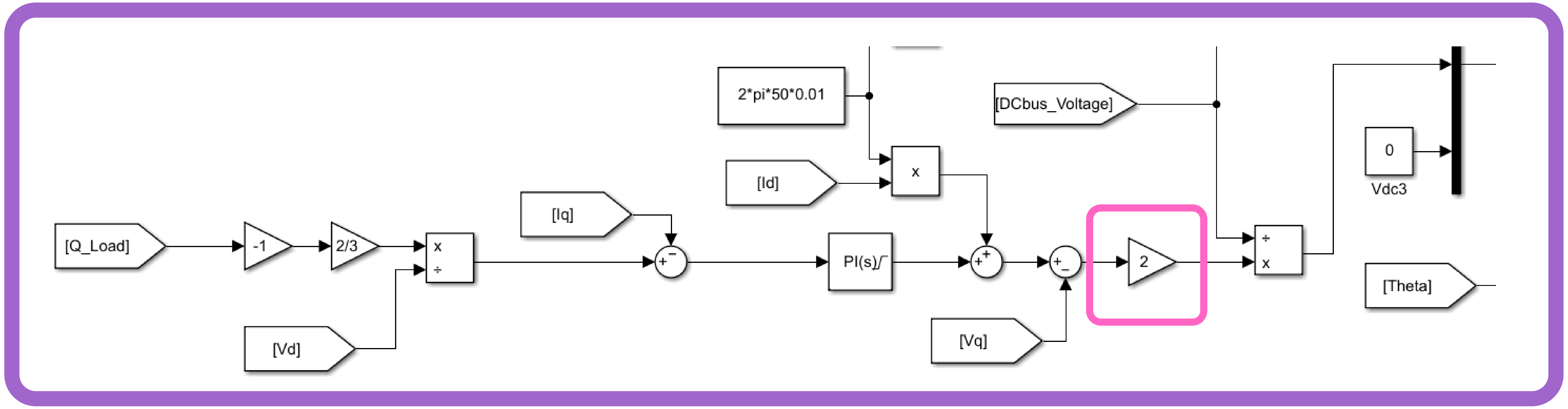
Reactive Power Compensation and Active Power Delivery

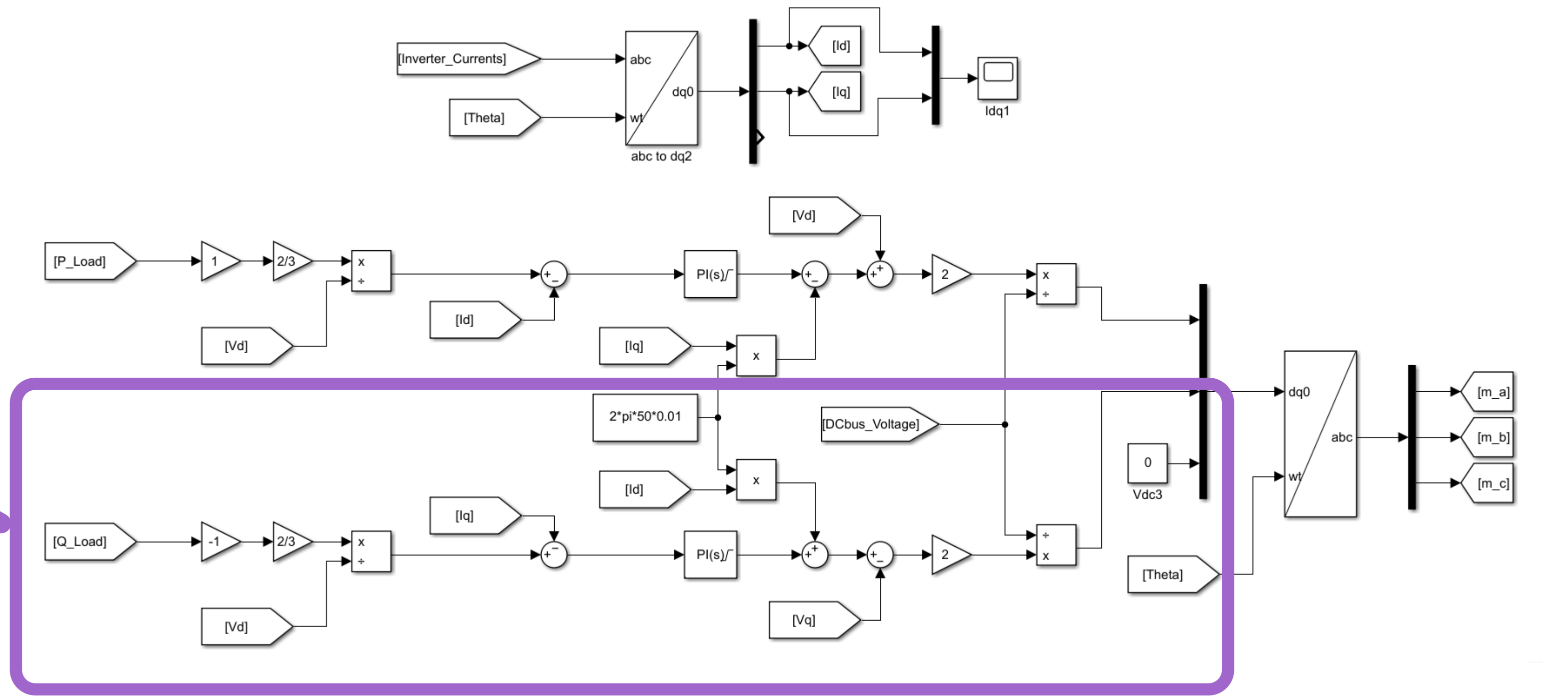




CURRENT CONTROL METHODOLOGY

Reactive Power Compensation and Active Power Delivery

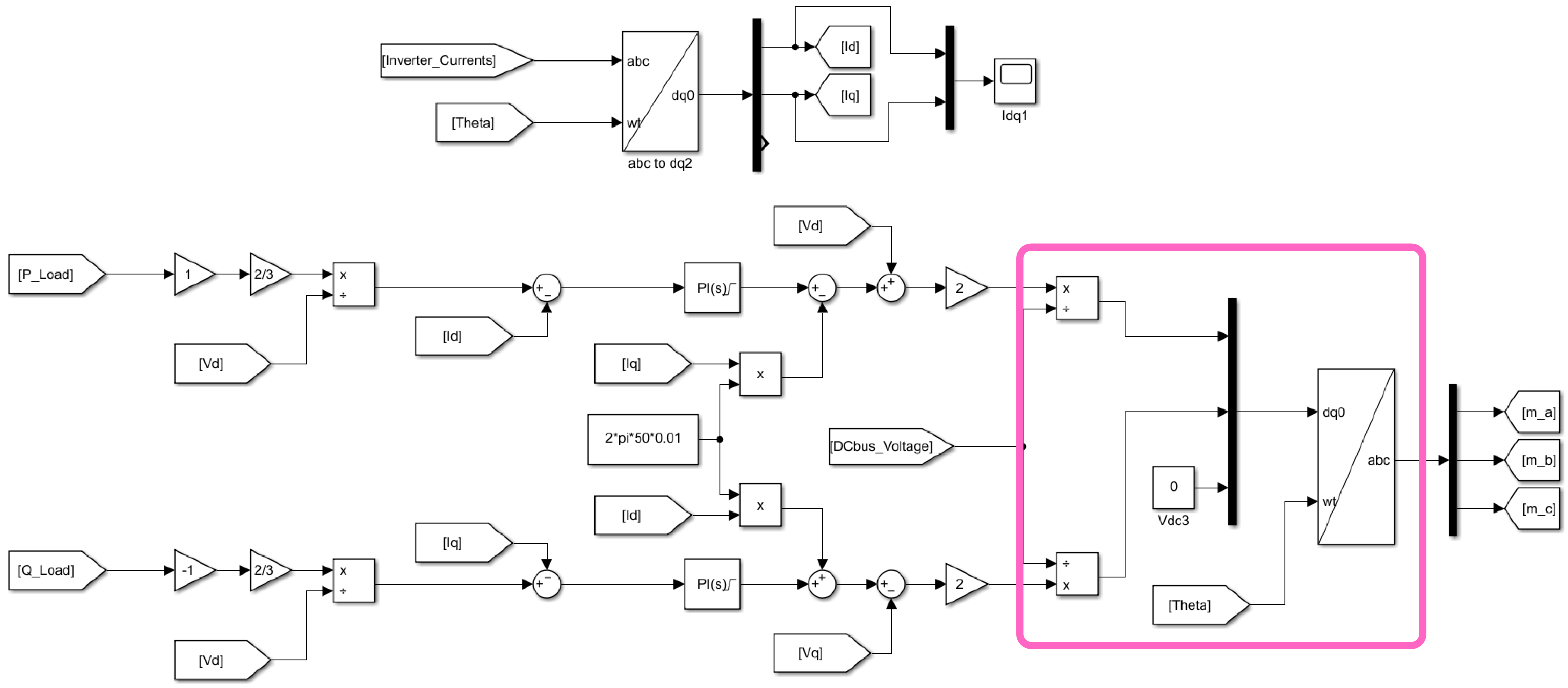




CURRENT CONTROL METHODOLOGY

Reactive Power Compensation and Active Power Delivery

- The outputs of both paths are combined and converted back to the abc frame to generate the reference waveforms for the PWM generation



PWM GENERATION

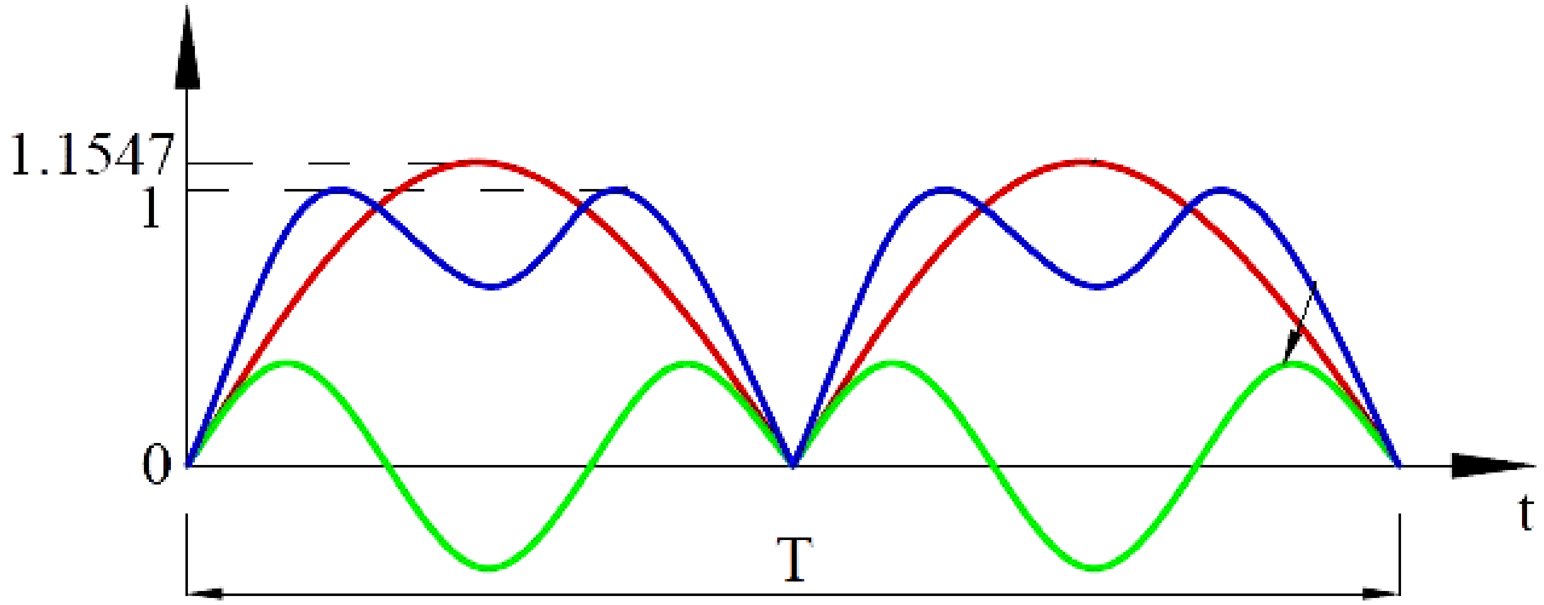
Methodology - Space Vector Pulse Width Modulation

Advantages

- Low harmonic content
- Higher DC bus utilization through third harmonic injection

Chen and Zhao documents an SVPWM achieving THD of 1.95% which is the lowest out of other considered options

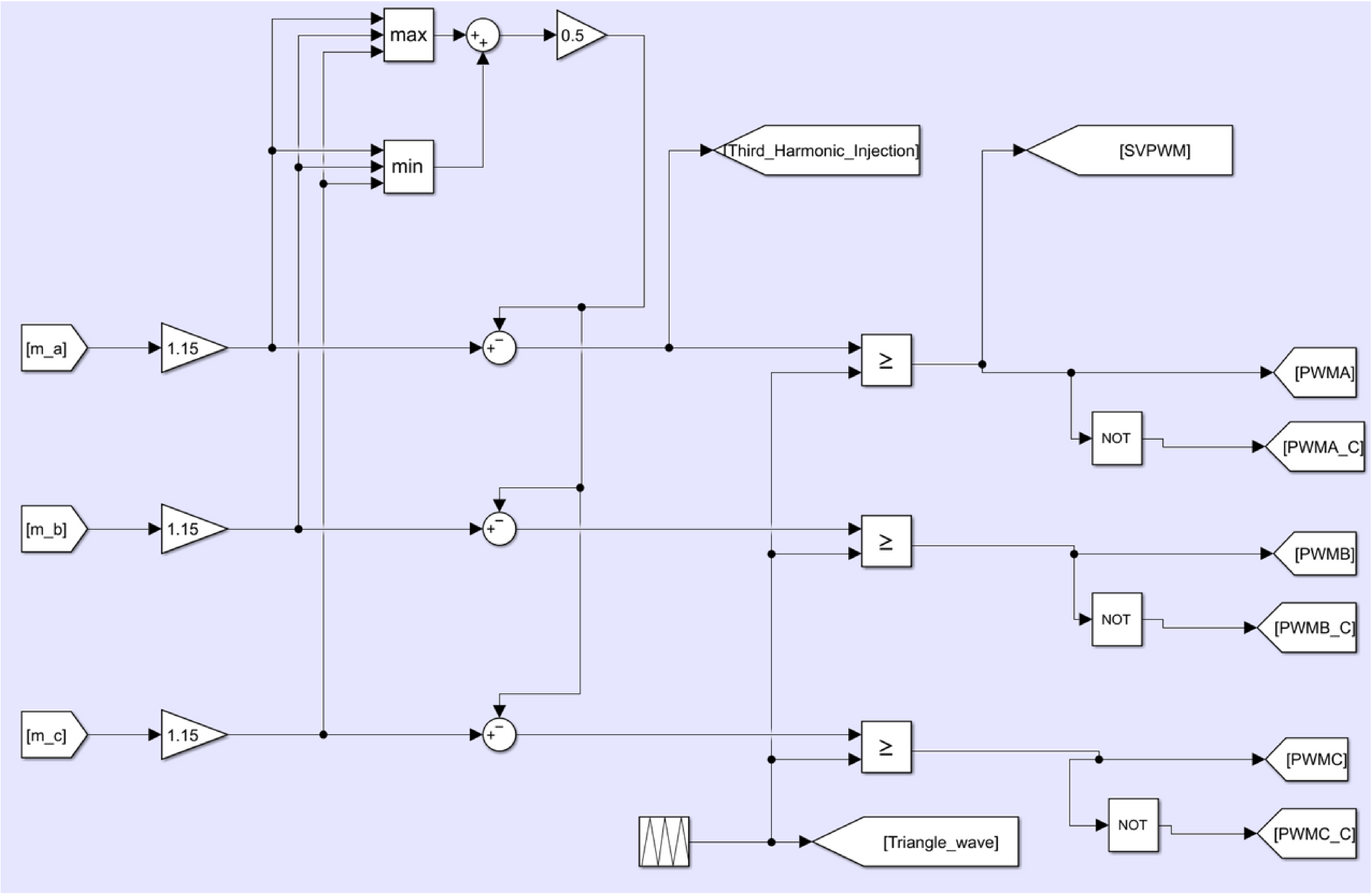
Chen, H. and Zhao, H. (2016), Review on pulse-width modulation strategies for common-mode voltage reduction in three-phase voltage-source inverters. IET Power Electronics, 9: 2611-2620. https://doi.org/10.1049/iet-pel.2015.1019



PWM GENERATION

Functionality

- Generate gate driving PWM signals for the MOSFETs in the H-Bridge.
- PWM Frequency - 5 kHz - 15 kHz



GRID SERVICES

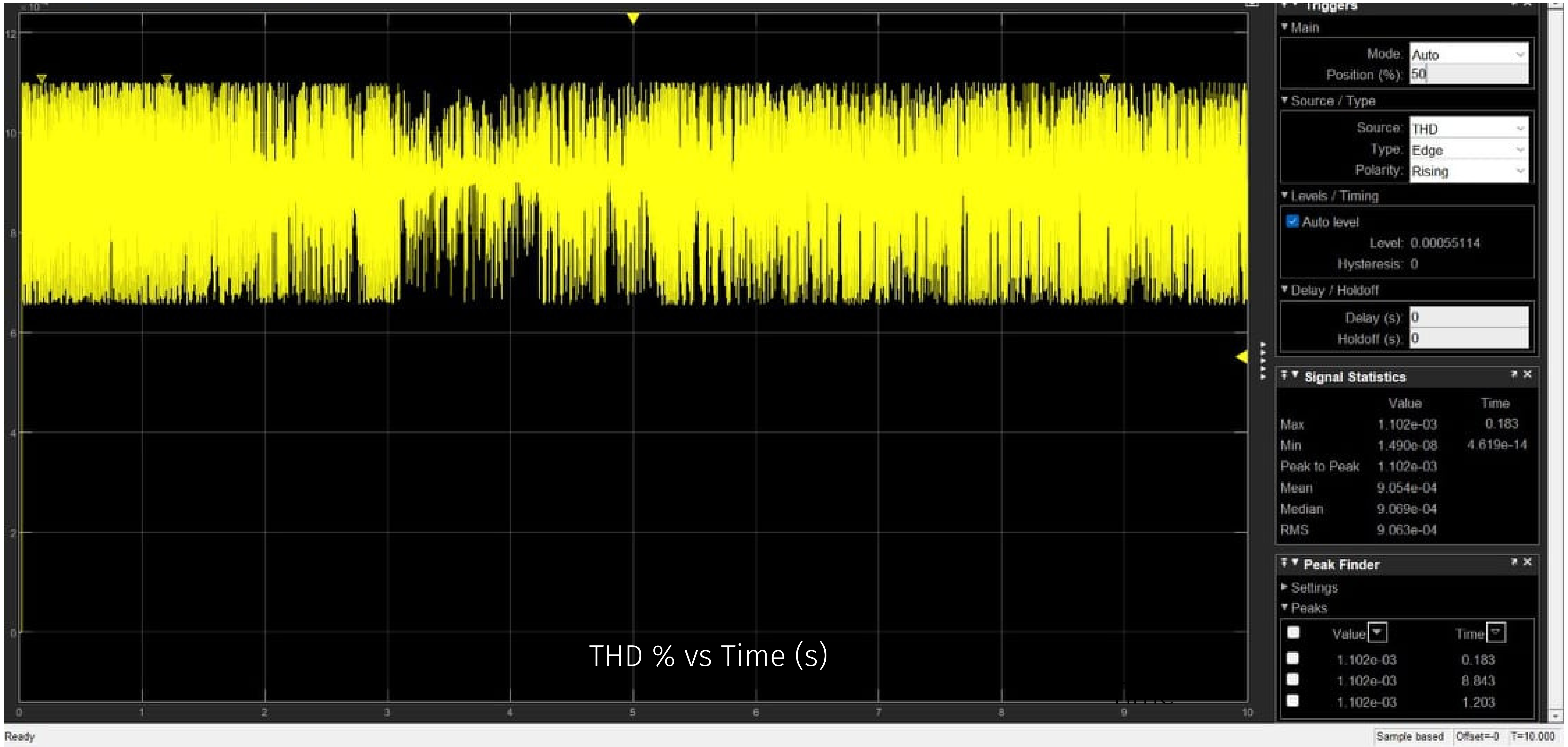
TOTAL HARMONIC DISTORTION

At 1 kW

THD at 1kW = 0.0009069

1.102e-3 →

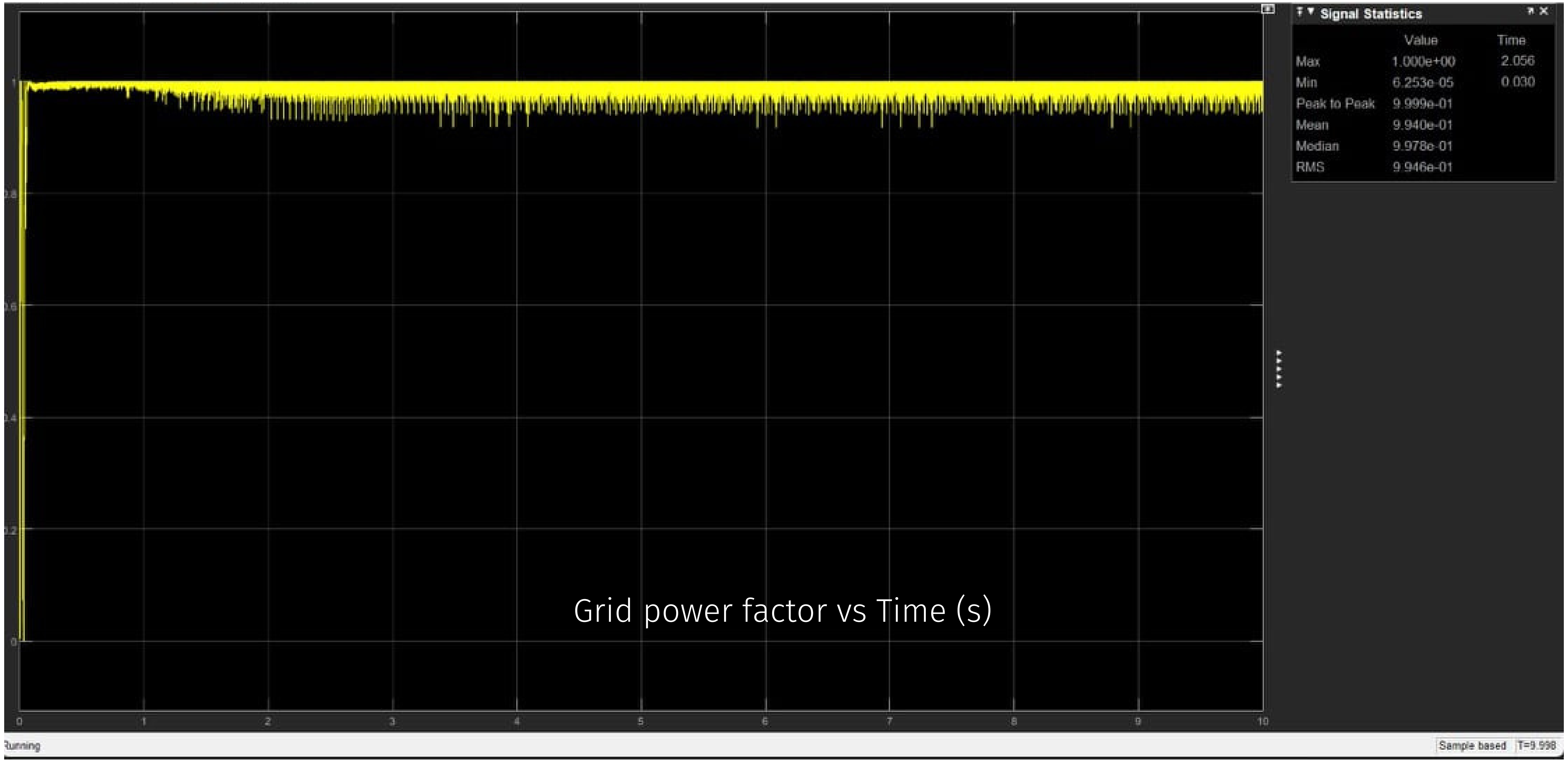
1.490e-8 →



GRID POWER FACTOR

When 1kW active power is demanded

Power Factor = 0.9945



Grid power factor vs Time (s)

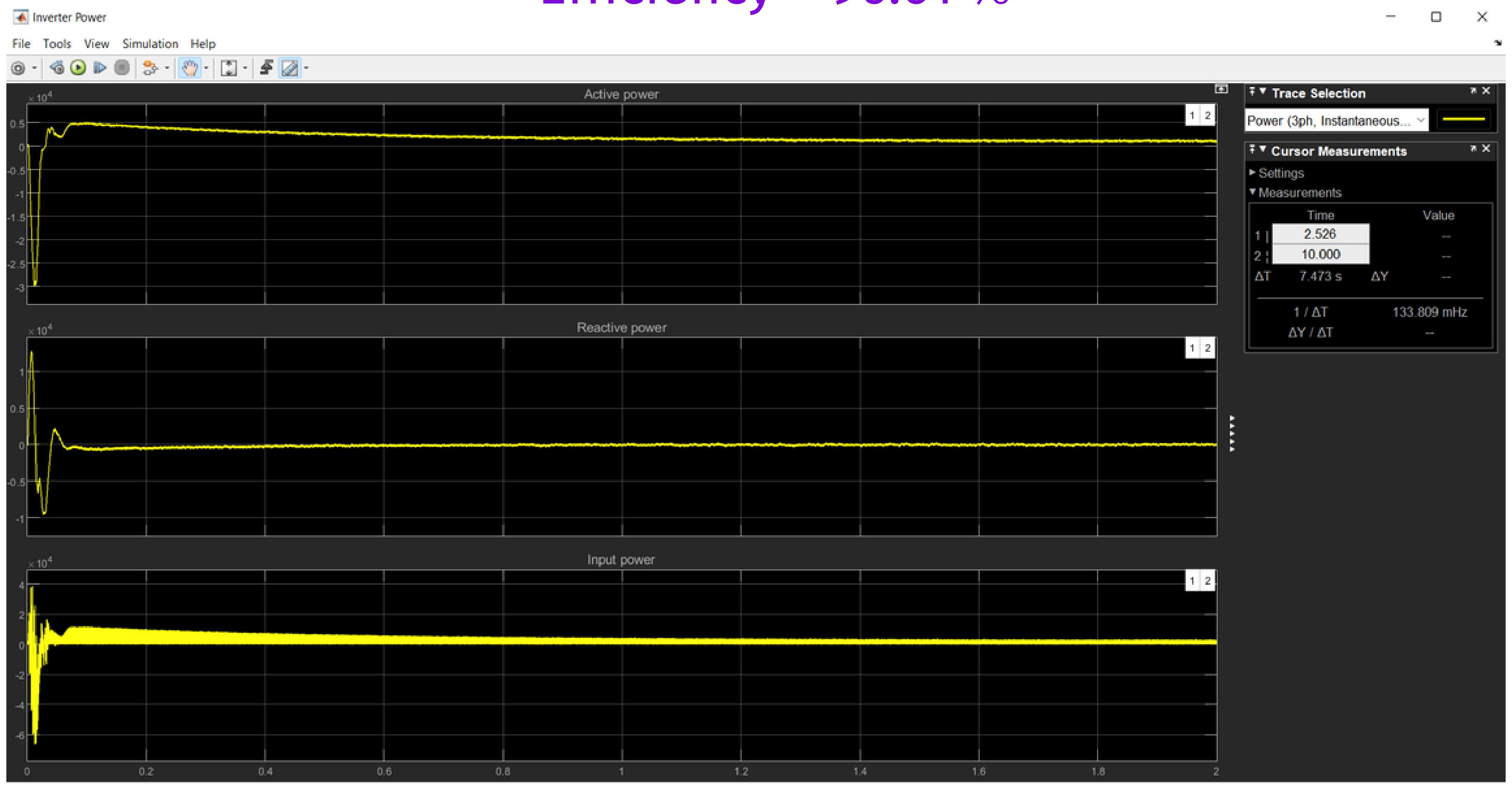
OVERALL SOLAR TO GRID POWER EFFICIENCY

When 1kW

Output power = 1.055 kW

Input power = 1.092 kW

Efficiency = 96.61 %

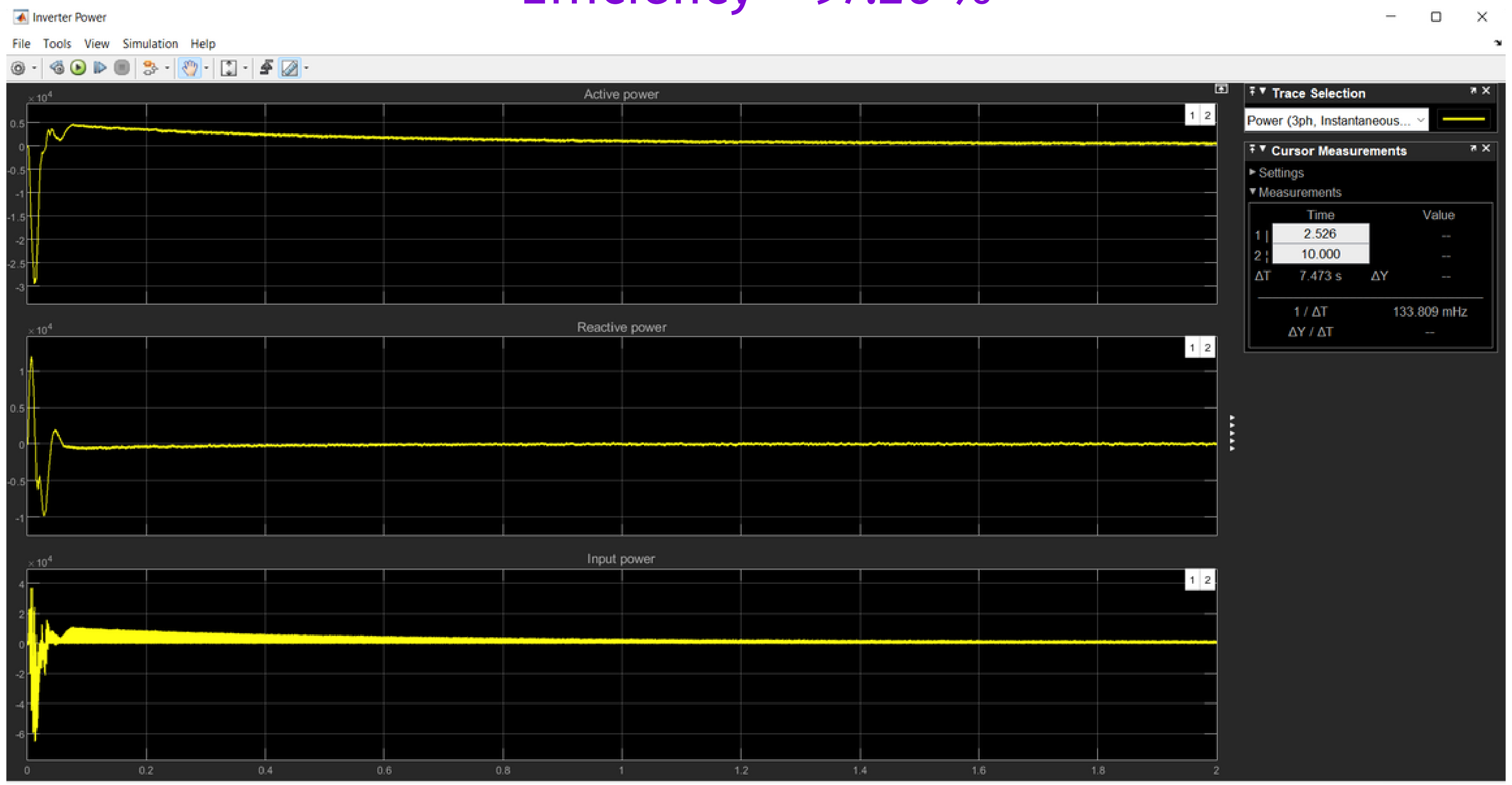


When 500 W

Output power = 533 W

Input power = 548 W

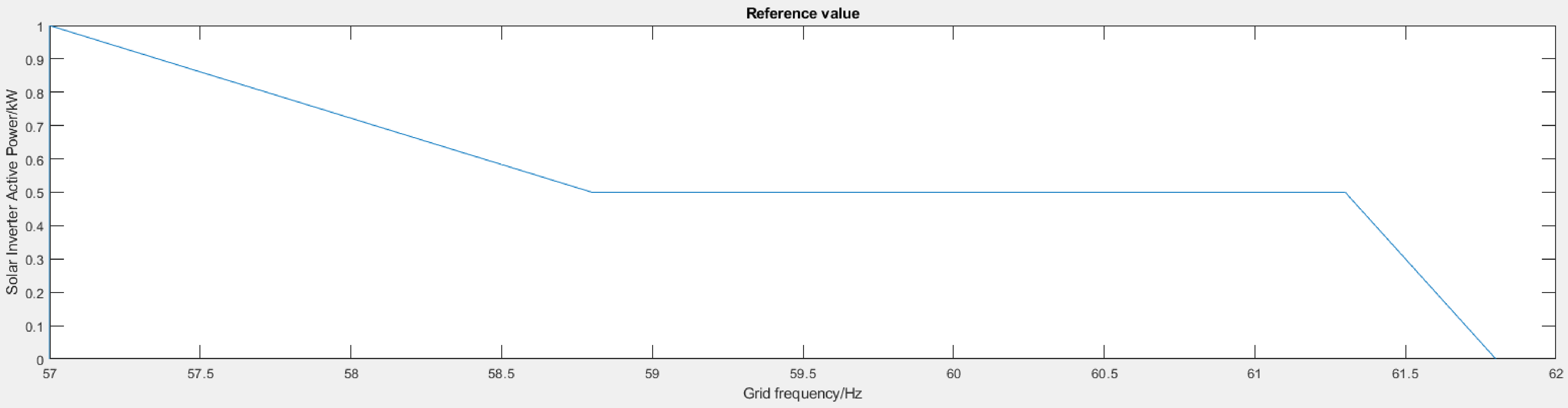
Efficiency = 97.26 %



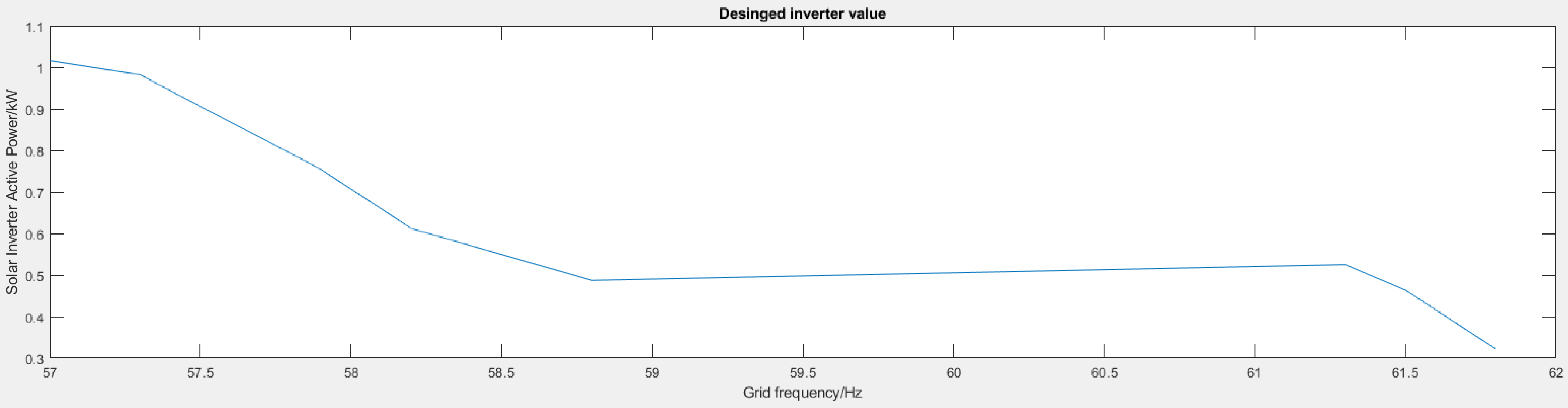
ACTIVE POWER DELIVERY

When the grid frequency is within (58.8Hz-61.3Hz)

Expected Graph in RFP



Achieved Graph in Simulation

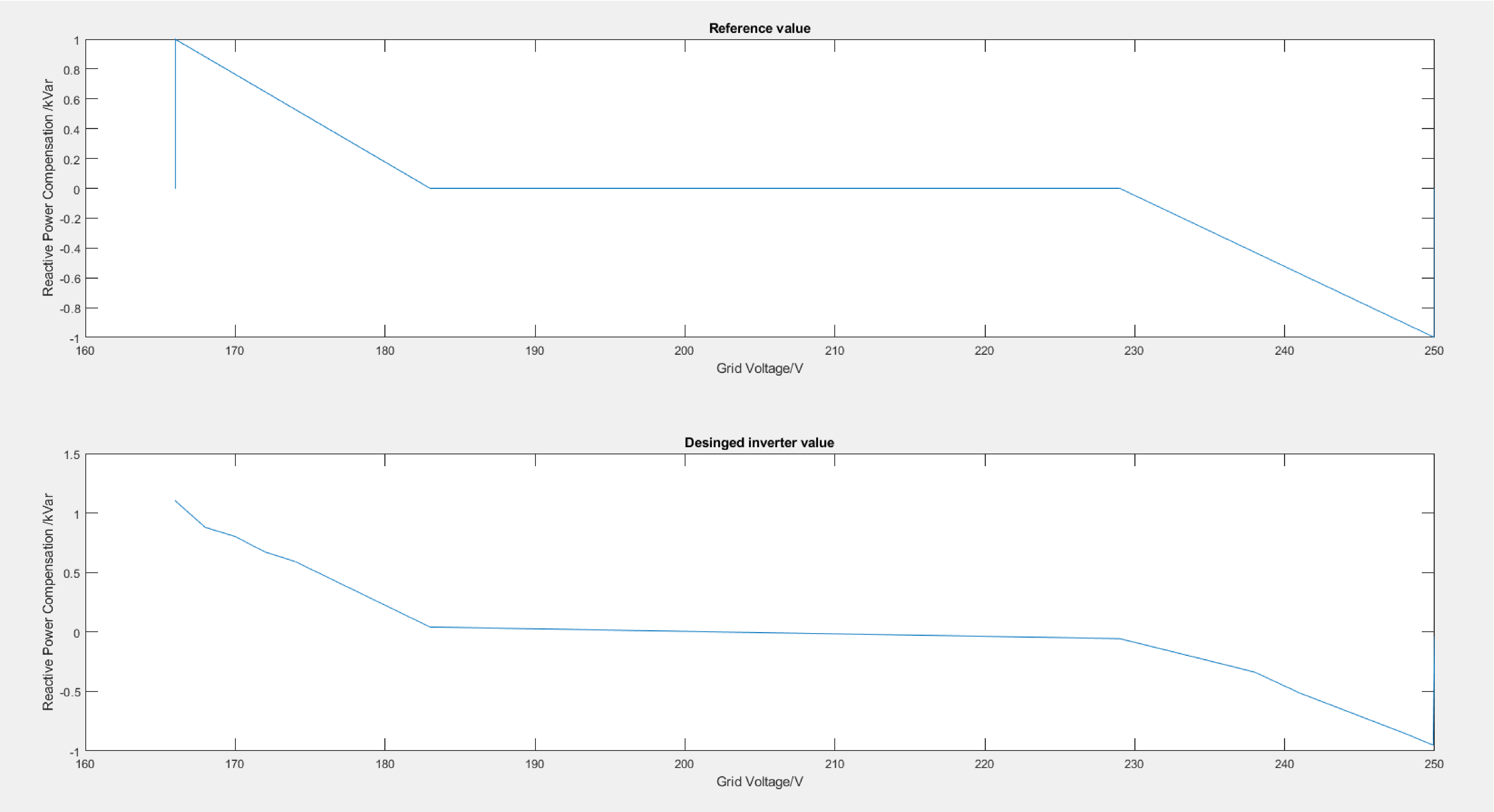


REACTIVE POWER COMPENSATION

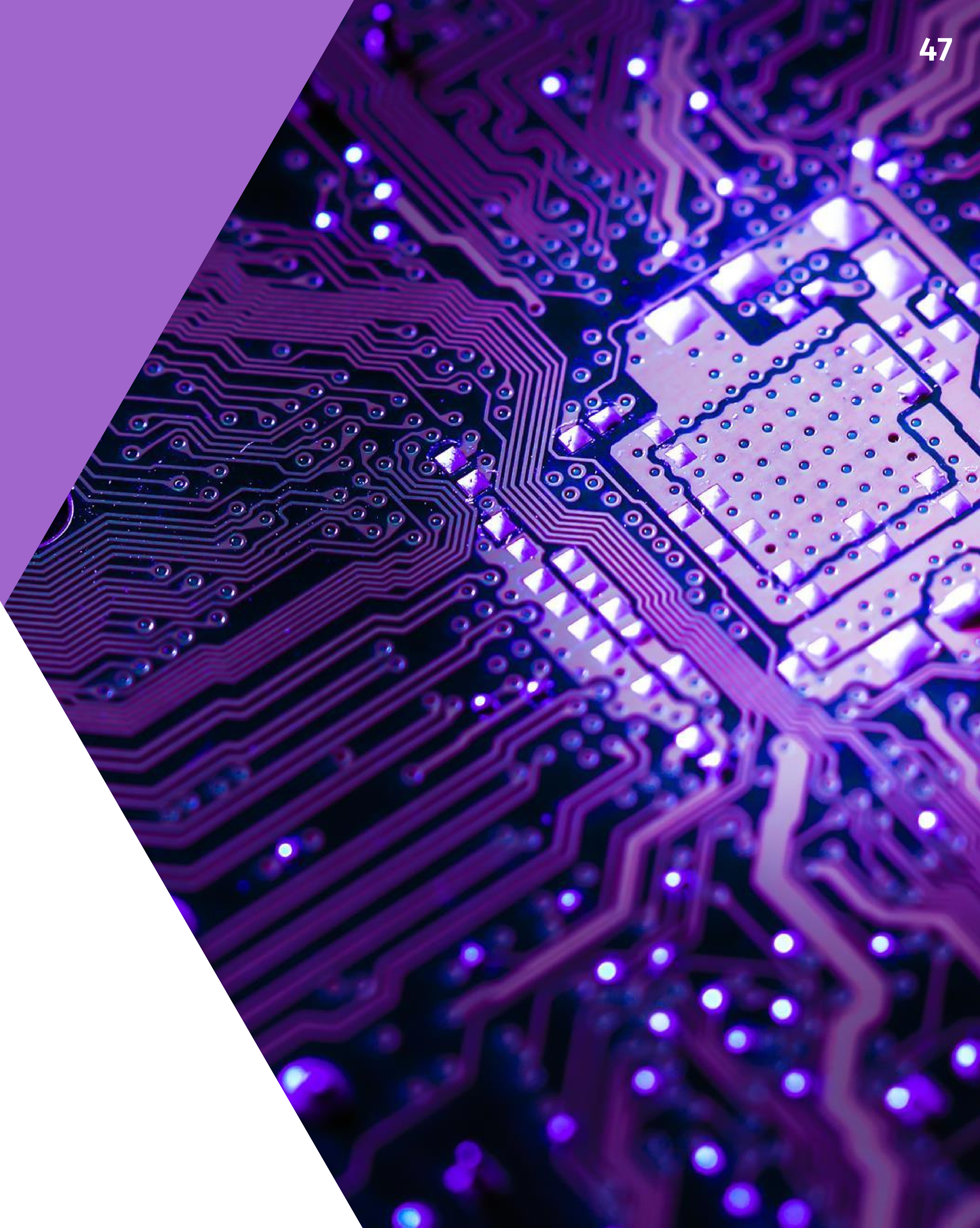
When 1kW active power is demanded

Expected Graph in RFP

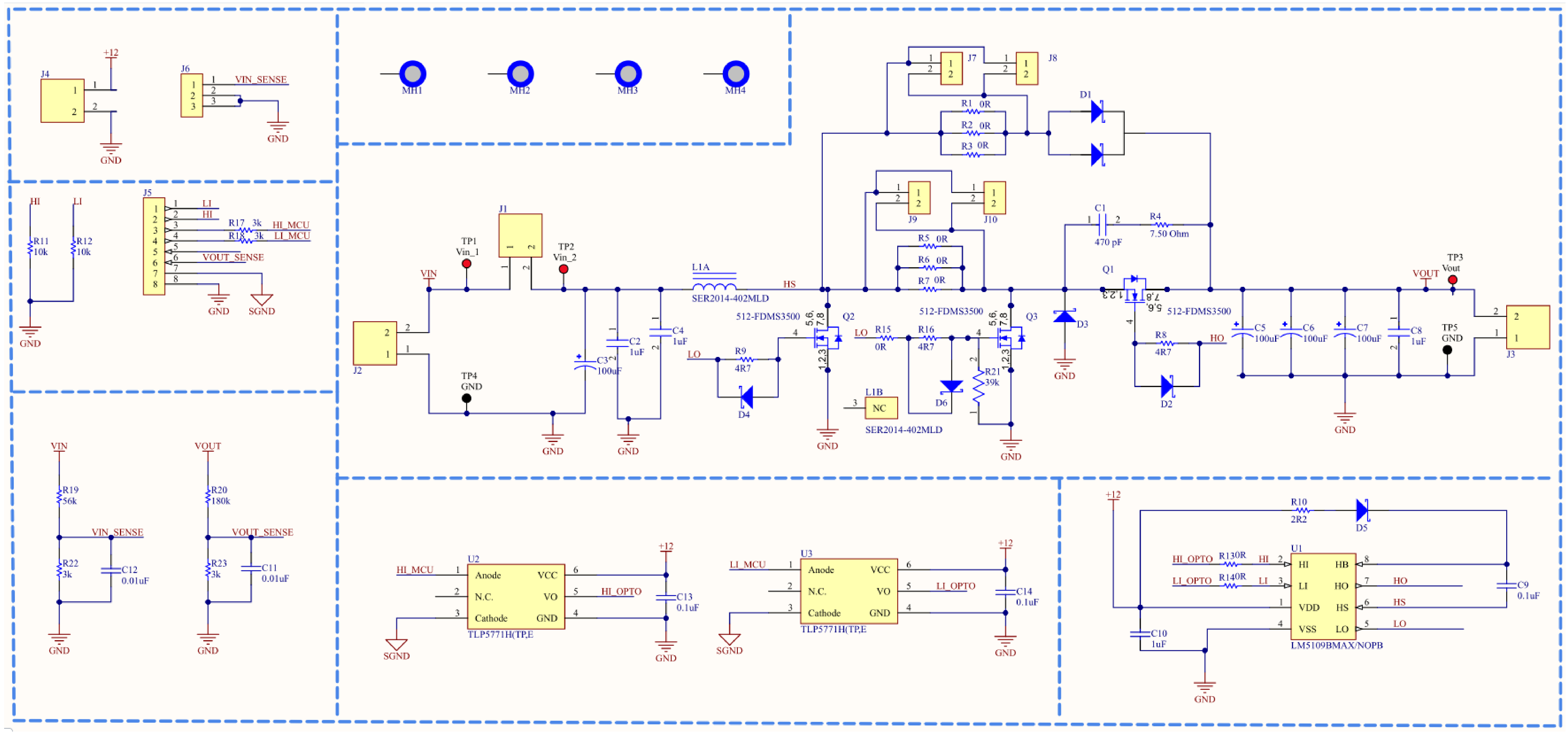
Achieved Graph in Simulation



HARDWARE IMPLEMENTATION



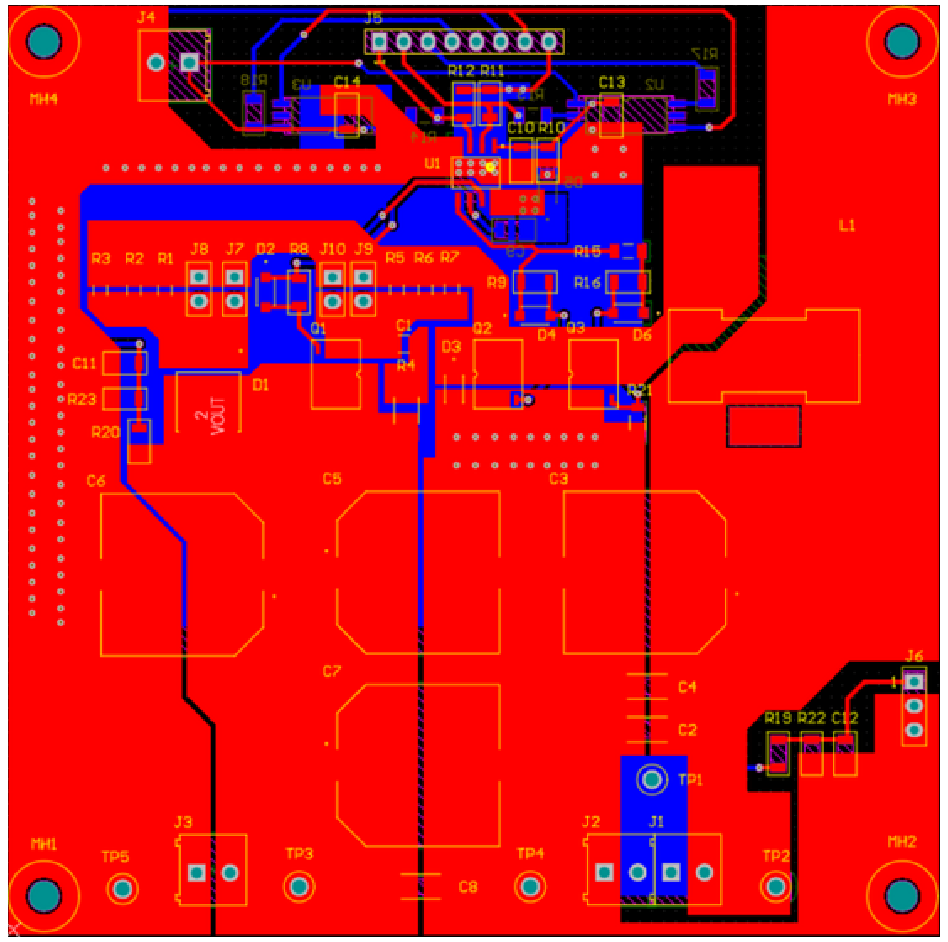
MPPT BOOSTER



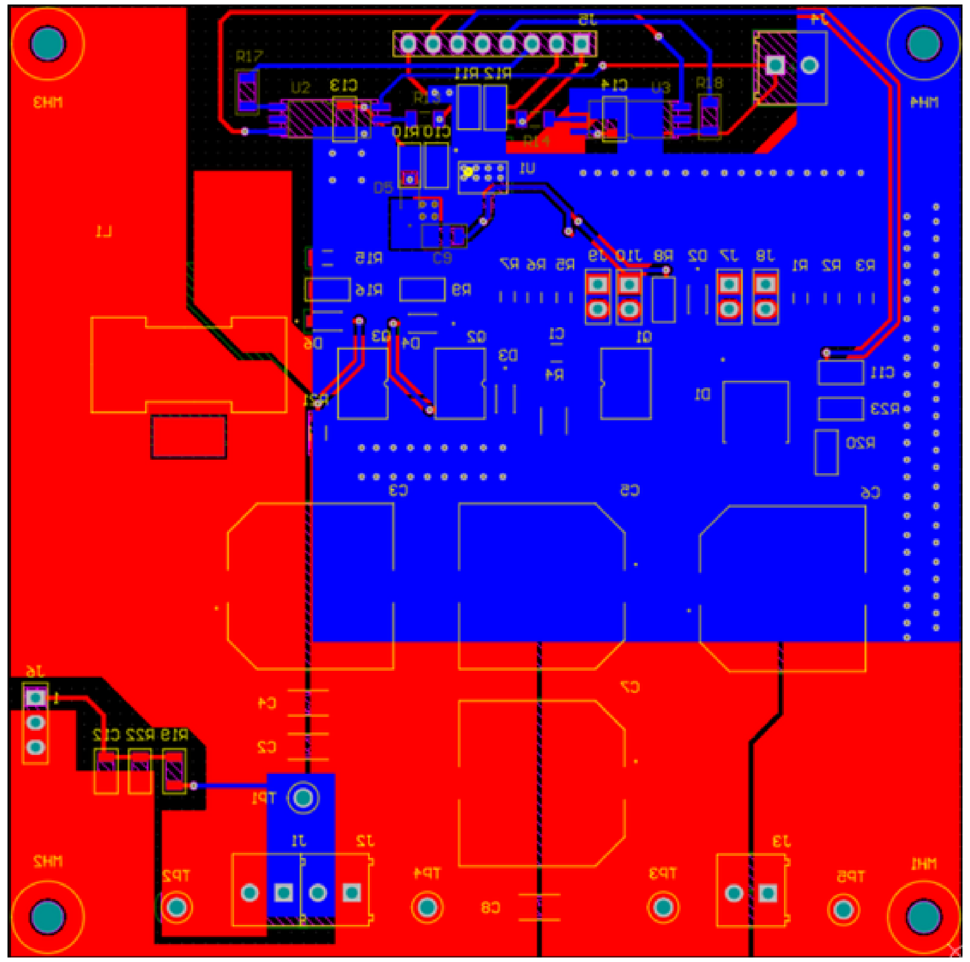
PMP9431
135W Single-Phase Synchronous Boost Converter Reference Design by Texas Instruments

https://www.ti.com/tool/PMP9431

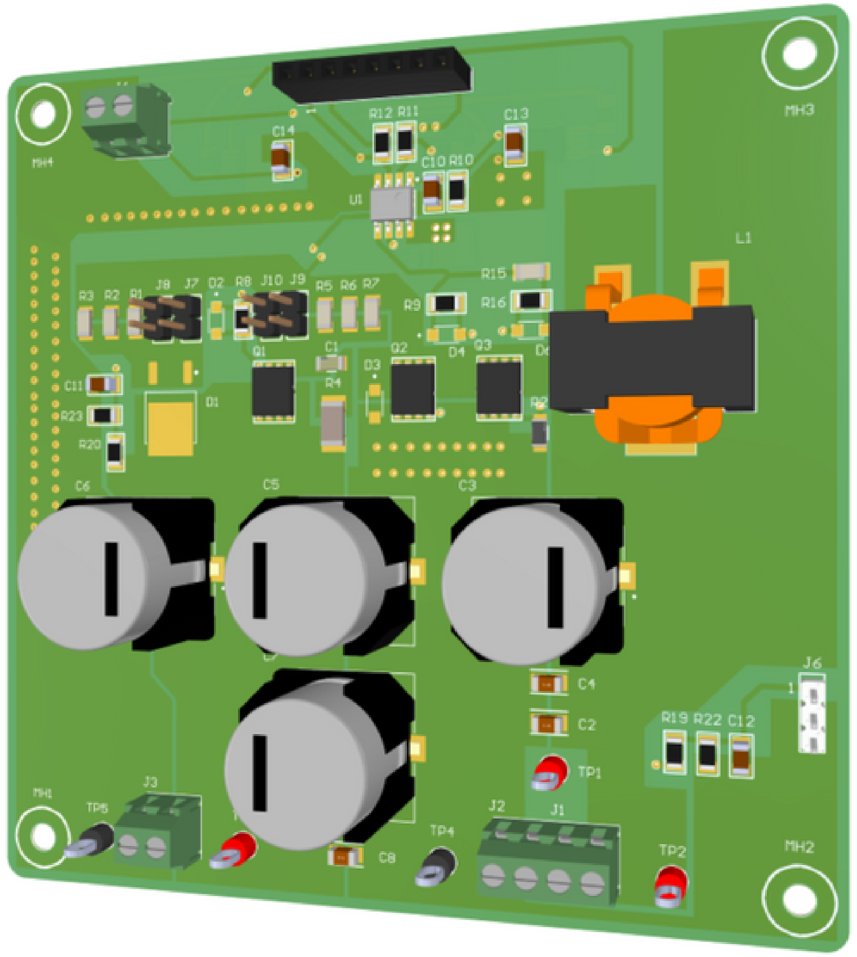
MPPT BOOSTER



Top side

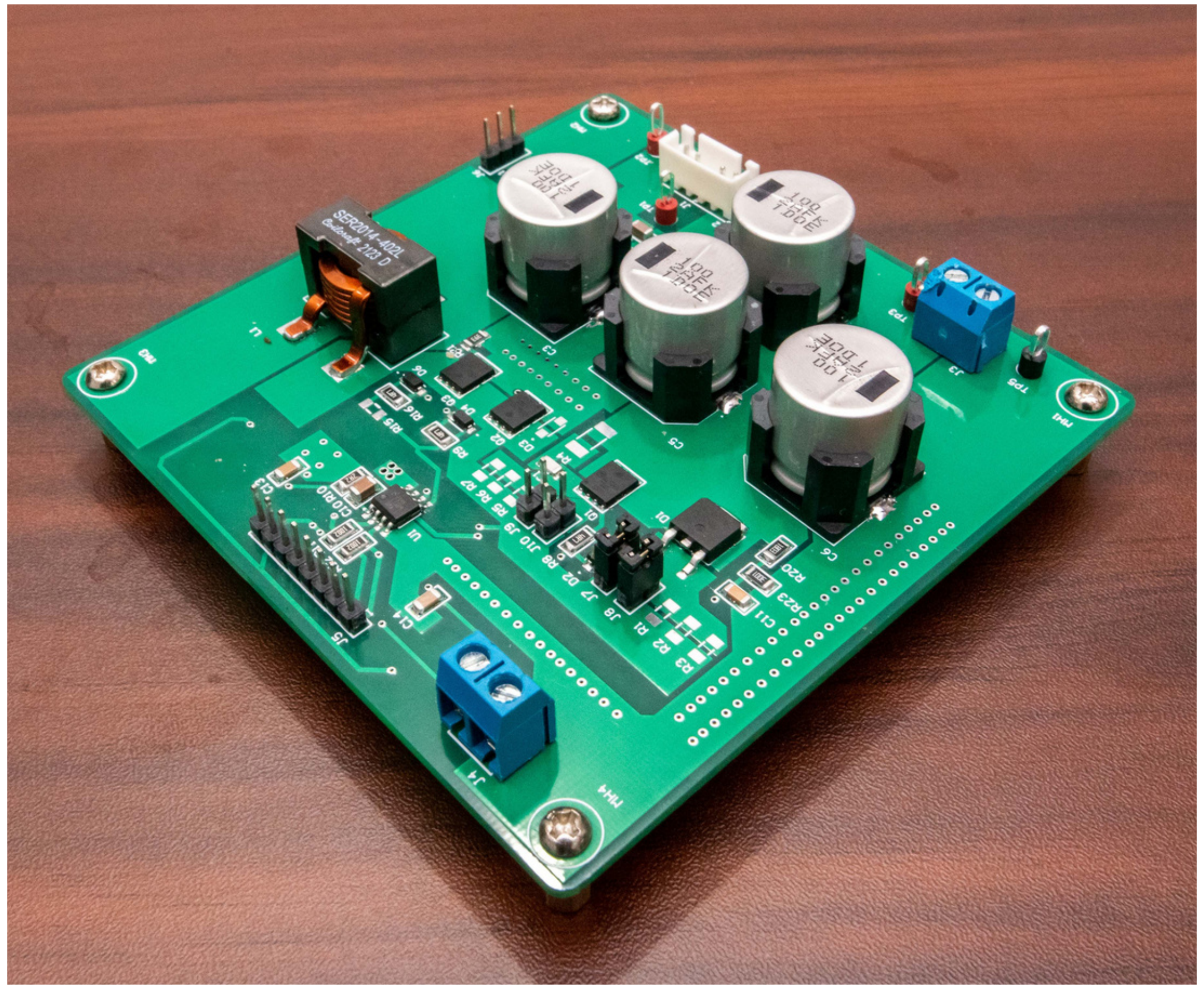


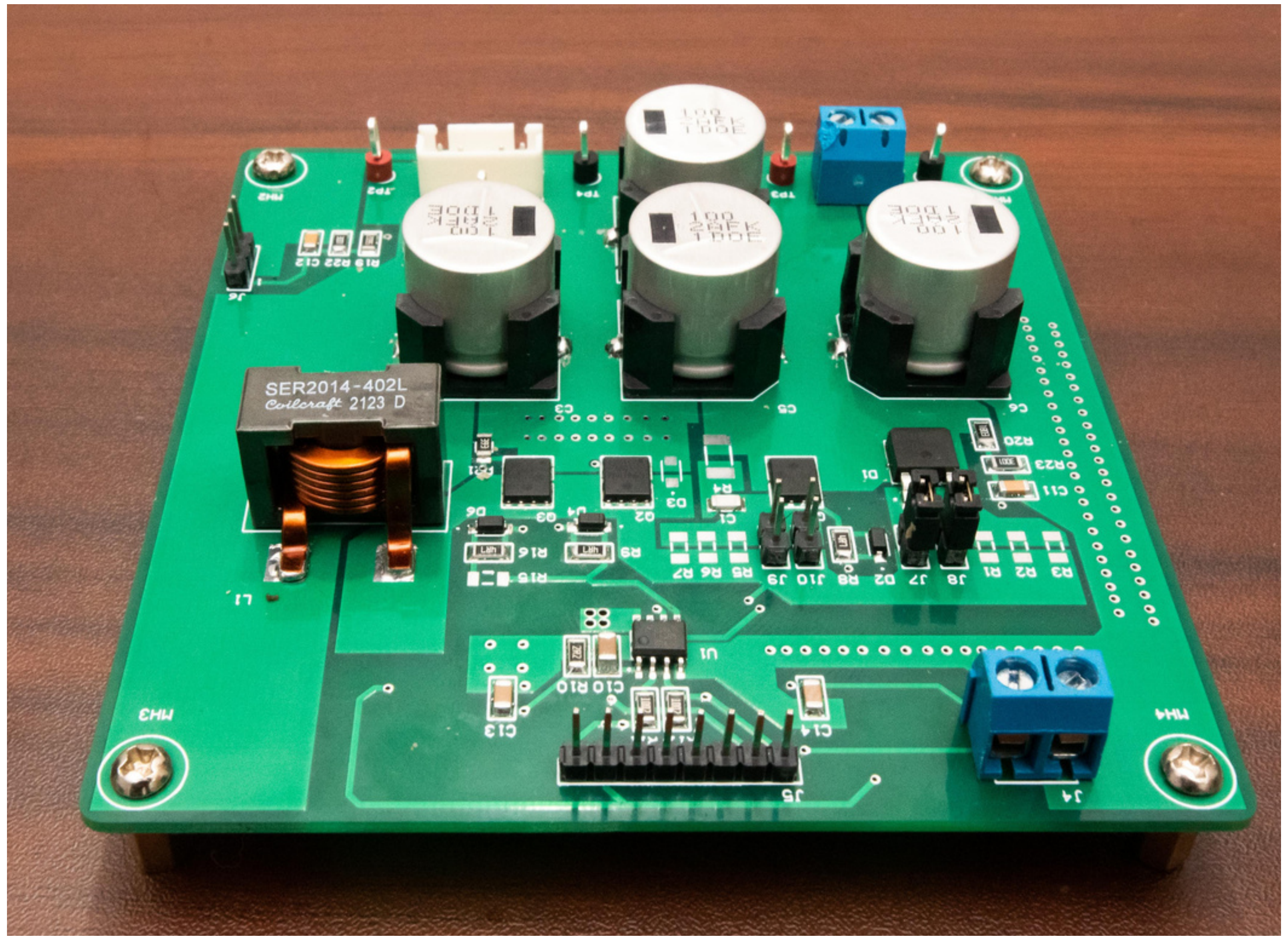
Bottom side



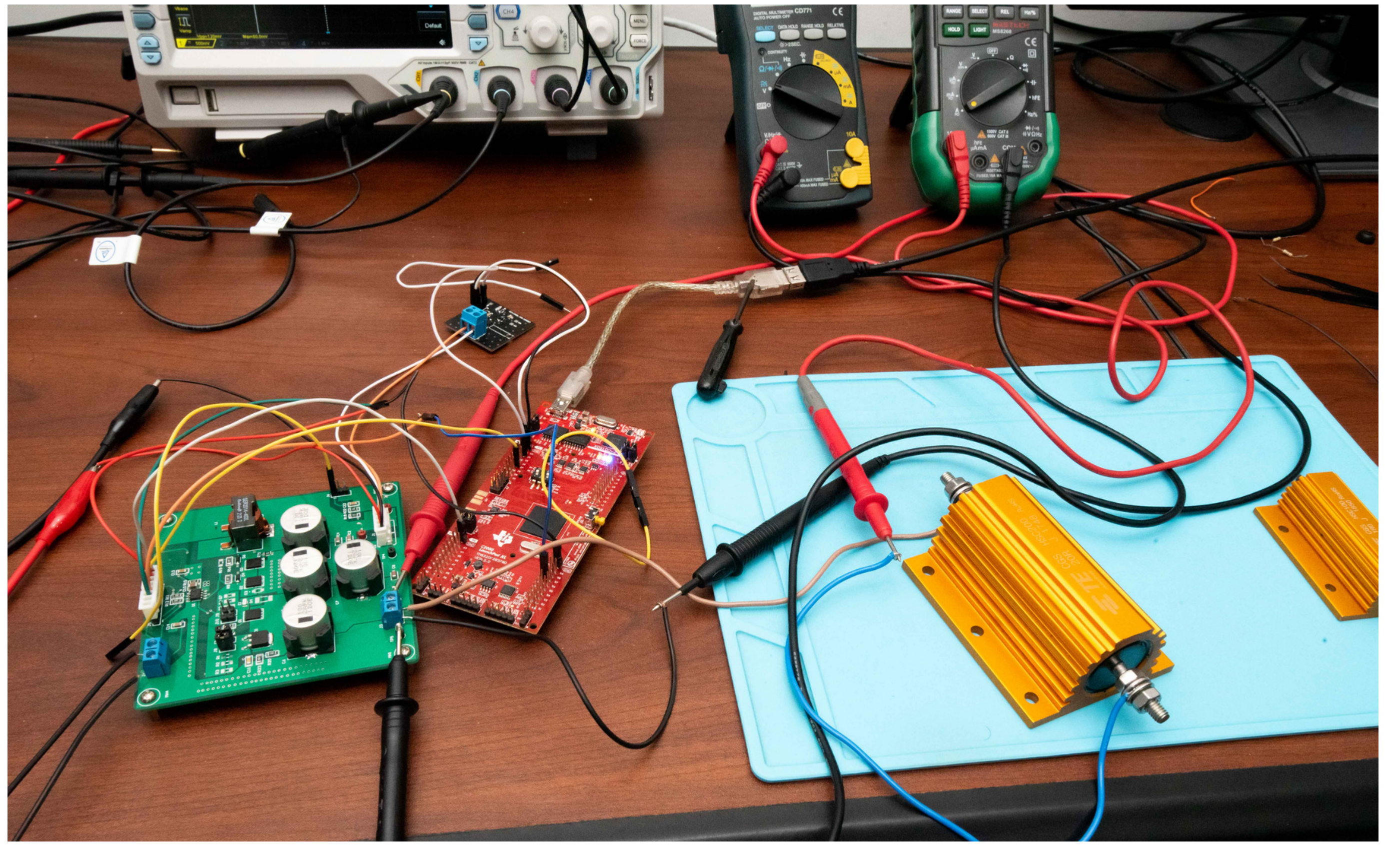
3D View of the PCB

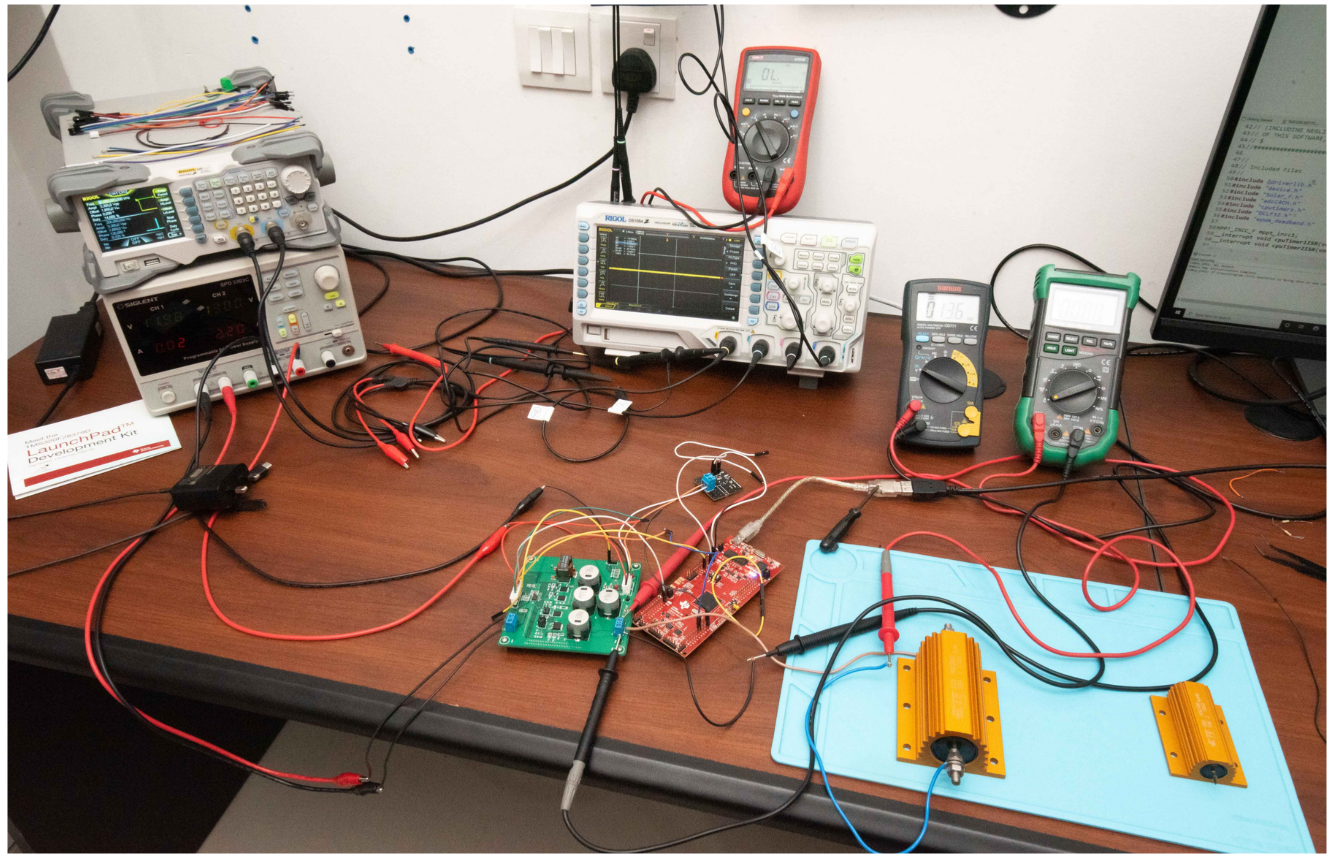
MPPT BOOSTER



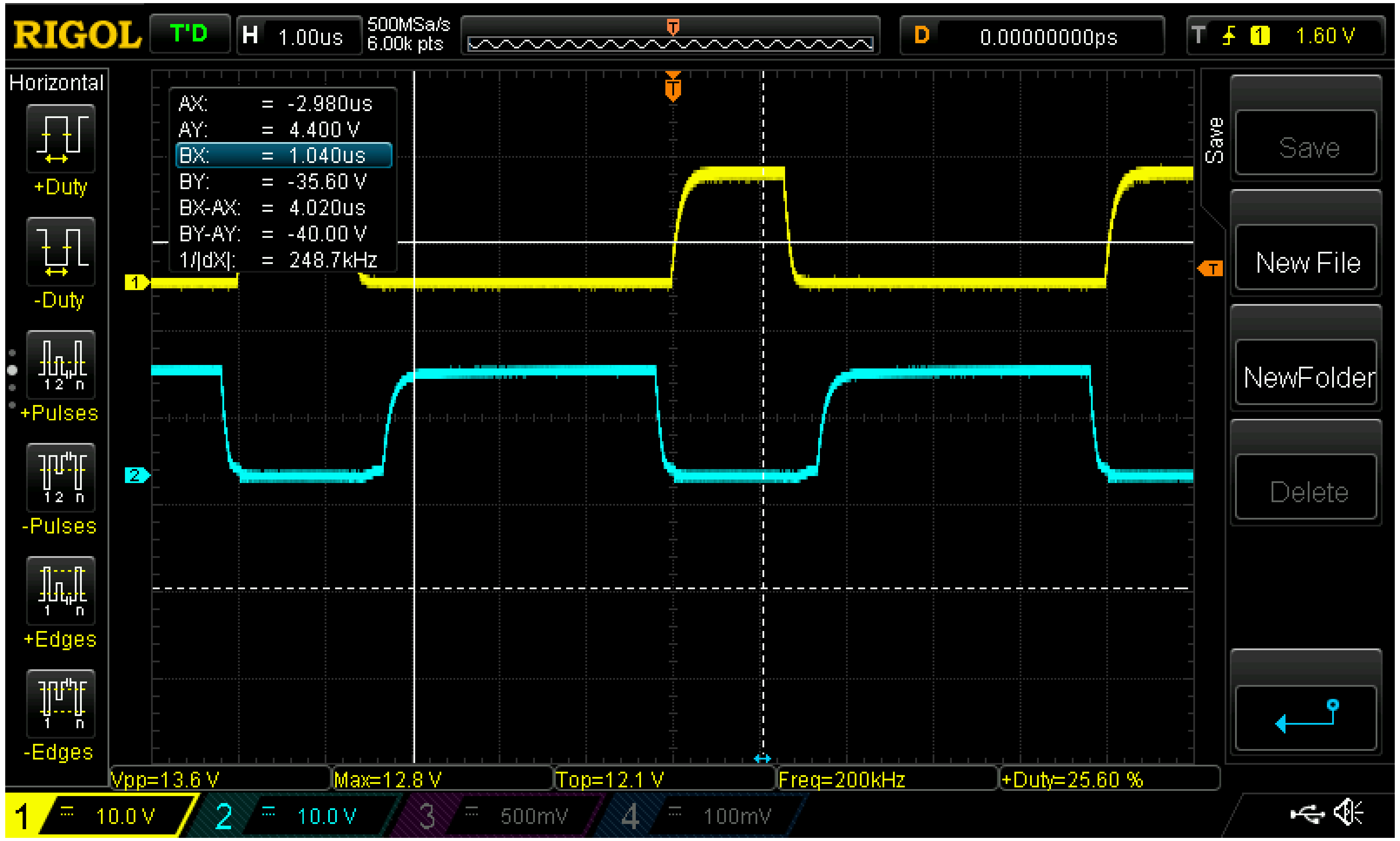


MPPT BOOSTER TESTING





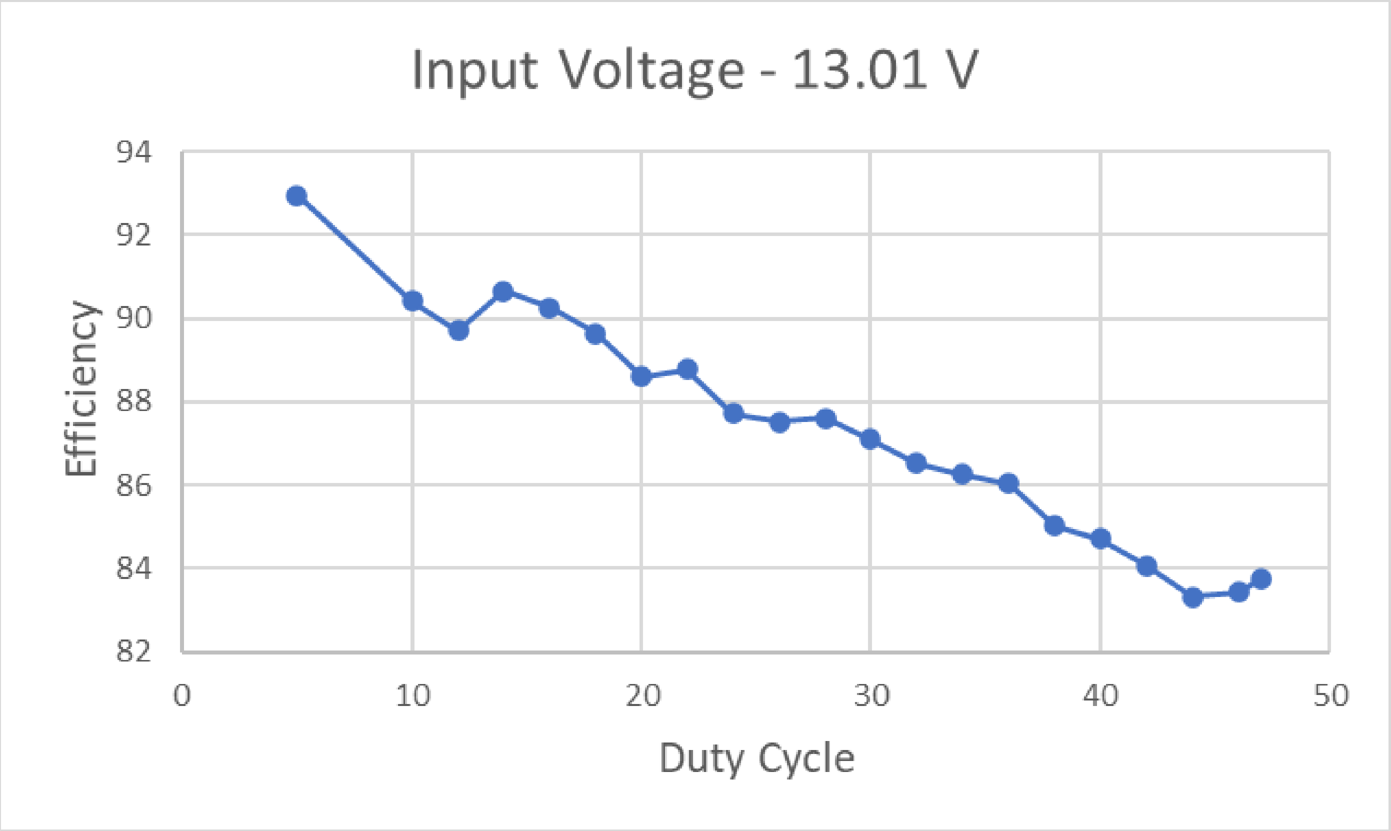
MPPT BOOSTER TESTING RESULTS

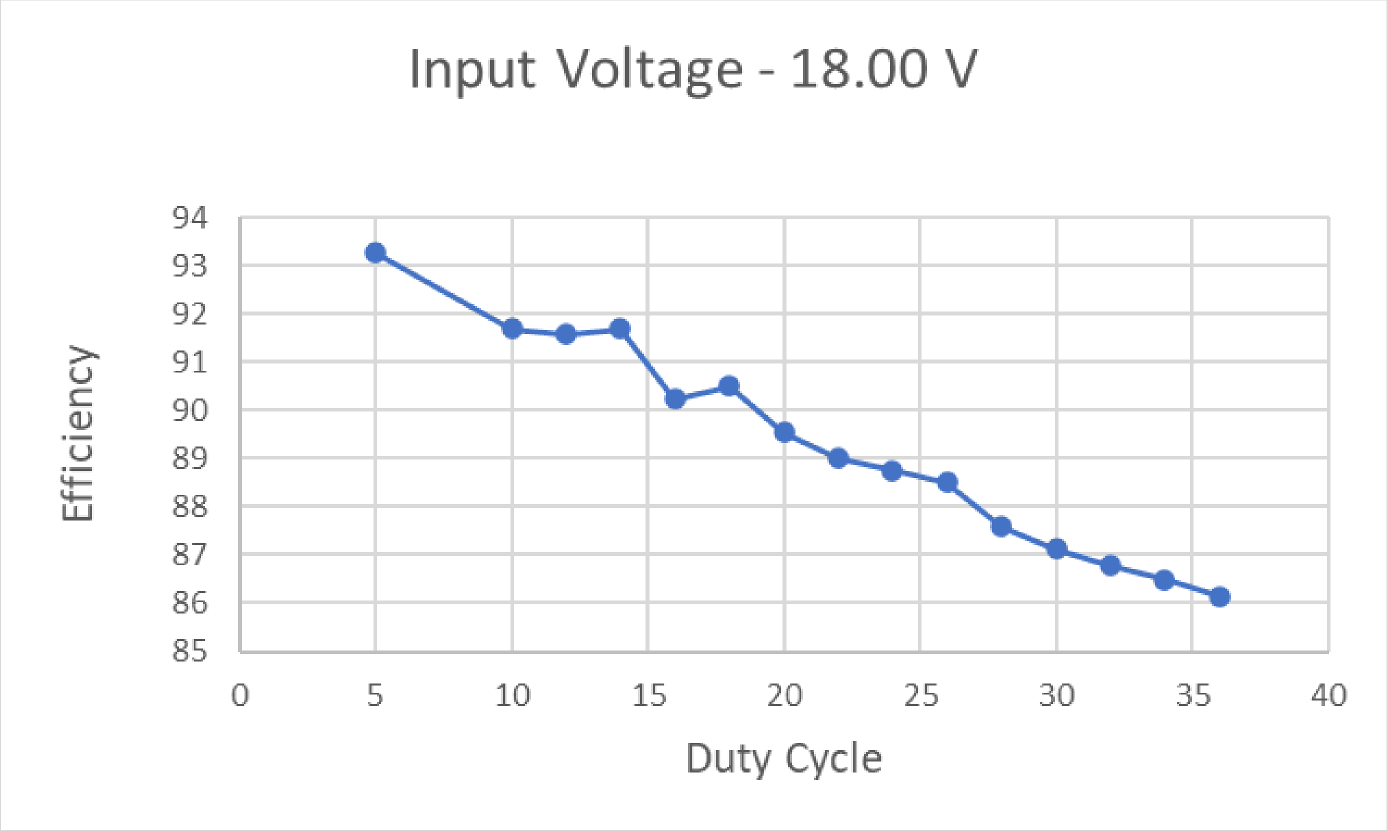


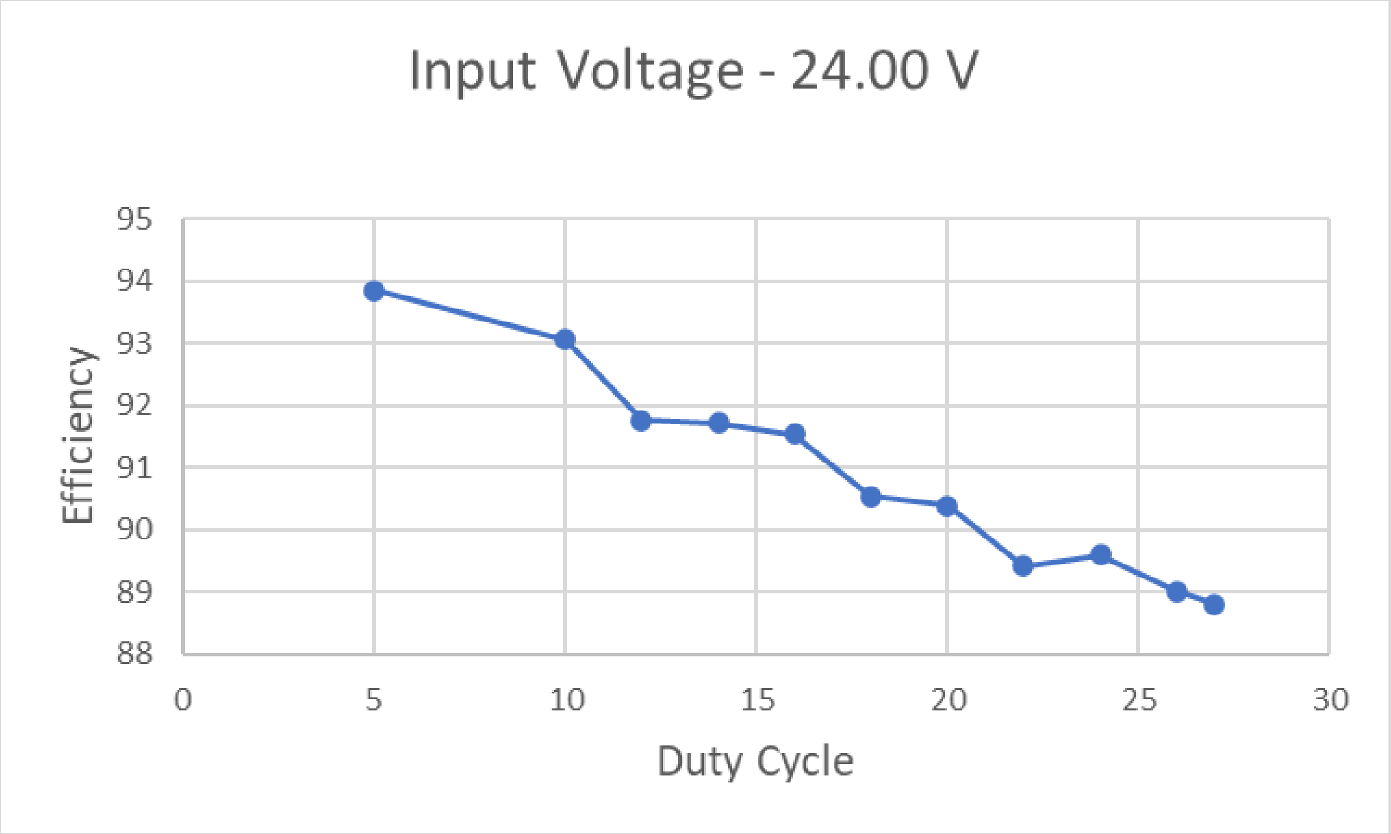
- The Gate Driving Signals of the two MOSFETs with the dead times in the Synchronous Boost Converter design
- The signals are generated from the C2000 microcontroller.

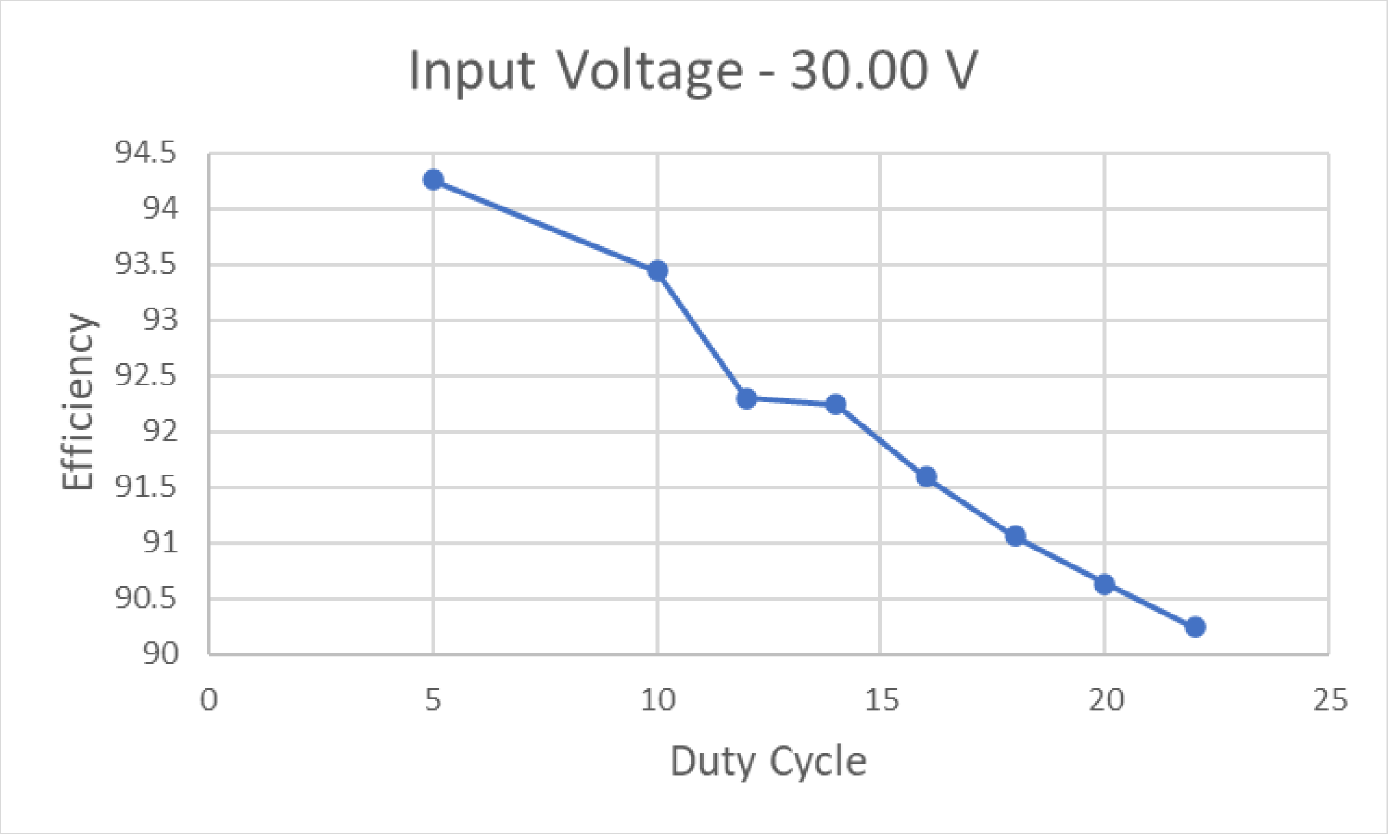
ASYNCHRONOUS BOOST CONVERTER

Duty Cycle vs. Efficiency Graph









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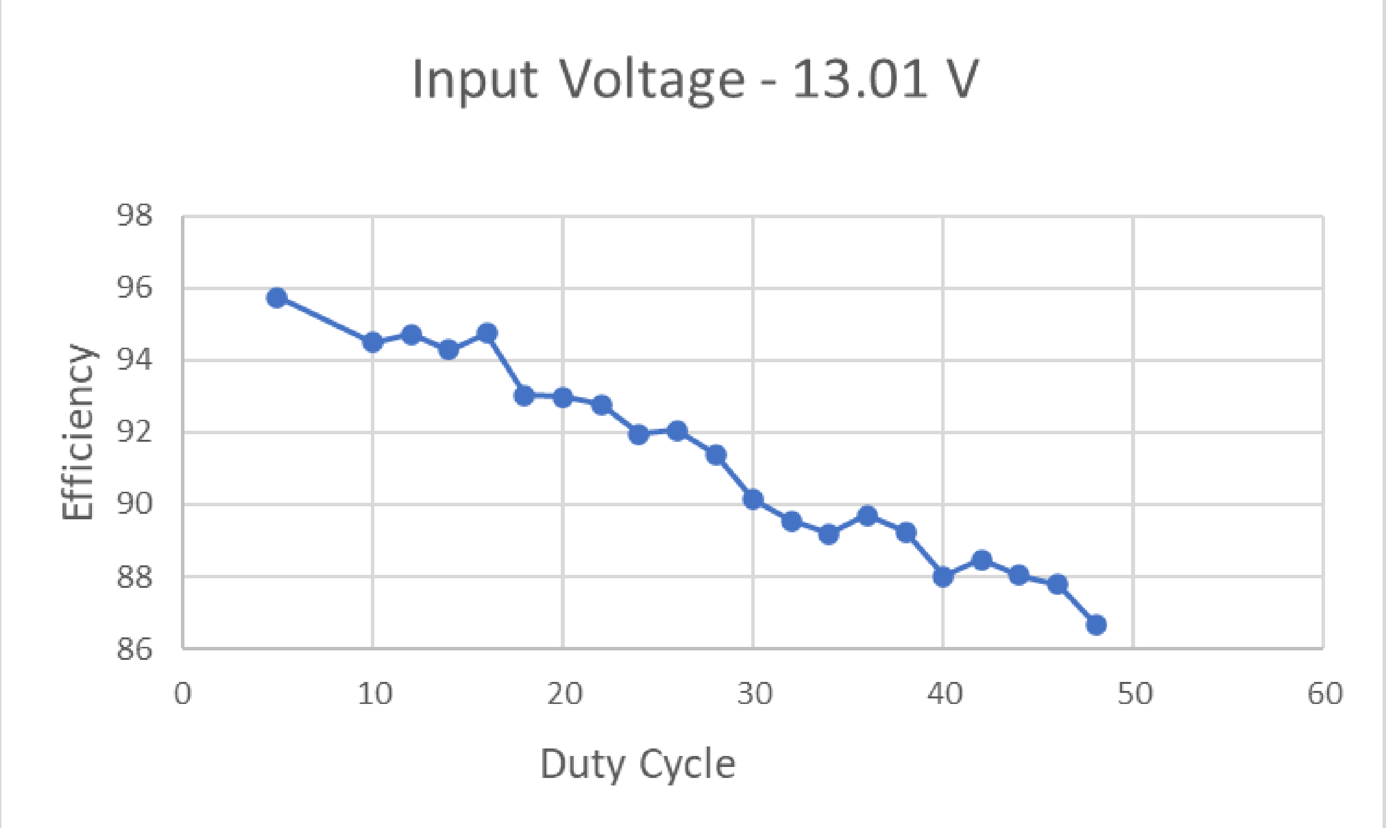
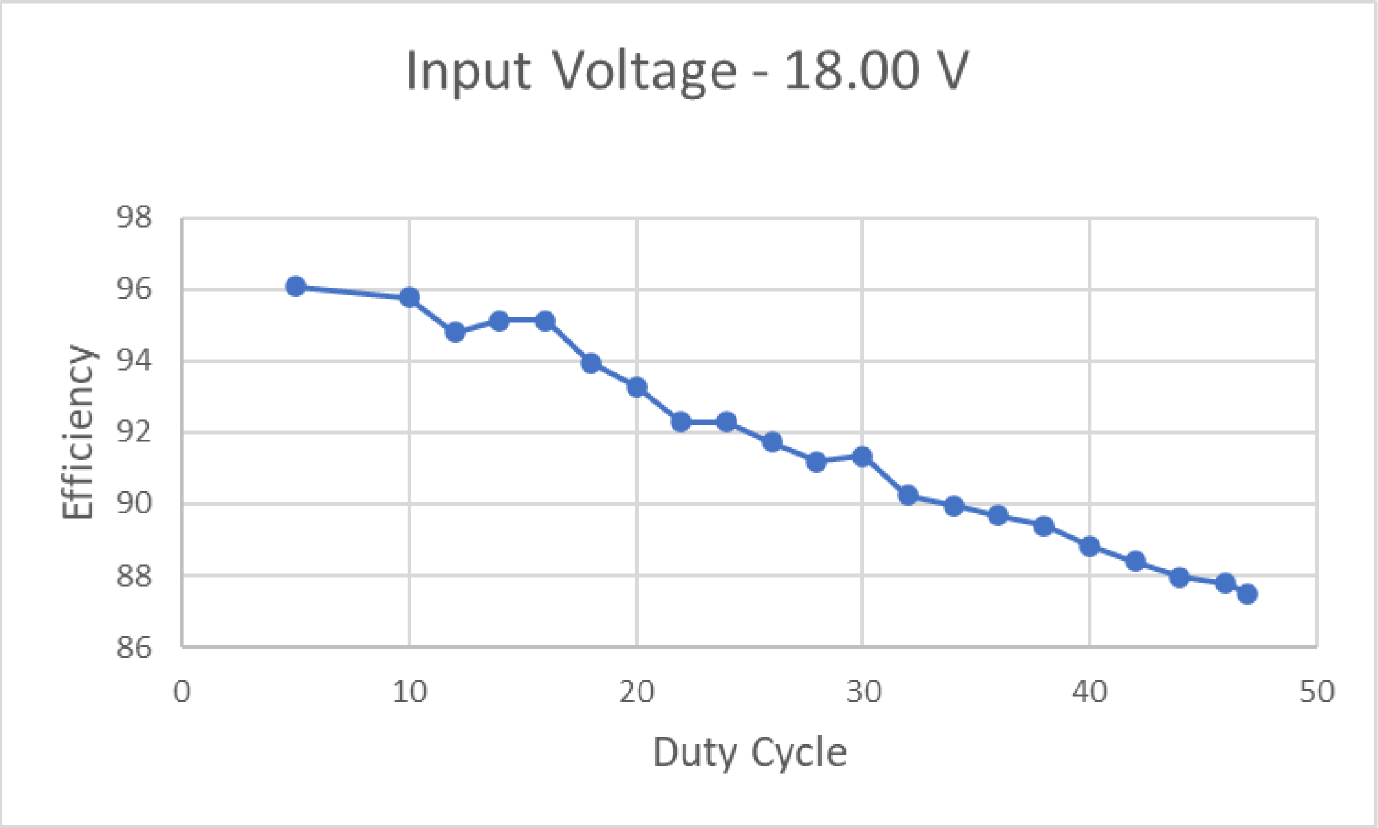
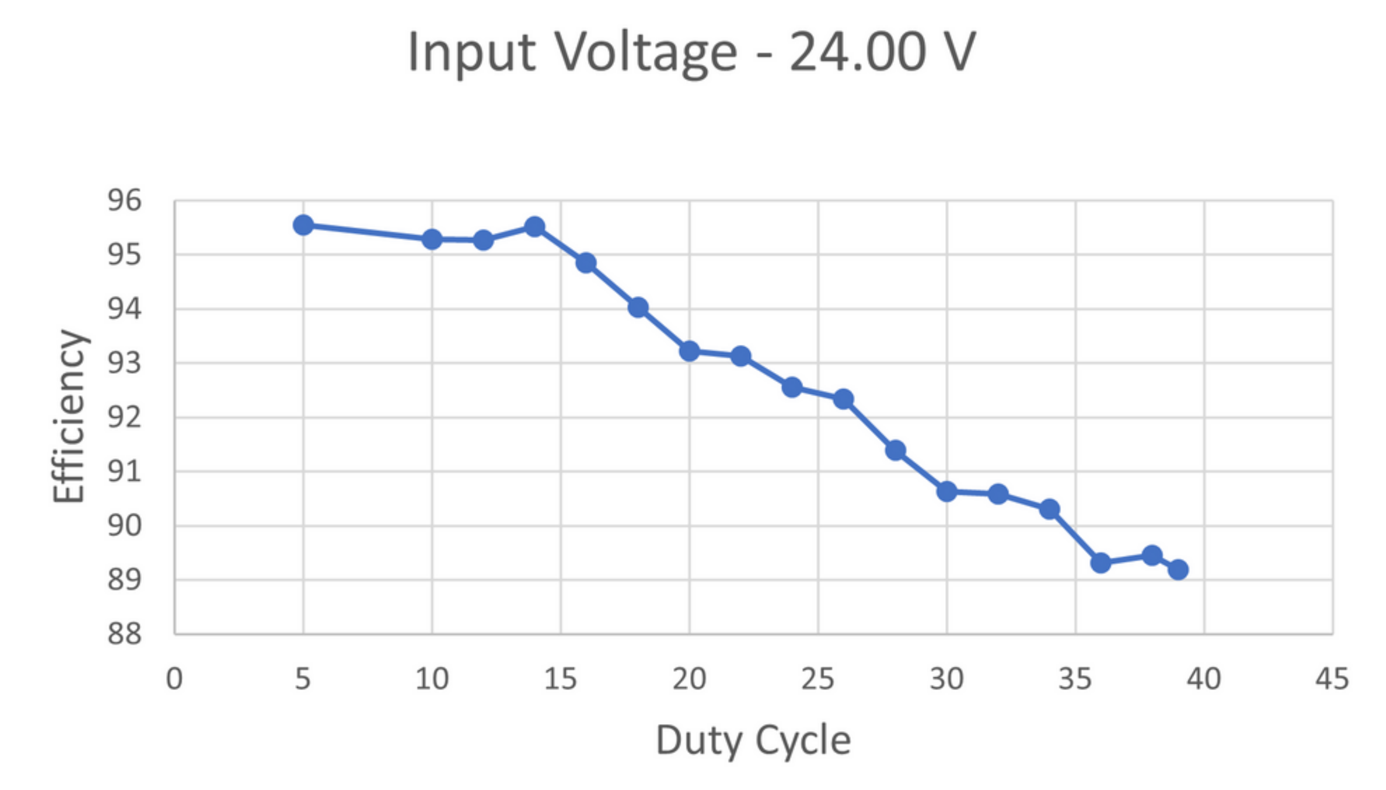
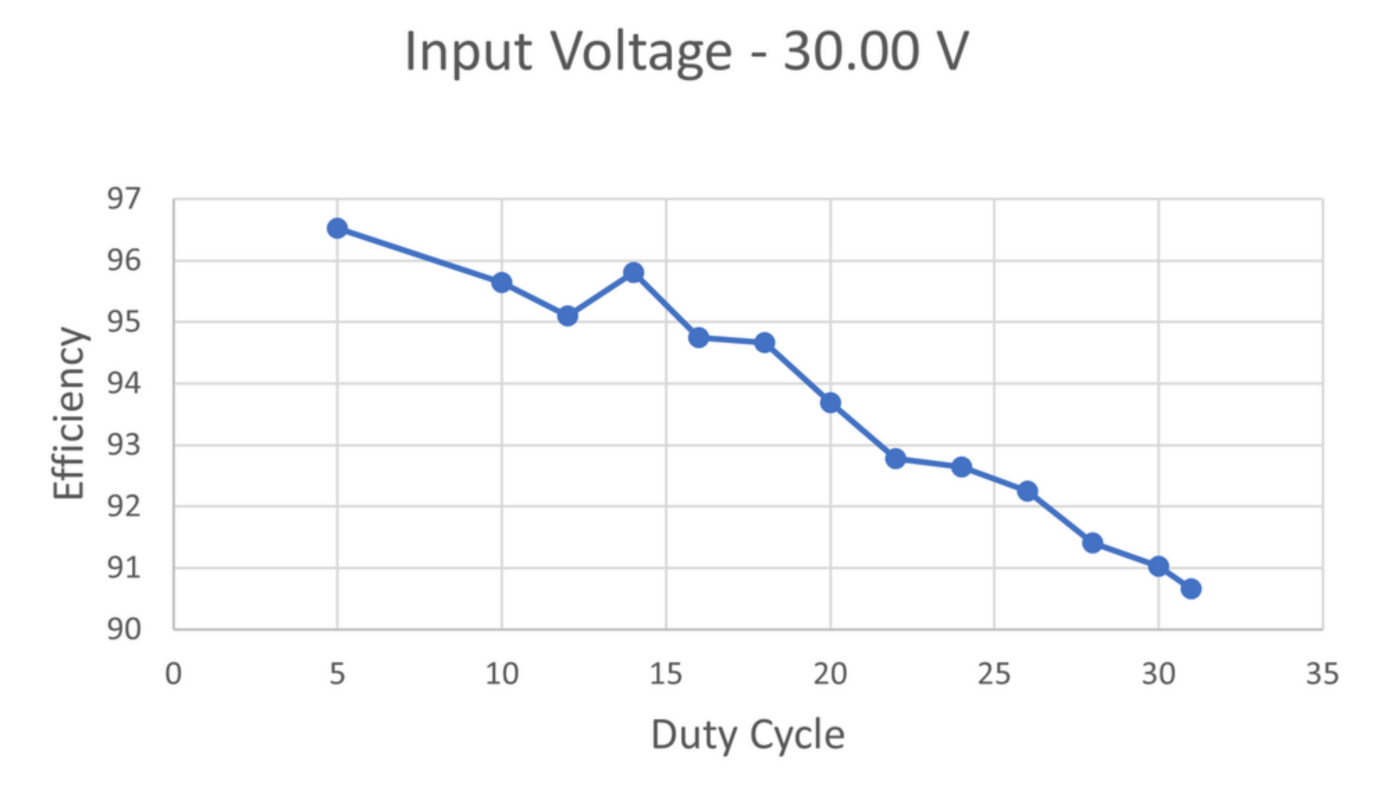
SYNCHRONOUS BOOST CONVERTER

Duty Cycle vs. Efficiency Graph



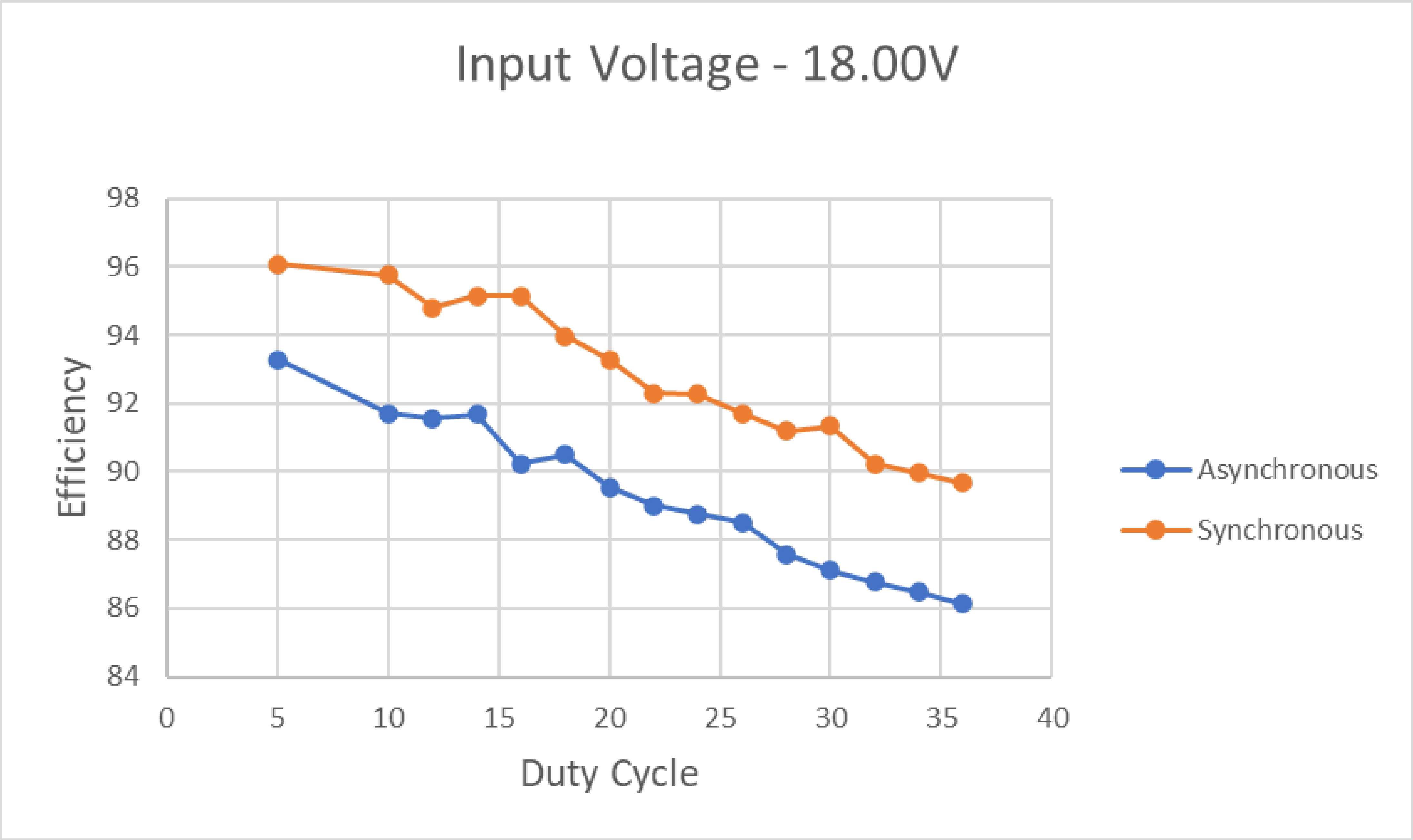




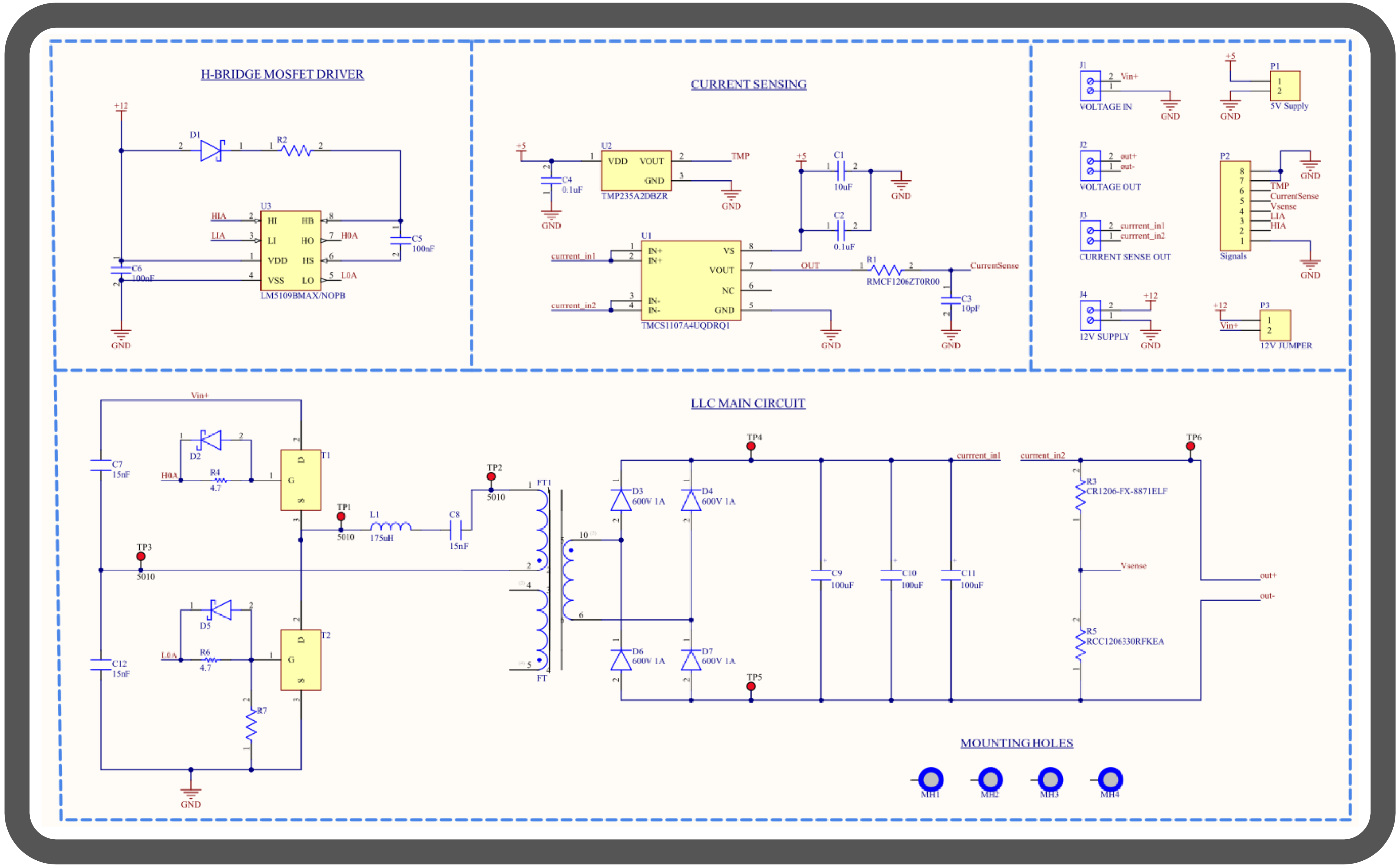


COMPARISON OF SYNCHRONOUS AND ASYNCHRONOUS BOOST CONVERTERS

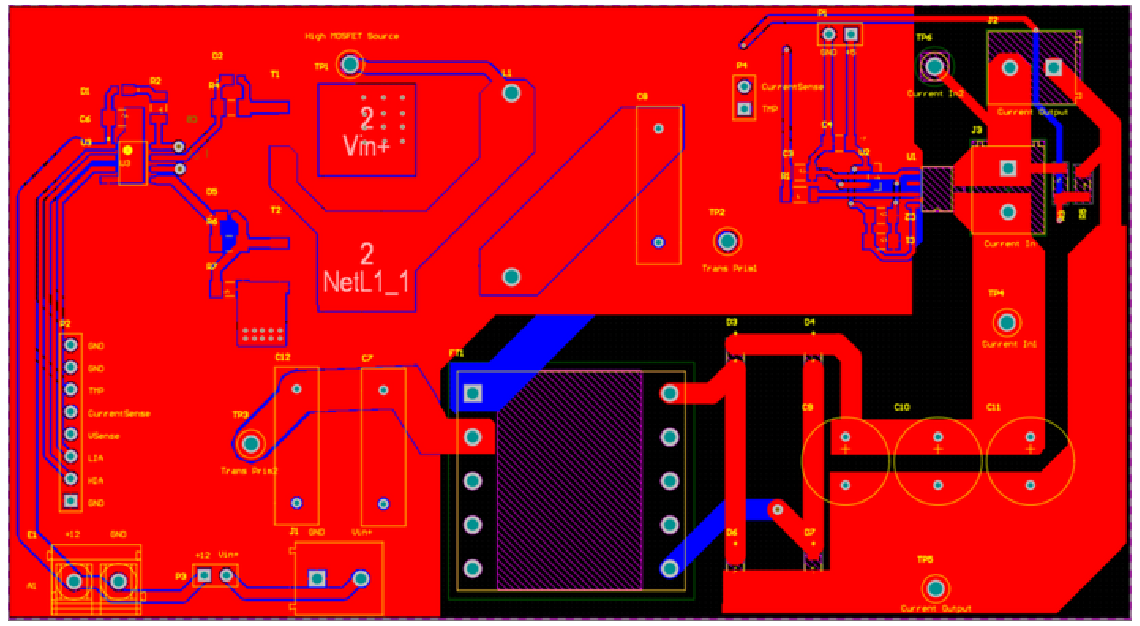
Duty Cycle vs. Efficiency Graph



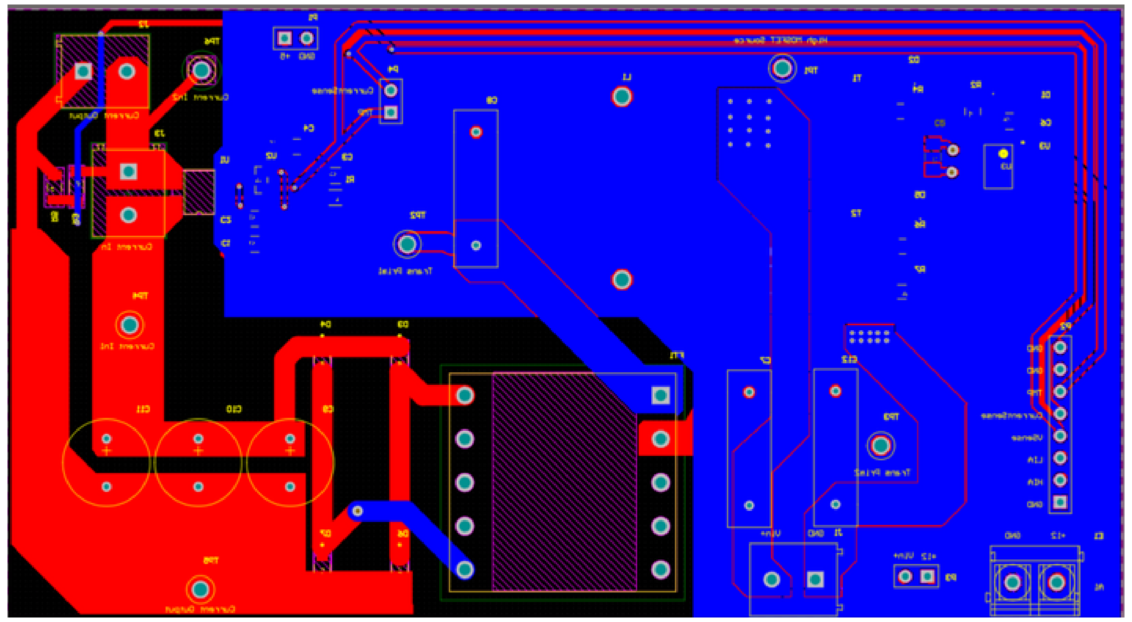
LLC DC - DC CONVERTER



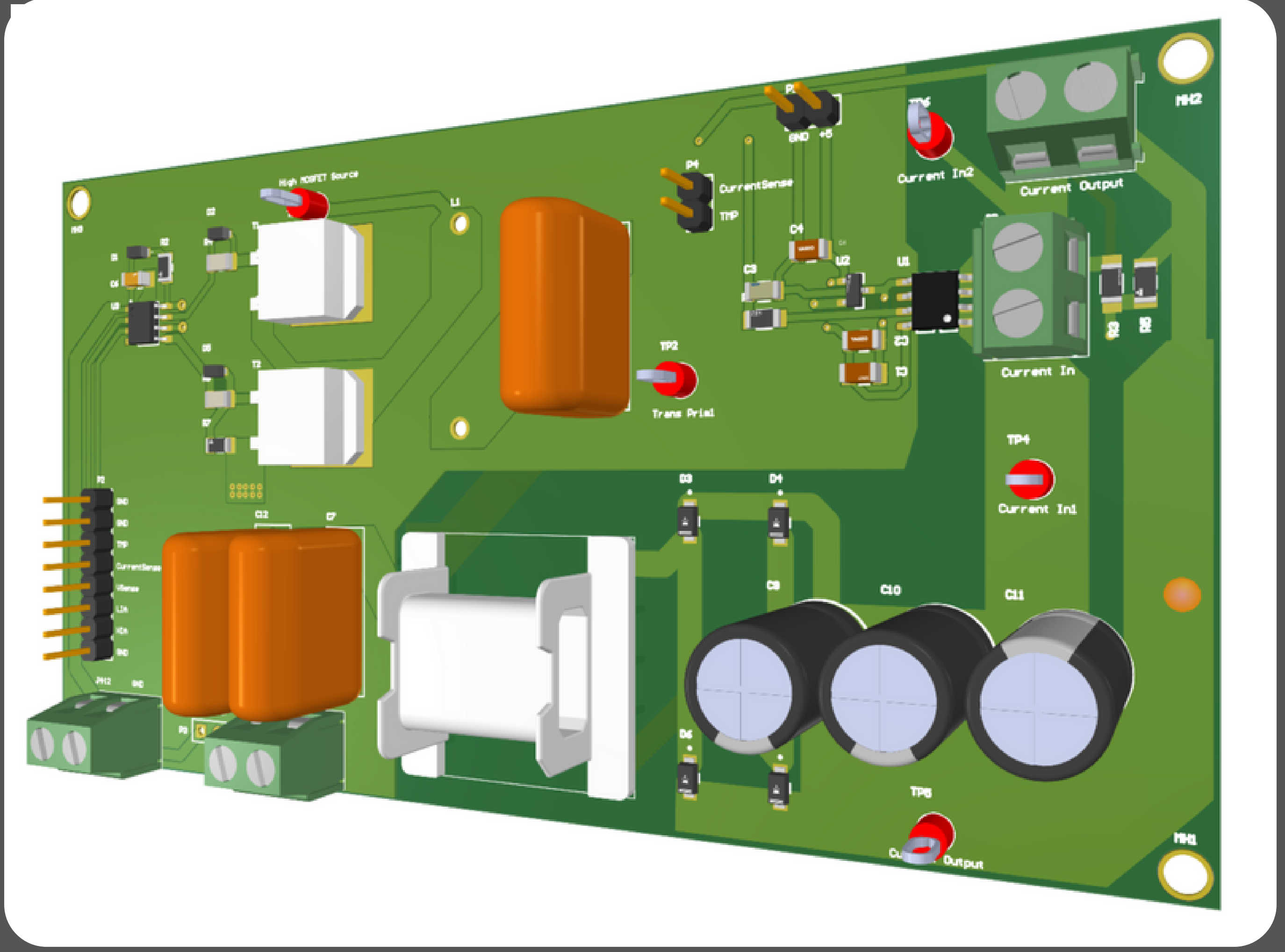
LLC DC - DC CONVERTER



Top side

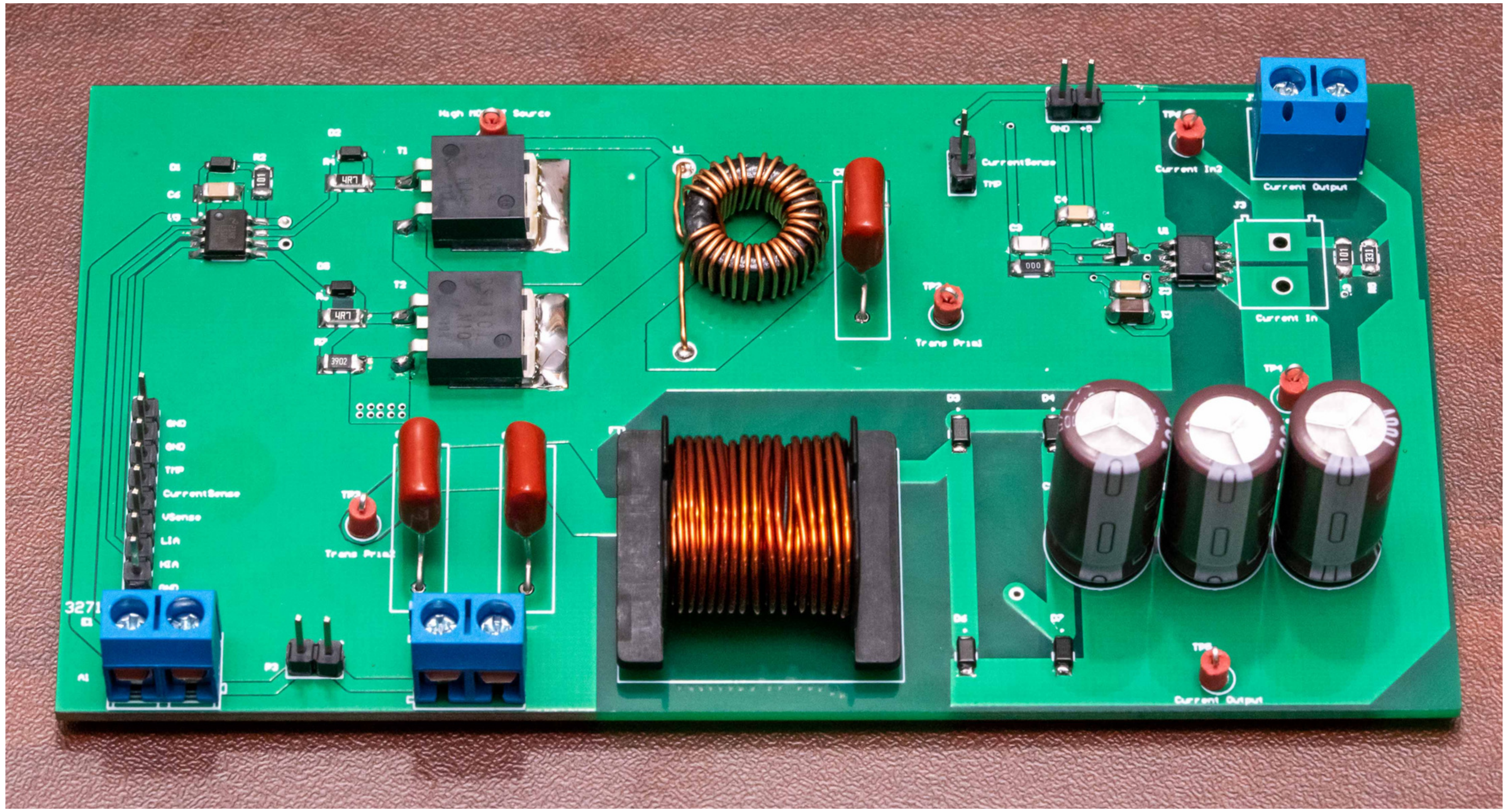


Bottom side

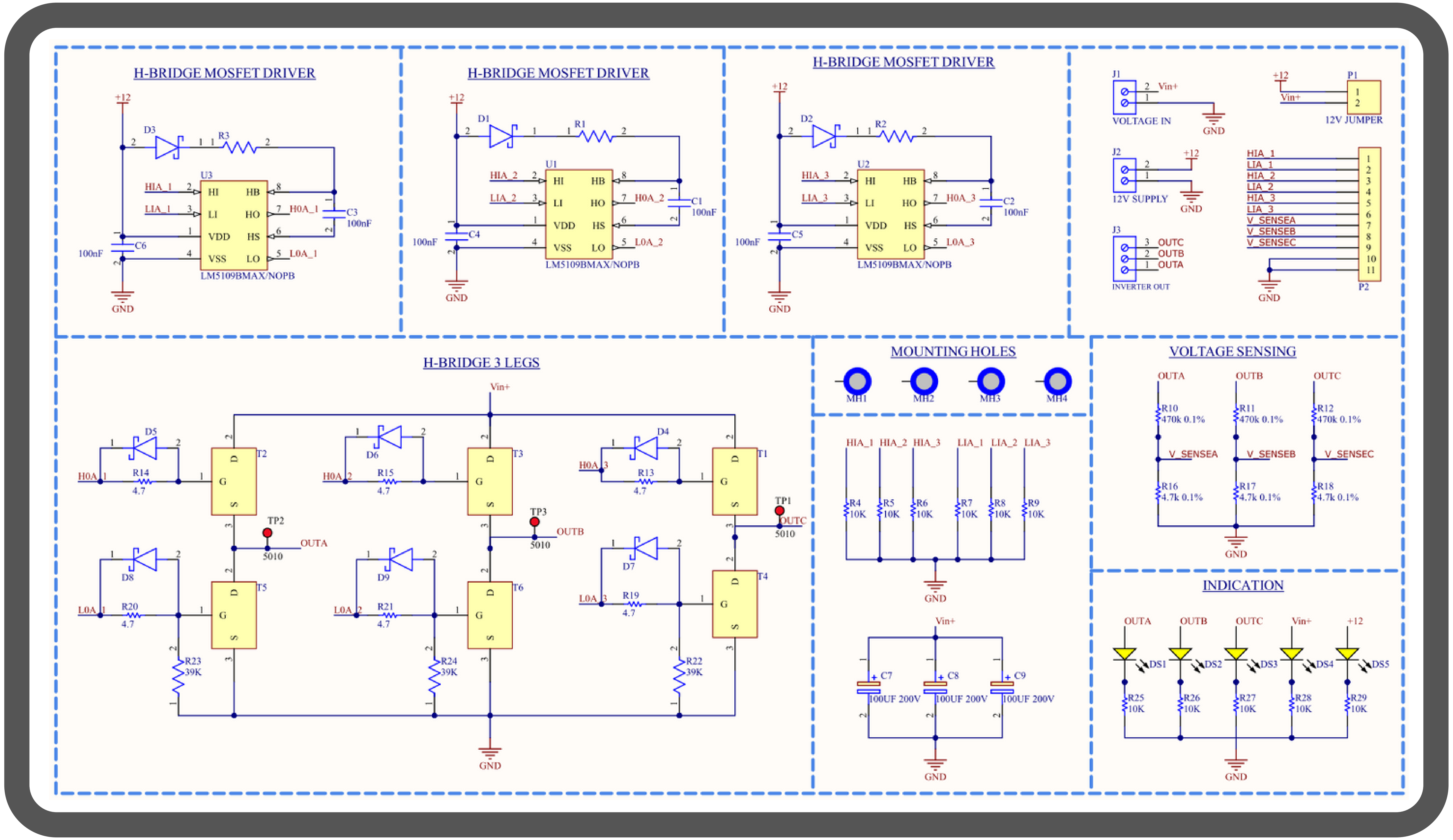


3D View of the PCB

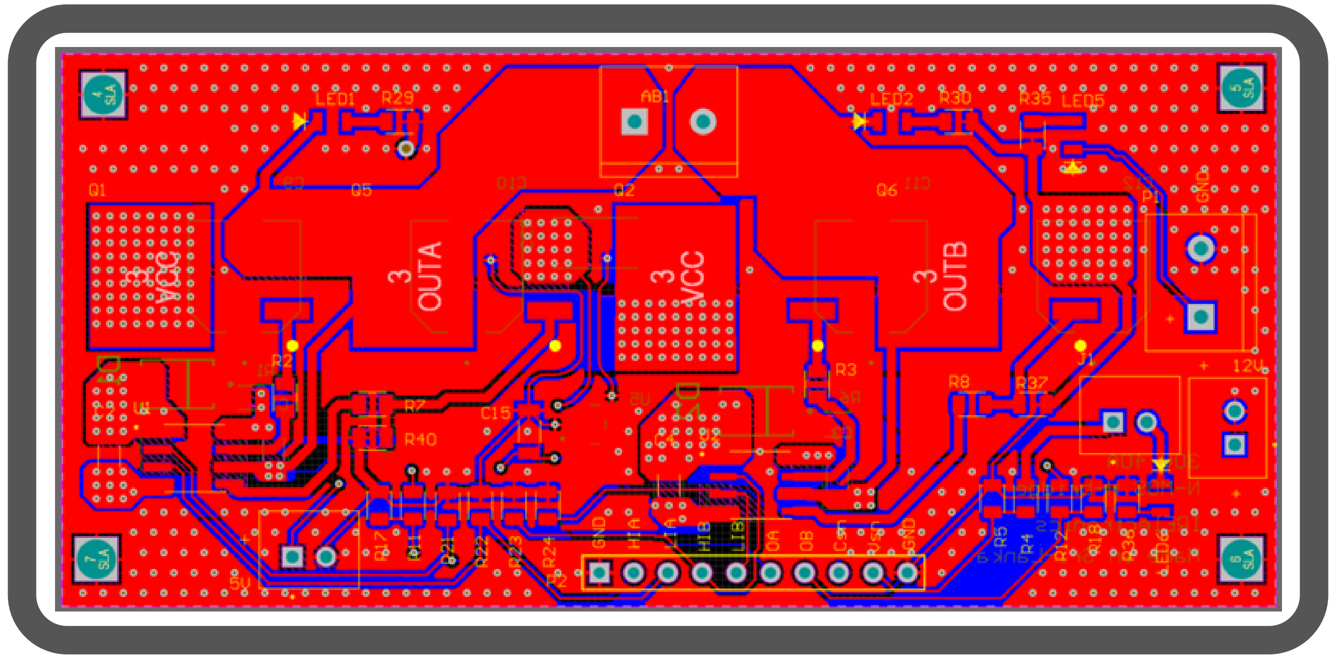
LLC DC - DC CONVERTER



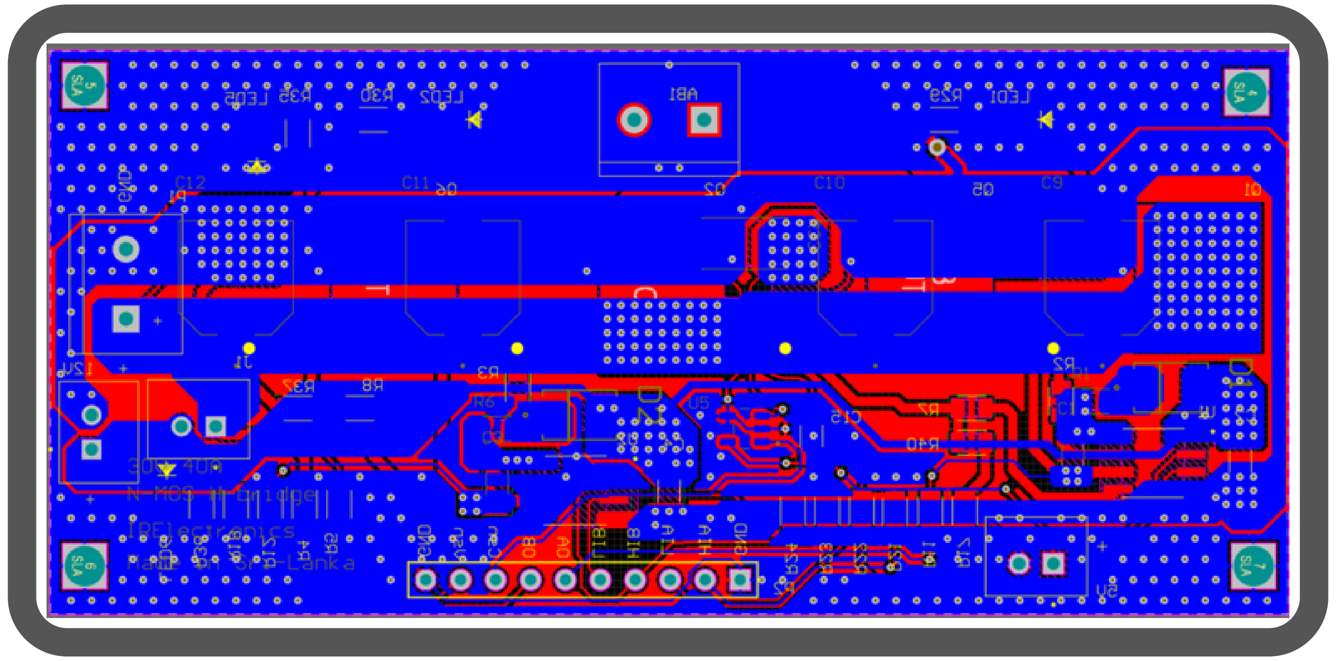
INVERTER CIRCUIT



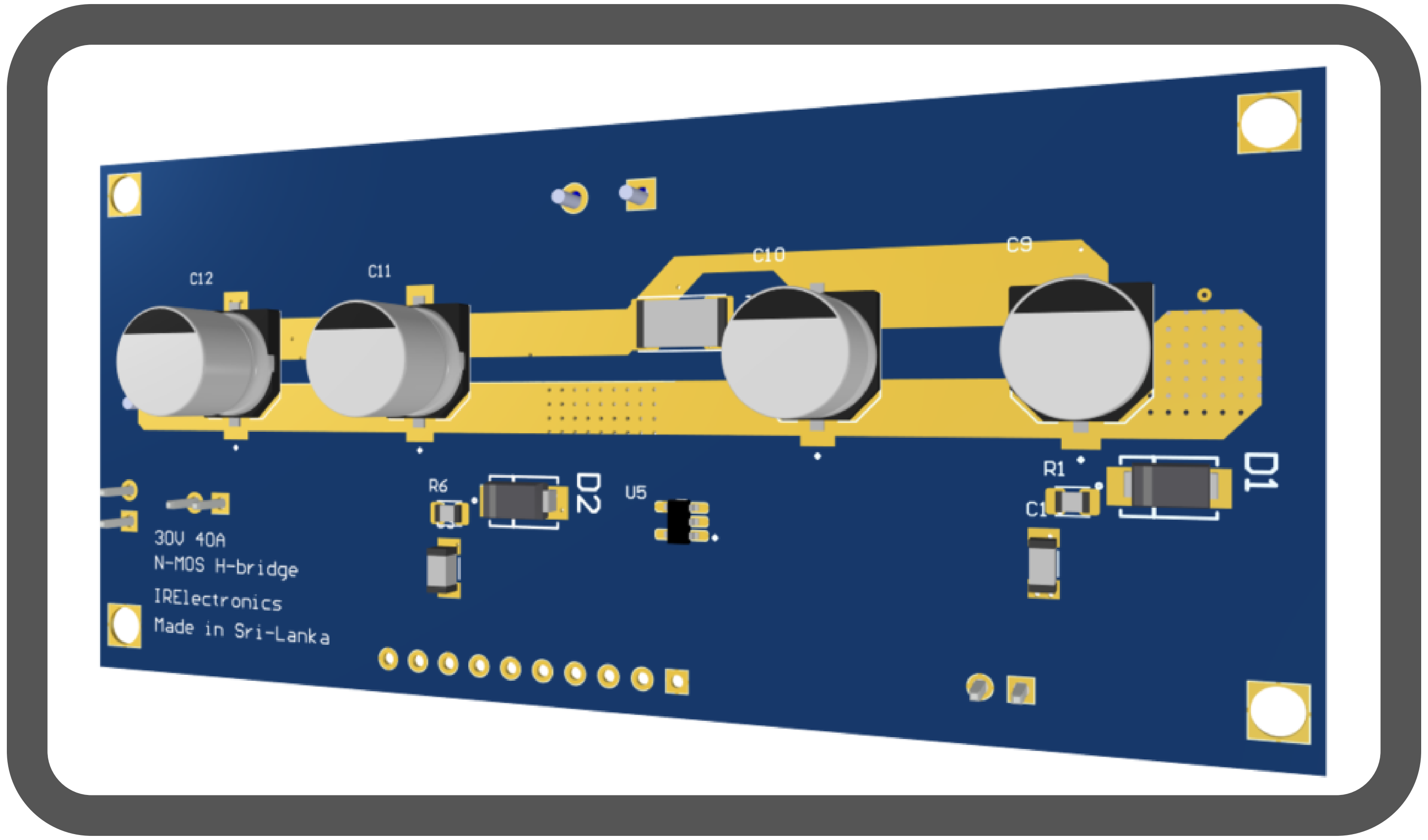
INVERTER CIRCUIT



Top side

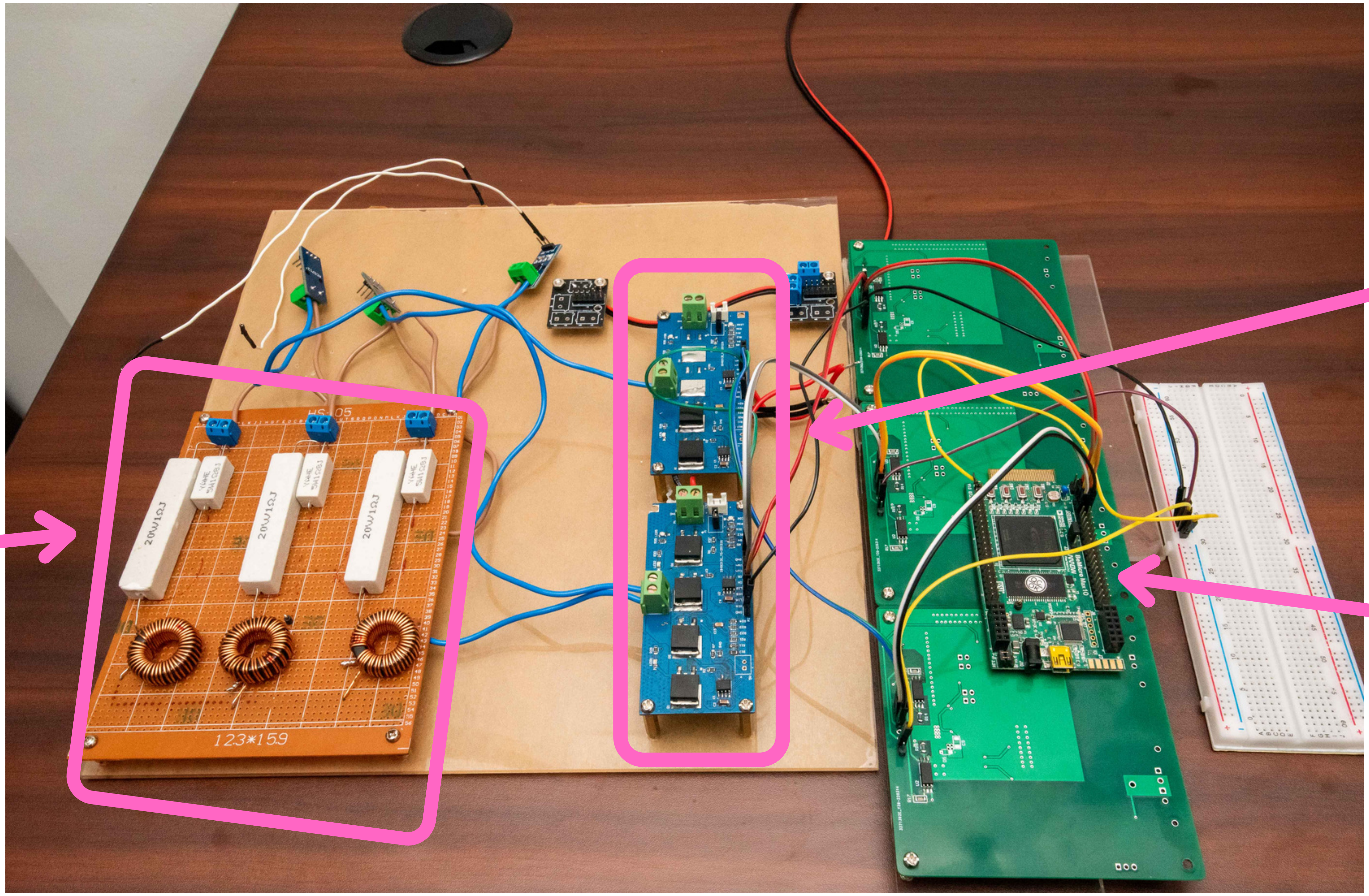


Bottom side



3D View of the PCB

INVERTER CIRCUIT TESTING



H-bridge circuit

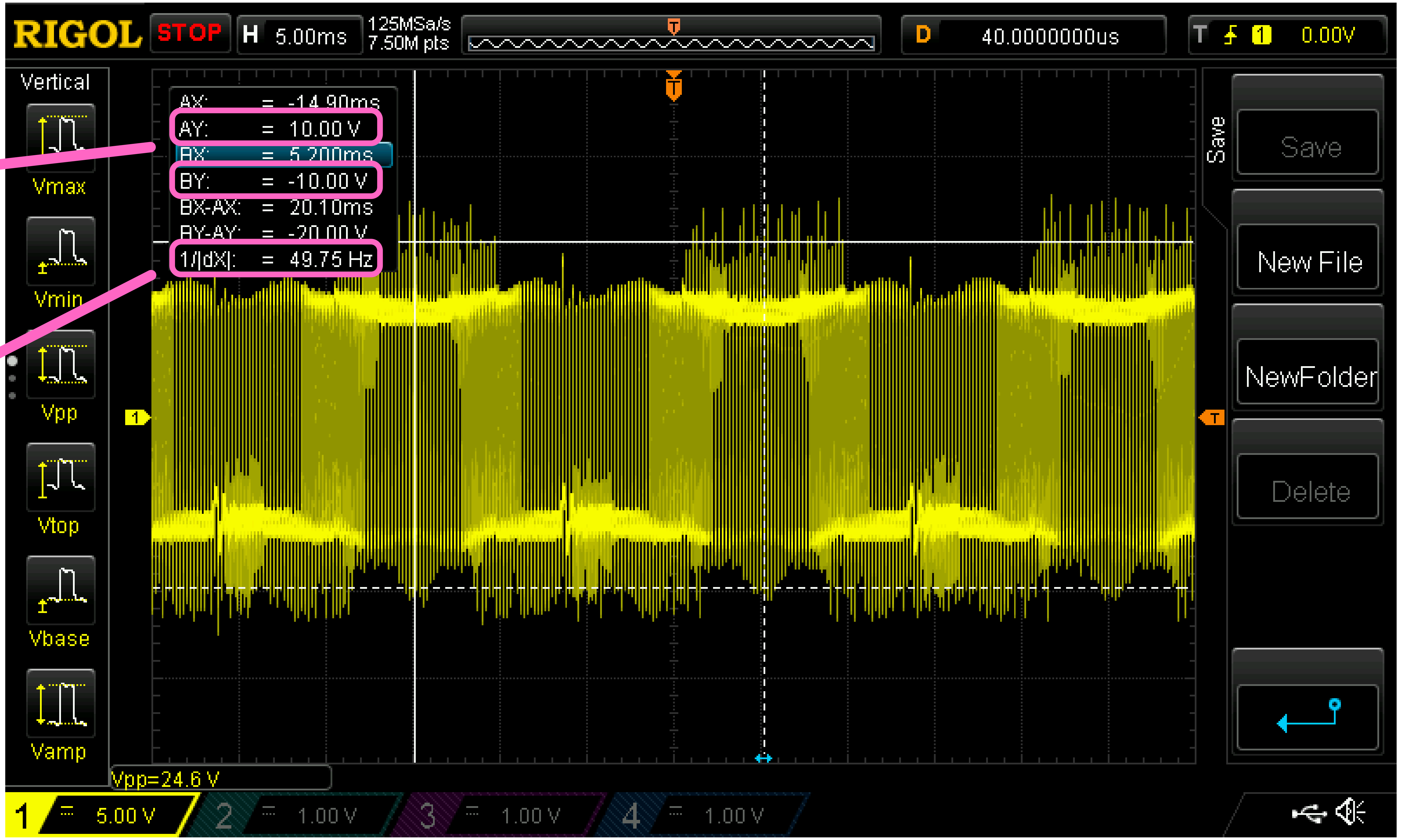
Loads

FPGA

INVERTER CIRCUIT TESTING RESULTS

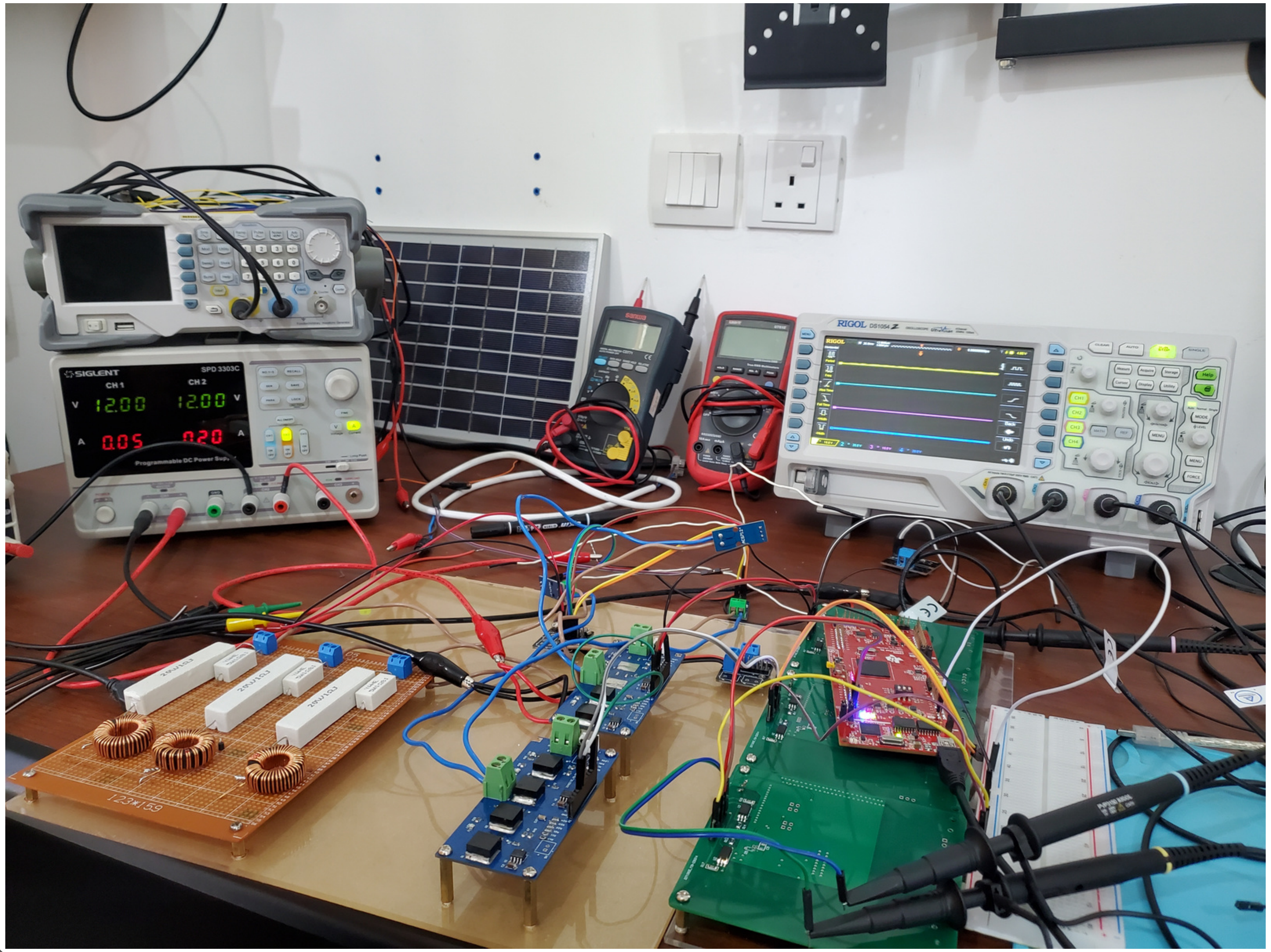
Inverted Output

Frequency 49.75 Hz

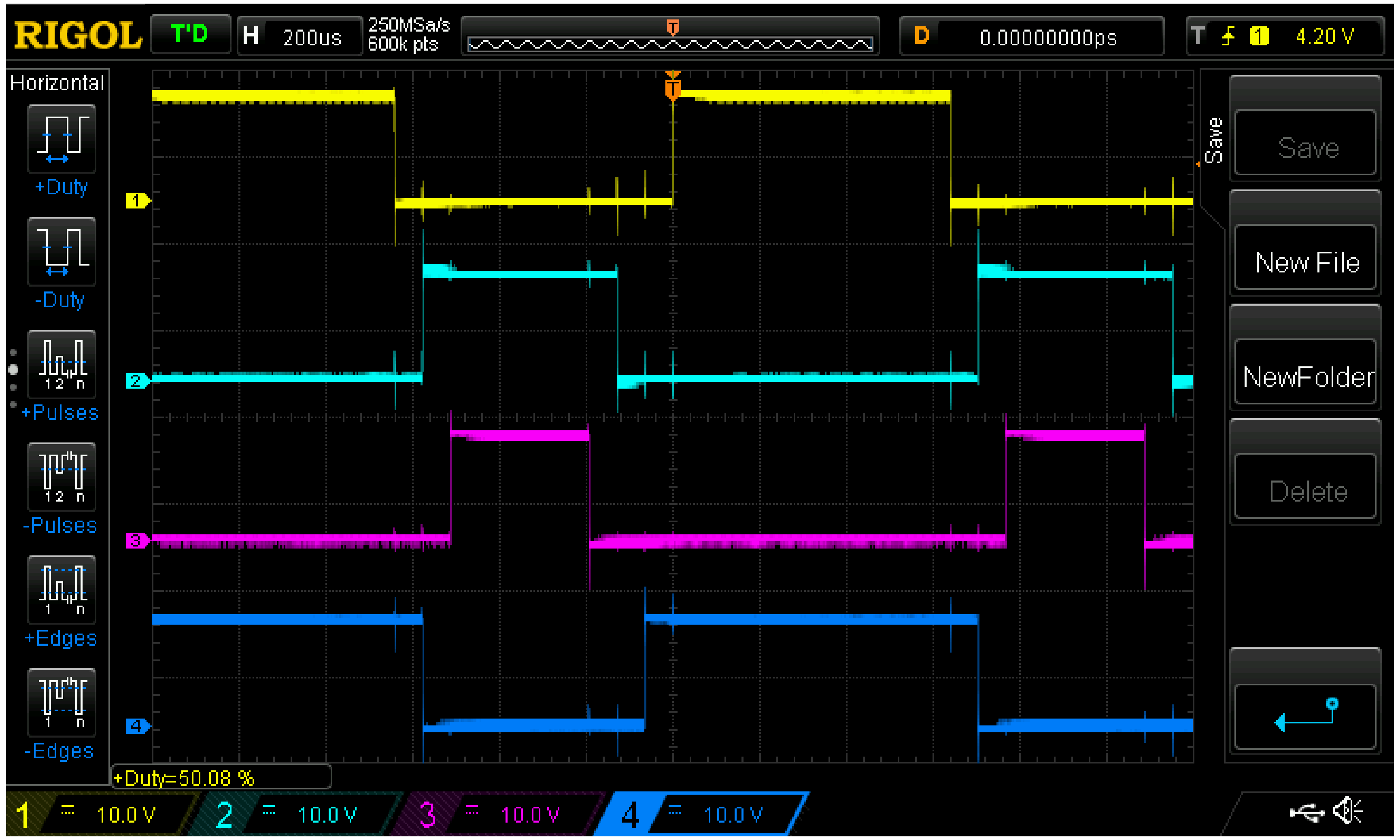


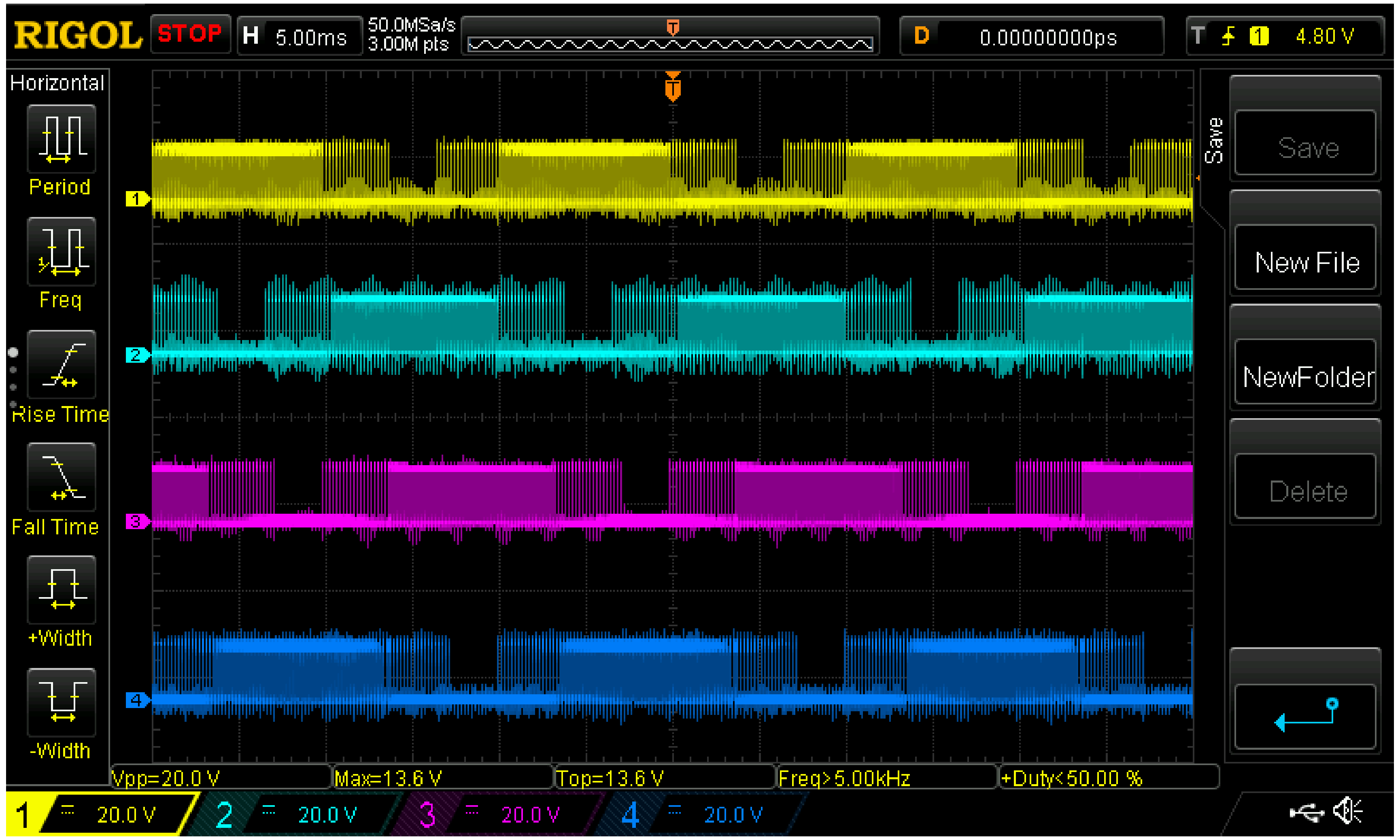
INVERTER CIRCUIT TESTING RESULTS

INVERTER CIRCUIT TESTING



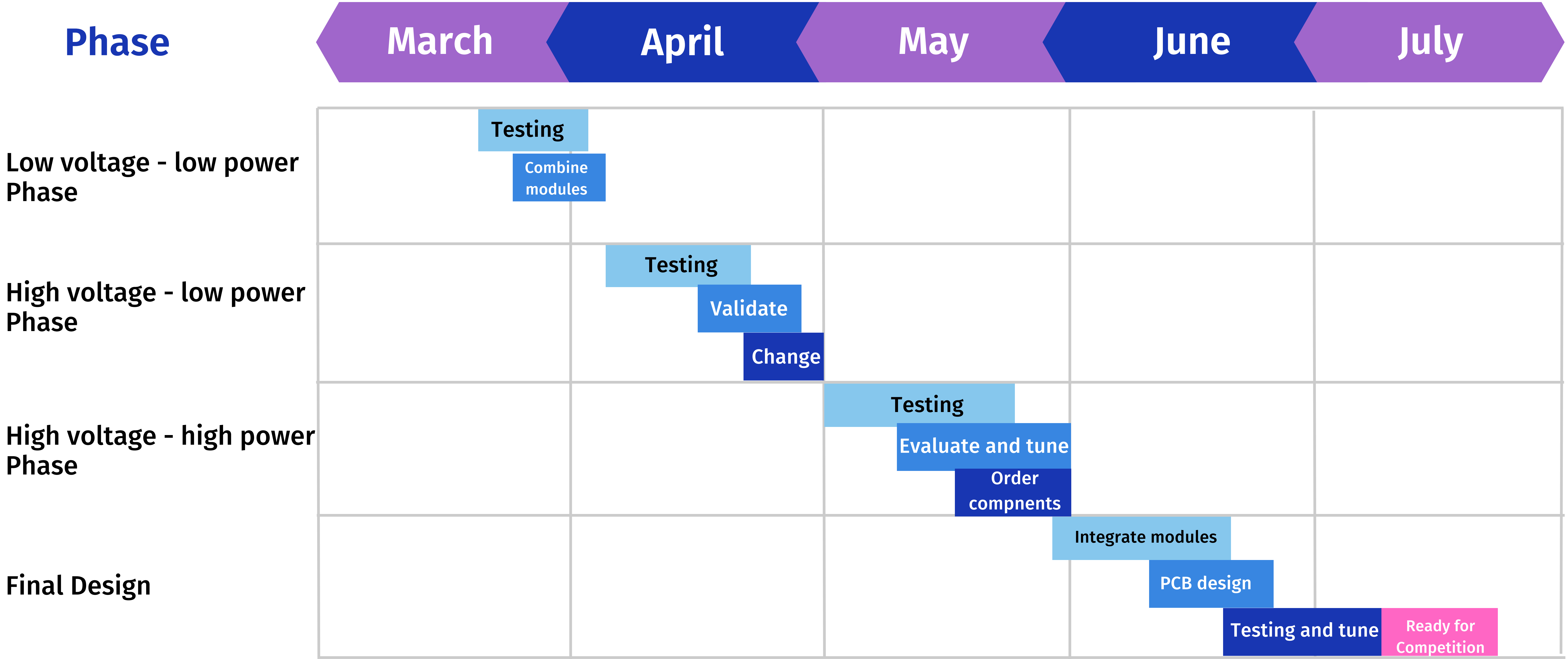
INVERTER CIRCUIT TESTING





PLAN FOR COMPLETION

COMPLETION PLAN



COST ANALYSIS

Component		Cost for low voltage, low power Implementation	Estimated Cost for final design
MPPT and Boost Converter Circuit	Capacitors	$8.11	$16.00
	Diodes	$0.79	$1.00
	Connectors	$1.00	$1.00
	Inductor	$0.87	$1.00
	MOSFETs	$2.56	$14.00
	Resistors	$0.21	$0.50
	Gate Drivers	$0.74	$0.75
	Optocouplers	$2.00	$2.00
	PCB Fabrication	$0.57	$0.57
LLC Resonant Converter	NCP4390 Controller	$1.12	$1.12
	MOSFETs	$4.68	$28.00
	Diodes	$0.41	$1.00
	Connectors	$1.00	$1.00
	Transformer	$0.50	$1.00
	Resistors	$1.50	$1.50
	Capacitors	$0.20	$1.00
	Gate Drivers	$2.00	$0.50
	PCB Fabrication	$0.50	$0.50
Inverter	MOSFETs	$7.02	$42.00
	Gate Drivers	$2.20	$0.75
	Capacitors	$8.00	$15.00
	Resistors	$0.50	$1.00
	PCB Fabrication	$0.50	$0.50
Measurements	Current Sensors	$7.20	$7.20
	Temperature Sensors	$1.60	$1.60
C2000 Dual Core TMS320F2837xD Microcontroller		$11.13	$11.13
Enclosure		$20.00	$30.00
Heat Sinks and Cooling		$20.00	$30.00
Total		**$106.90**	**$211.62**

- A cost analysis was conducted for low voltage, low power implementation and for bulk manufacturing.
- The highlighted components are subjected to upgrades as we progress on to high voltage and high power implementations.
- The cost is estimated to be doubled in the final design up to $212.
- The final cost of $212 was estimated by assuming their maximum component costs. Therefore, it will be an upper bound our final design cost. We will try our best to reduce the cost as much as possible and come up with an efficient yet cost effective final design.

CHALLENGES FACED

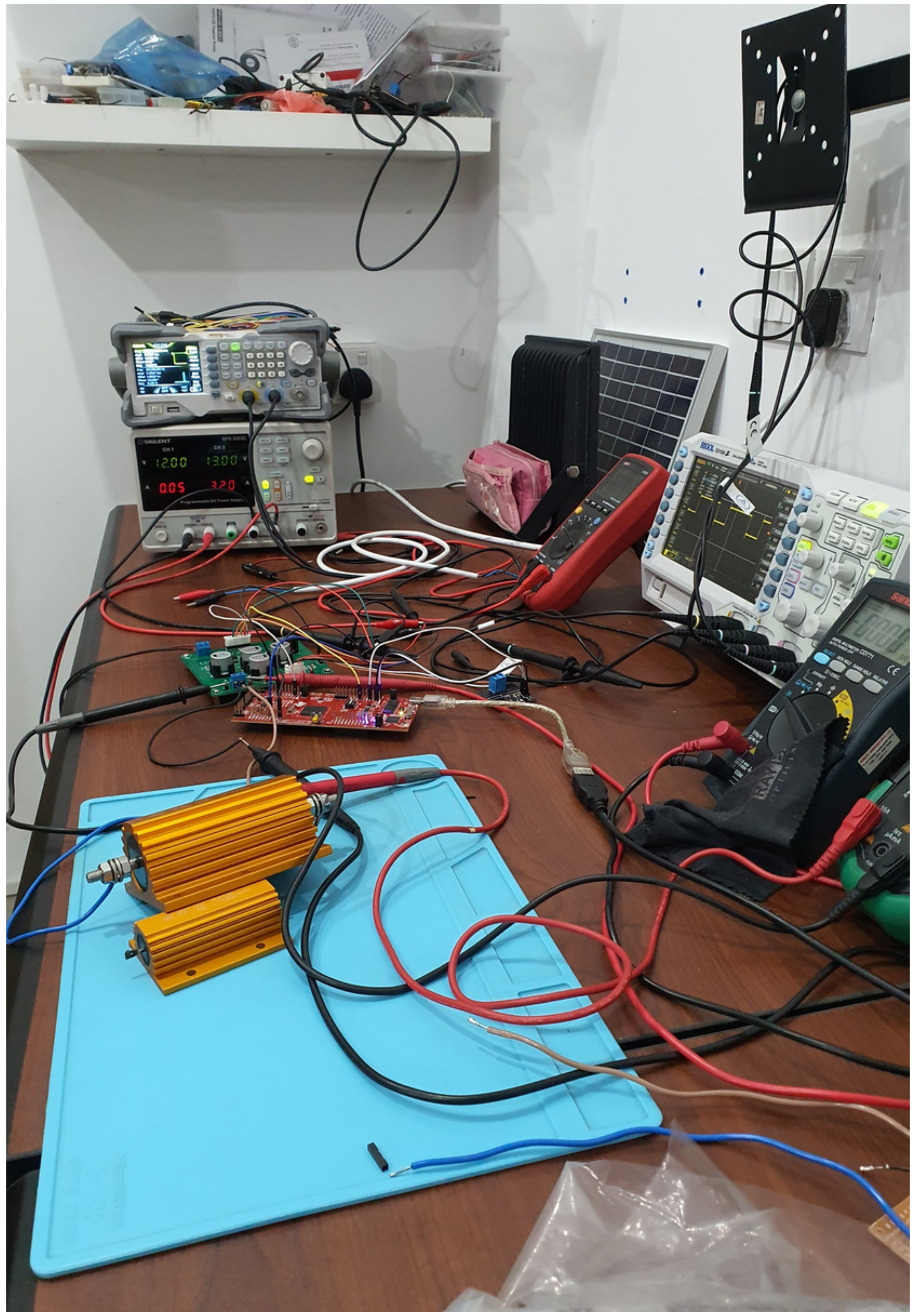
- Due to the pandemic situation, the team had to work remotely during the initial phases of our project. Most of the discussions, progress reviews were conducted virtually.

- As we progressed on to the hardware testing, we had to follow health guidelines as the team gathered.

- Sri Lanka is facing scheduled power cuts up to 7 hours a day island-wide since February. It was a struggle but we divided work among the team members efficiently to keep up with our timeline and achieved satisfactory results.

- Due to the devaluation of the Rupee and inflation in the country, the costs for hardware increased by nearly 50% within the period of our project. Therefore, we always looked for cost-effective ways during our hardware implementation like ordering components together to reduce shipping costs.

- We designed our PCBs and ordered components ahead of time but there were huge shipping delays due to the war. Therefore we had to make compromises like disassembling existing circuits to retrieve some components for our hardware testing.



Team UOM

THANK YOU!