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High Voltage Module Development and Characterization for Automatic Test Equipment

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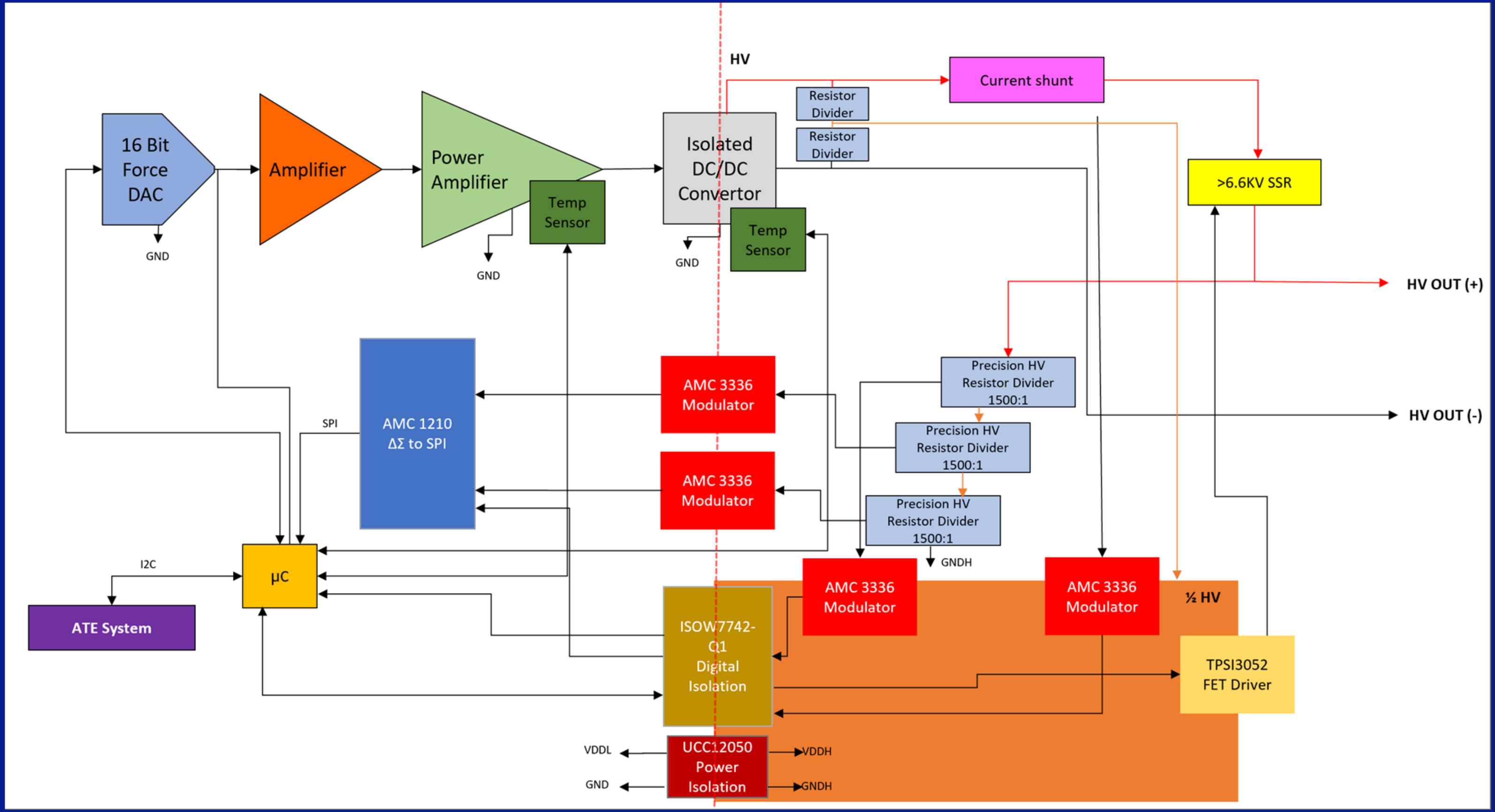
Introduction

- The growth in semiconductor industry drives the demand for greater testing capabilities of Automated Test Equipment (ATE) such as high voltage testing
- Industry growth and demand for high voltage testing inspired this effort to develop an ATE resource capable of forcing up to 4kVDC, with voltage/current readback as well as over-limit protection
- This resource should be compact, low-cost & developed promptly.

Requirements and Constrains

- Requirements
  - Output voltage [Vout(p) - Vout(n)] ≥ 4 kV
  - Output voltage error ≤ 1V across all operating conditions
  - Output voltage ripple < 1%
  - Solid state relay to isolate the high voltage from DUT on command
  - High-side current measurement
  - Current limiting mechanism to protect against short circuit failures
  - Temperature sensors in different places on the resource to monitor the temperature during operation
- Constraints
  - Resource integration with modern ATE testers.
  - Size of the board to remain smaller than a mobile cell phone as a reference
  - Resource temperature to remain within the operation range of all the devices on-board

Block Diagram

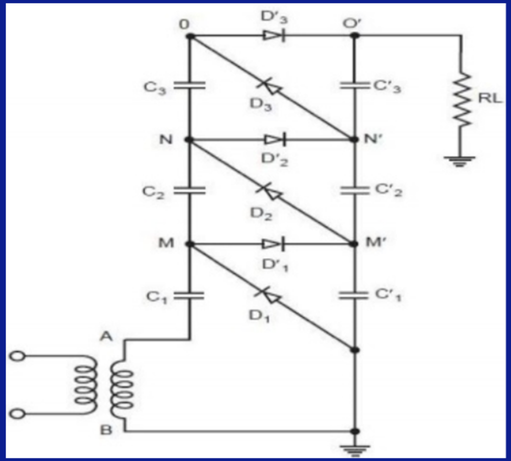


Design Choices

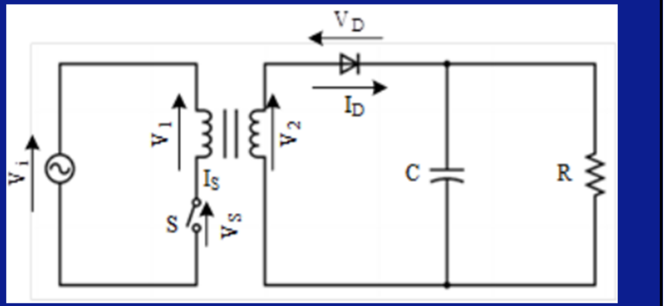
- Commercial off the shelf isolated DC/DC converter
- Isolated modulators for current and voltage sensing
- Digital feedback loop for output voltage accuracy correction
- On-board µC for ADC and DAC interfacing
- Temperature sensors on the low and high side
- High-side current measurement
- Half high voltage island for device operation range
- 4-channel modulator filter
- Solid State Relay

Common Methods to Step-Up Voltage

- Common methods for designing a DC/DC convertor are:
  - Minimum: 0.5 V Boost Converters
  - Boost Converters
  - Cockcroft-Walton Voltage Multiplier
  - Marx Generator
  - Flyback Transformers
- DC/DC converter manufacturers provide calibrated products that adhere to safety standard making it the preferred choice for the step-up part of this specific application



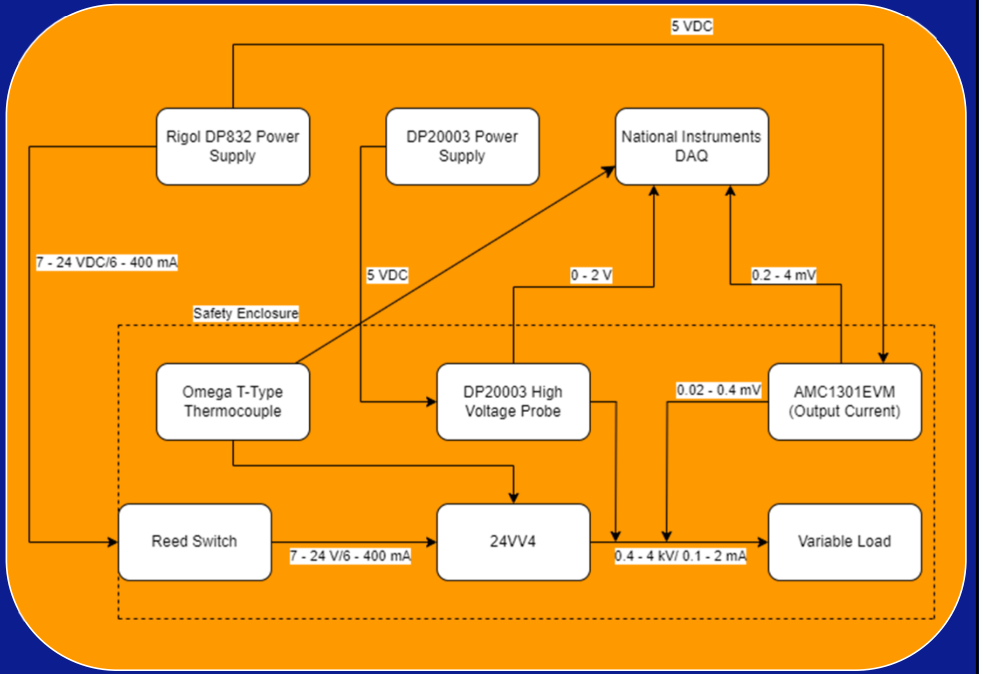
Cockcroft-Walton Voltage Multiplier circuit



Flyback transformer circuit

DC/DC converter Characterization Test Setup

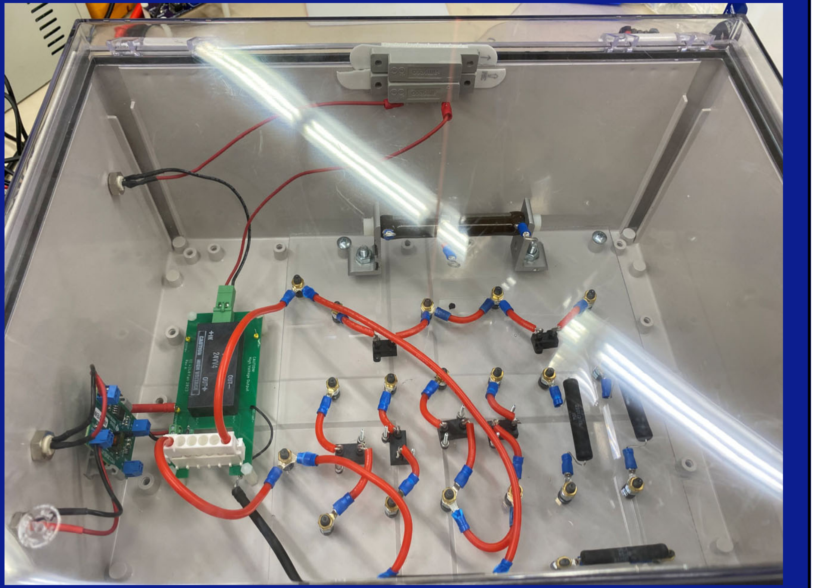
- To characterize the performance of various DC/DC converters a test setup was built
- This setup is meant to characterize multiple converters and the final product
- The variable load consists of resistors that are manually configured for better flexibility
- Tests are automated using NI’s LabVIEW
- For high-side current measurement an isolated amplifier is used with a shunt to collect variation in output current

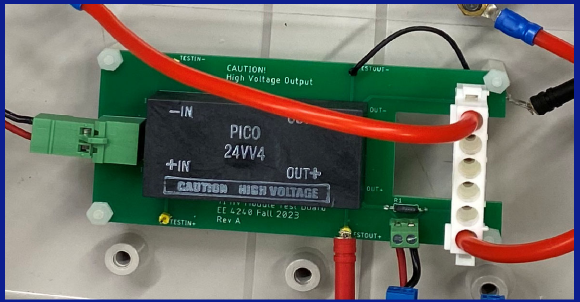


Characterization Test Setup Block Diagram

Characterization Test Setup Inside the Box

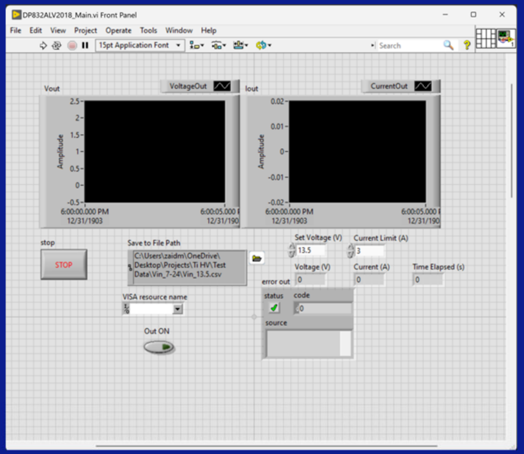
- A PCB was designed and fabricated to mount the 24VV4 with access to test points and the shunt
- The device was tested to the full range of operation and with multiple loads to evaluate its performance
- BNC panel mounts used to access the inputs and outputs of the converter
- For high-voltage safety the setup is enclosed in a polycarbonate box and uses a Reed switch to ensure closed box operation
- High voltage isolation cables used on the HV side
- Surface temperature of the DC/DC converter is measured using a thermocouple placed on the body of the converter
- The box is placed in a room temperature environment





Characterization Test Setup Outside the Box

- LabVIEW is used to communicate with the force and measure devices to automate the tests
- Analog input and temperature measurements were made with NI-9223 and NI-9213 cards, respectively
- The NI-9223 can sample up to 1 MSPS per channel and is used to measure the output voltage and current
- Rigol’s DP832A programmable power supply is used to power the converter and read back input voltage and current



Save to File Path C:\Users\zaidm\OneDrive\Desktop\Projects\Ti HV\Test Data\Vin_7-24\Vin_13.5.csv

Set Voltage (V) 13.5

Current Limit (A) 3

Voltage (V) 0

Current (A) 0

Time Elapsed (s) 0

VISA resource name

error out

code 0

DC/DC Convertor Options

- The 24VV4 is the lowest in cost and operates within the required range
- Although the UMR and HRL30 has a wider range and better DC power quality that comes at a higher cost and greater size
- The 24VV4 was selected for its low cost and small size
- The device from Dean Technologies was acquired since it meets the requirements and was available to ship immediately

	Requirements	Pico 24VV4	Dean Technology UMR-AA-4000P-30	HiVolt HRL30 series
Operating Temp. (°C)	--	-40 to +85	-40 to +65	-40 to +70
Dimensions	<3 cubic inches	2.25 x 1.25 x 0.95"	2.97 x 1.5 x 0.75"	3.0 x 1.5 x 0.73"
Vin (in V)	0 – 24V DC	24V DC	24V DC	24V DC
Max Vout (V)	≤ 4000	400 - 4000	0 - 4000	0 - 5000
Vout Ripple @Max load	<1% post calibration	<2%	<0.036%	<0.05%
Max Iout	--	2 mA	7.5 mA	6 mA
Max power	--	8 W	30 W	30 W
Cost	--	$162	$450	$900

Characterization Tests- 24VV4 Slide 1

Output Voltage VS Input Voltage Test

- Input Voltage Range:
  - Minimum: 0.5 V
  - Maximum: 24 V
  - Increments of 0.5 v
- Determine the gain and stability of the output voltage as a function of the input voltage.

Temperature Endurance & Performance Test

- Data Sheet Operating Temperature Range:
  - 25º C to +70º C
- Temperature is monitored over an hour of test time to determine the change in temperature and performance of the device at each input voltage.
- The temperature is measured on the surface of the device using a thermocouple which leaves a blind spot of the internal device temperature.

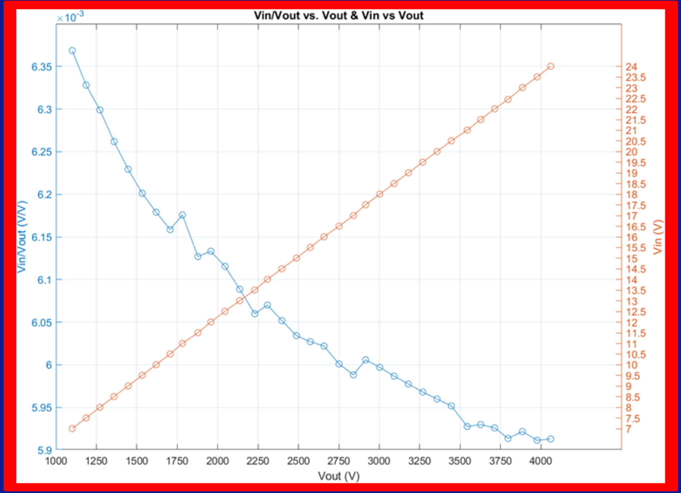
Characterization Tests- 24VV4 Slide 2

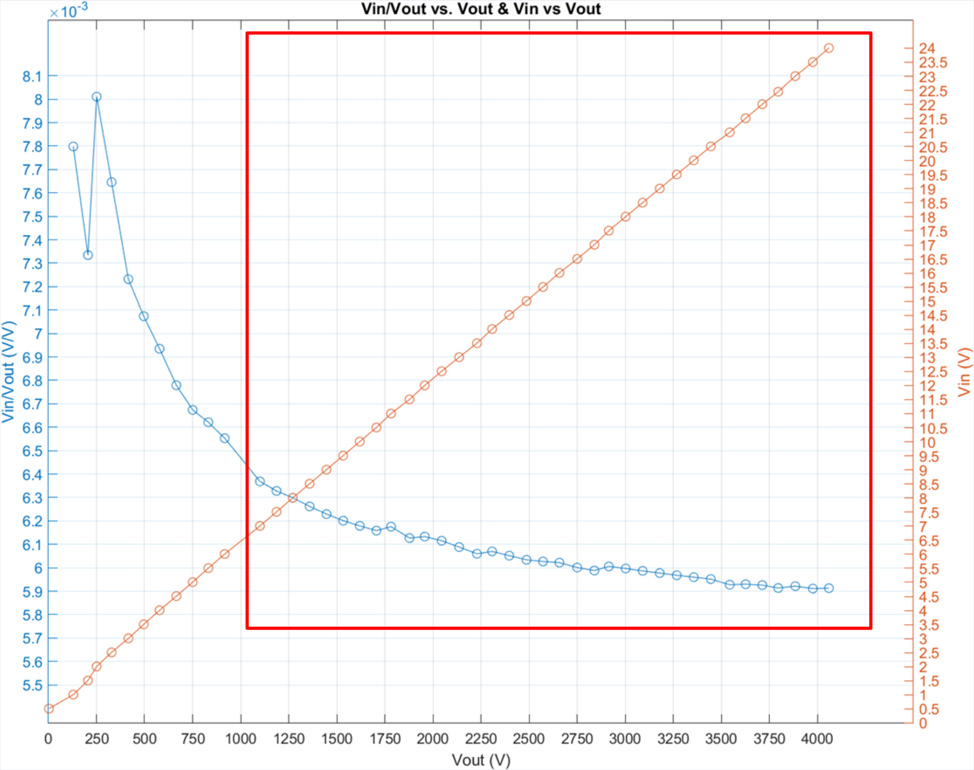
Load Regulation Test

- This test aims to determine the load regulation, output voltage ripple, and efficiency of the device
- The DC/DC converter is required to operate between 1000-4000 V so it must meet all the requirements in the entire range of operation
- These parameters are determined for the entire spectrum of operation for the device
- A total of 15 resistance values were used and the input voltage was swept across all of them
- Load Range:
  - Minimum: 600 kΩ
  - Maximum: 14.5 MΩ
- Load Current:
  - Minimum: 0.55 mA
  - Maximum: 2.85 mA

Input Voltage VS. Output Voltage Linearity and Gain

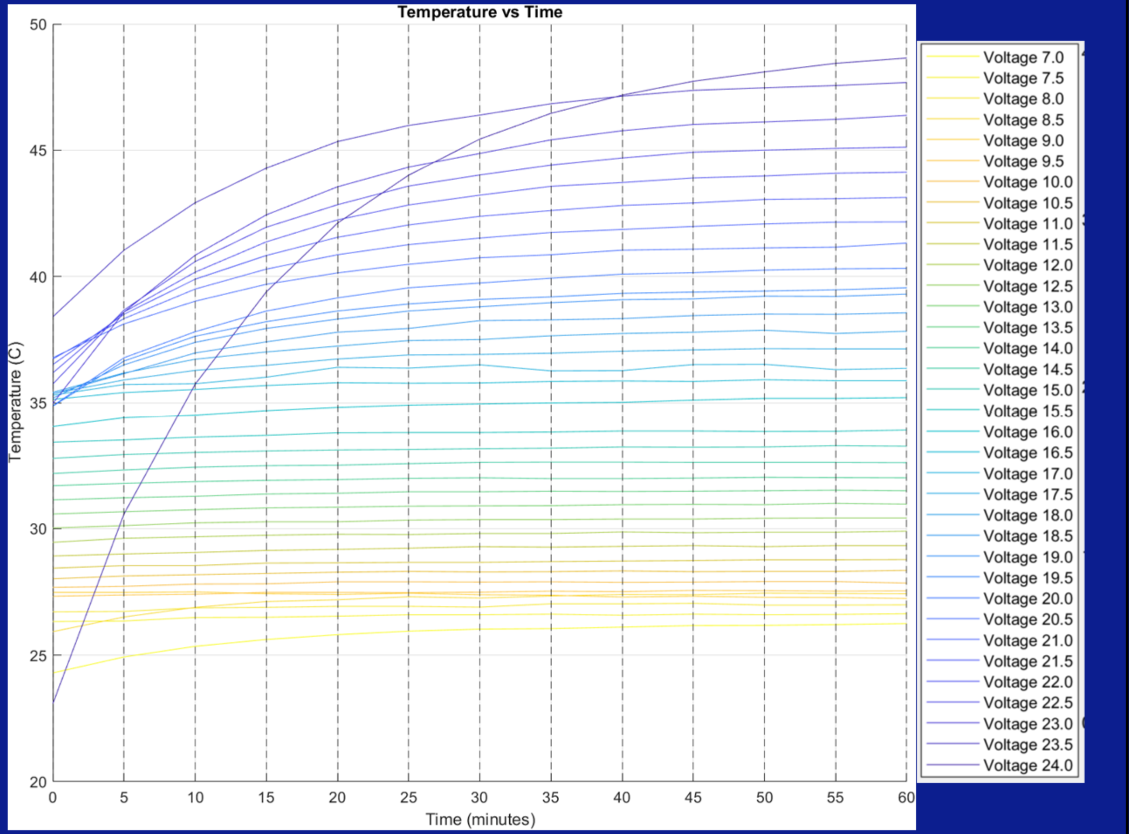
- Input voltage varied to determine the range of output voltage the device operates in
- The datasheet suggests a minimum voltage of 400 VDC in the range of 7-24 V however 1100 VDC is seen at 7 V
- The resistance is set to 2 MΩ to draw the maximum current from the device at the peak voltage output





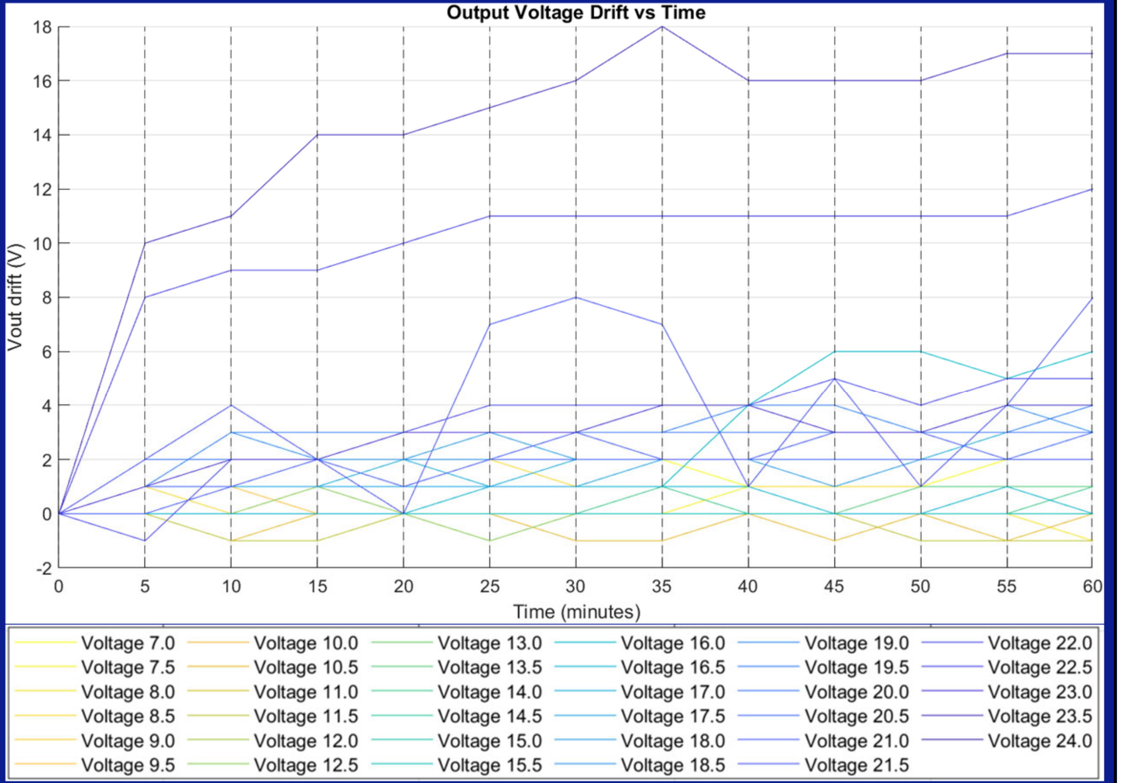
Temperature Endurance & Performance Test

- Temperature collected every 5 minutes using a thermocouple on the surface of the device
- After 60 minutes elapsed before increasing the voltage the device is cooled down to 35^{o}C
- The final test at 24 V was cooled down to room temperature before starting since it was done on a different day
- Device temperature reaches a peak of 48.6^{o}C
- Devices peak temperature reached on a test that started from room temperature



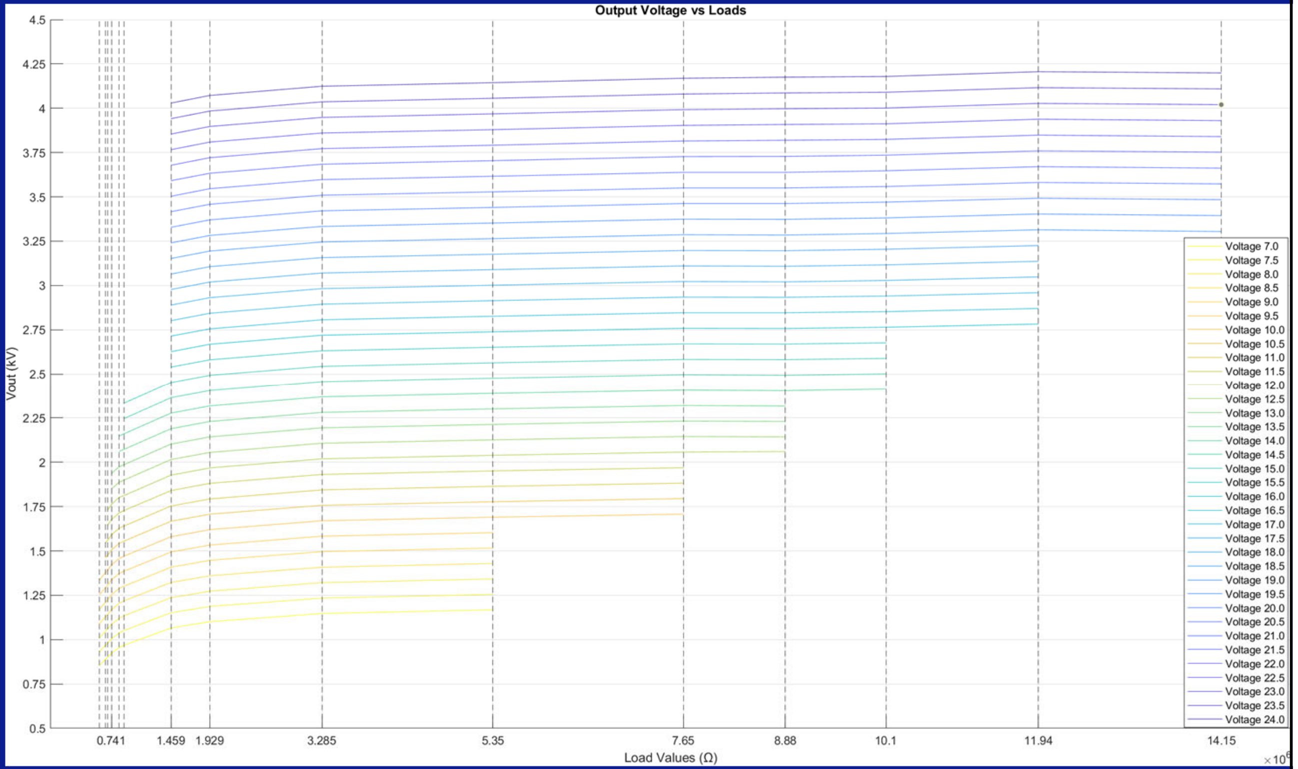
Temperature Endurance & Performance Test

- The output voltage drift is shown in the plot versus time
- The output voltage of the device is measured versus time or operation to determine the effect of time and temperature
- The output voltage drift is mostly affected by the increase in temperature
- The output voltage shows greater drift versus time at the higher voltages
- The increase in output voltage drift as the voltage increases is due to the temperature increase at a higher rate at higher voltages



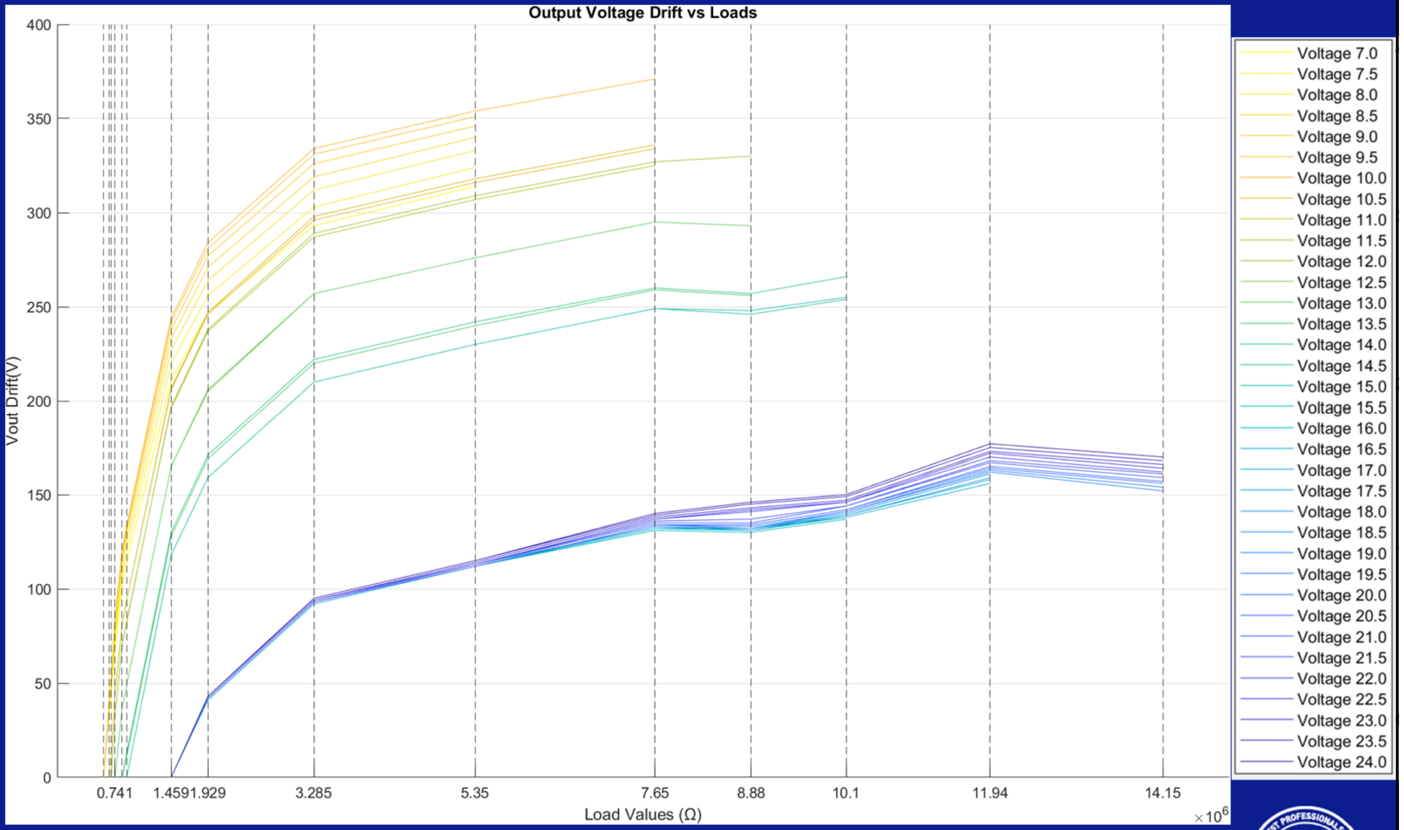
Output Voltage vs Load Values Results

- The plot shows the output voltage levels versus the load resistance
- Device shows better output voltage accuracy at higher loads
- Below 1.5 MΩ load output voltage is considerably lower



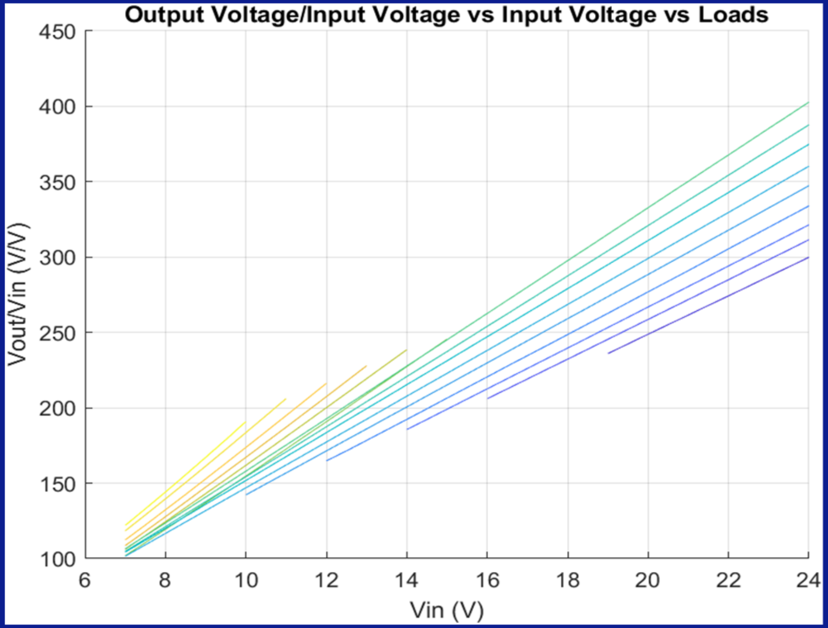
Output Voltage Drift vs Load Values Results

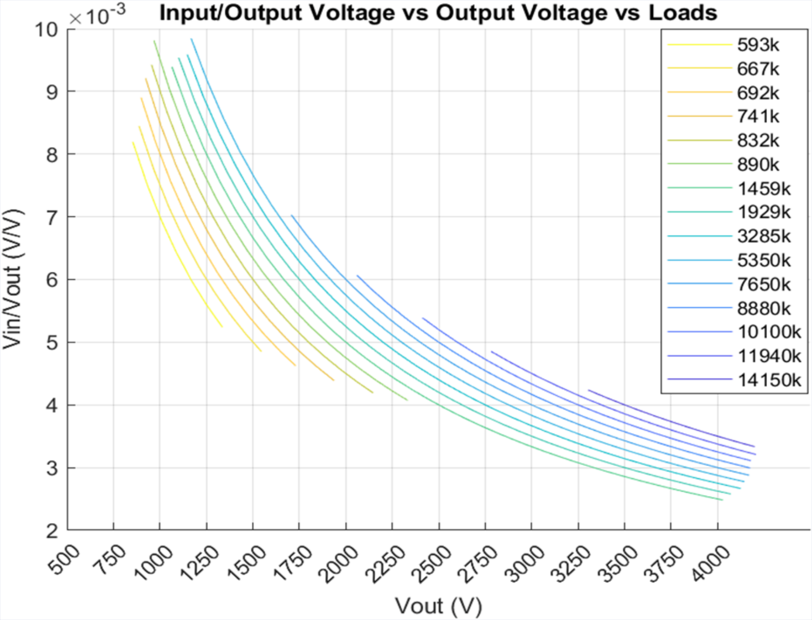
- Device shows better output voltage accuracy at higher loads
- The higher voltage at the lower load shows higher change due to high current draw from device
- Even at the lowest voltages at the low loads the drift is high which shows a lower current limit at the lower voltages



Voltage Gain vs Load Values Results

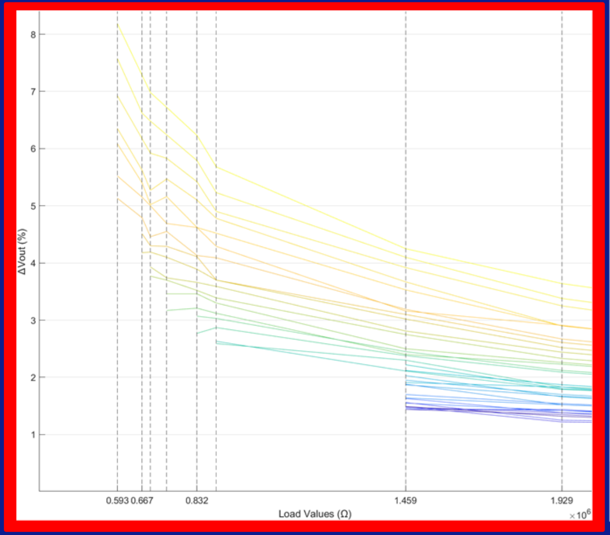
- Device shows better output voltage accuracy at higher loads.
- Higher voltages at lower loads shows higher change due to higher current draw.
- Even at the lowest voltages at low loads the drift is higher which shows a lower current limit at the lower voltages

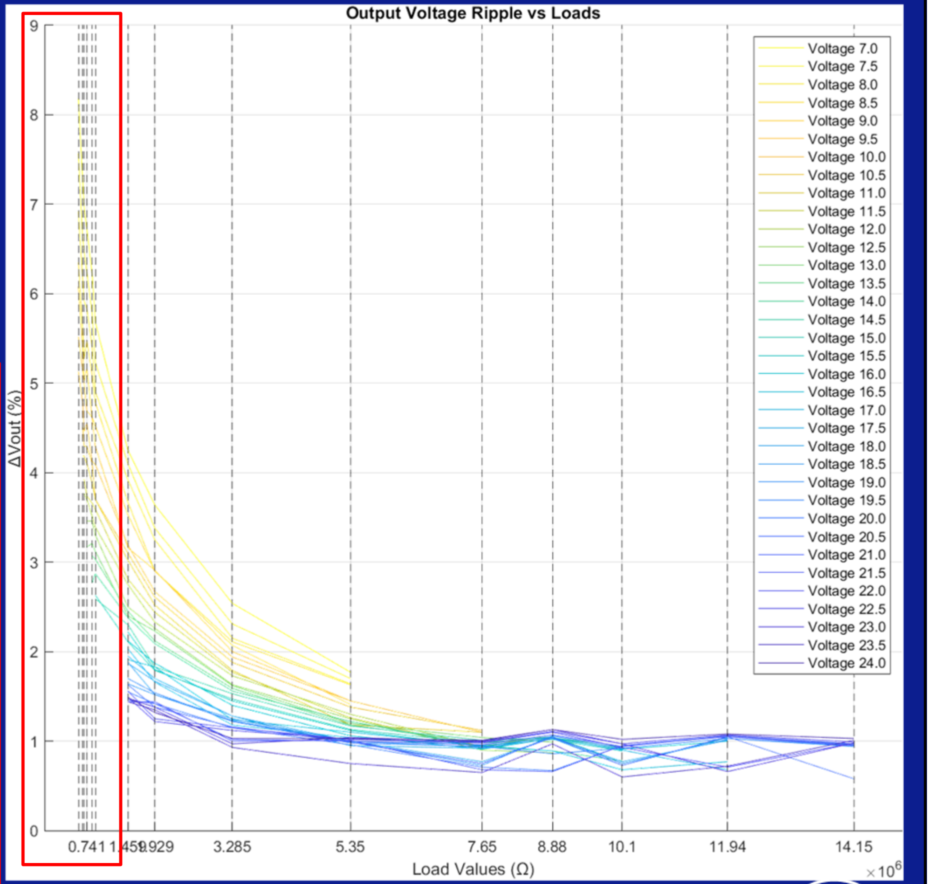

Output Voltage/Input Voltage vs Input Voltage vs Loads


Input/Output Voltage vs Output Voltage vs Loads

Output Voltage Ripple vs Loads Values

- Output voltage ripple is higher at lower voltages and much higher at lower load
- The increase of ripple at lower loads is attributed to the higher output current
- A high of 8% output voltage ripple seen at 593 kΩ
- Datasheet suggests 2% voltage ripple at max load



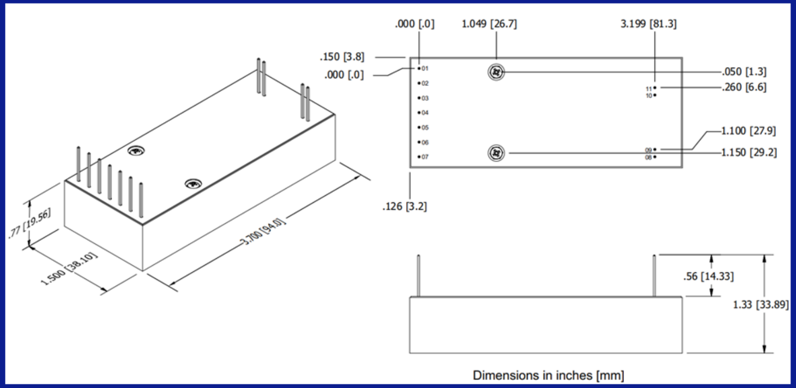


Summary of DC/DC Convertor Test

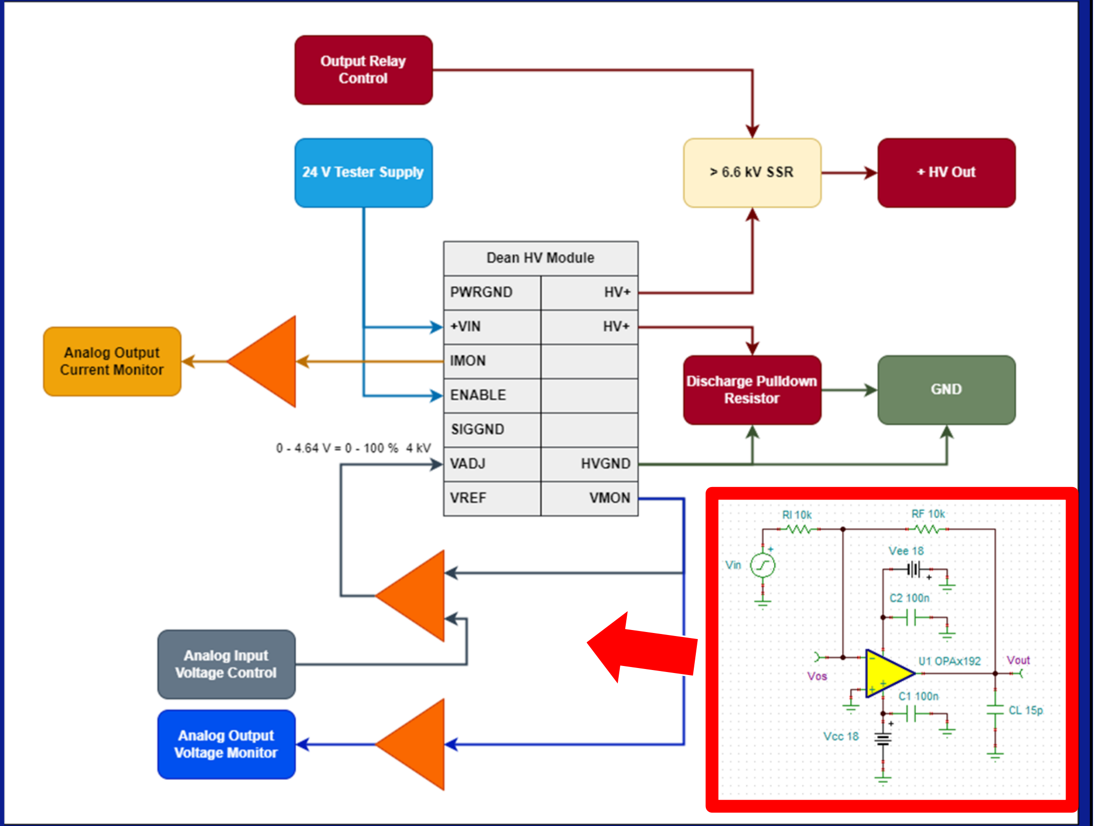
- The 24VV4 DC/DC converter falls short of meeting the specified requirements, revealing weaknesses in certain areas including:
  - At the specified minimum input voltage, the output reaches 1000 V instead of the intended 400 V, significantly limiting the operation range
  - The device fails to meet the output voltage ripple requirement, displaying a high ripple (8%) at the lower voltage range, posing challenges for improvements
  - The device exhibits indications of current limitation at lower voltages, rendering its performance unexpected and unreliable within that range

Possible Alternative: UMR-AA-4000P-30

- The UMR-AA-4000P-30 is going to be characterized the same way as the 24VV4.
- This device has more pins for voltage and current monitoring
- The picture shows a preliminary design of a possible final product with an analog feedback loop



Dean Technology UMR-AA-4000P-30 [2]

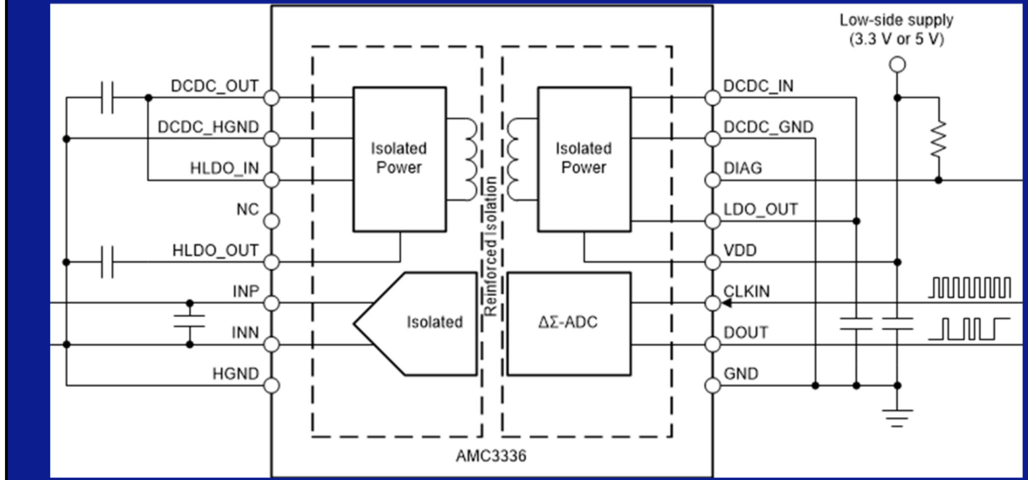


UMR-AA-4000P-30 Controller Block Diagram

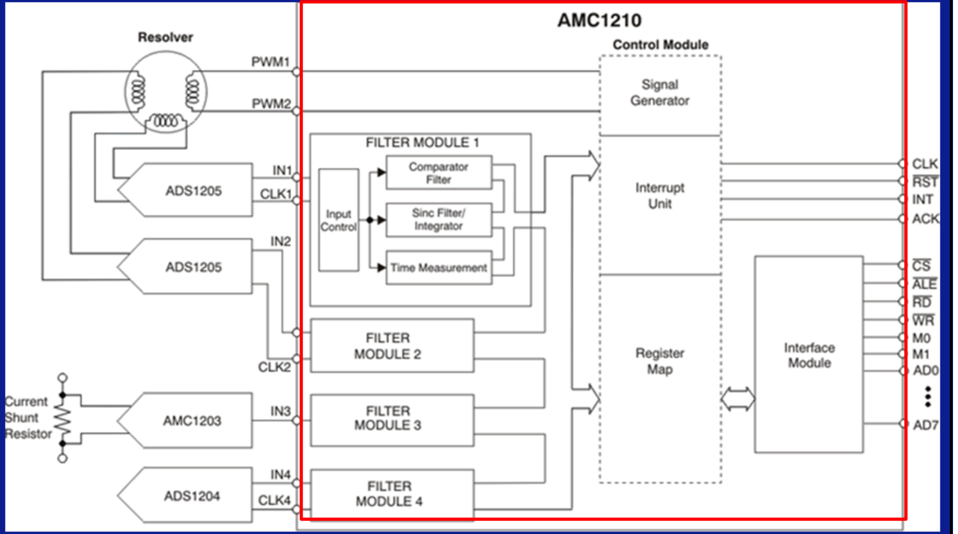
Voltage and Current Sense

- TI's AMC 3336 is a precision ΔΣ modulator with reinforced isolation
- Integrated DC/DC converter for isolated power on both sides
- A series precision voltage divider and AMC 3336 for voltage sense

- TI's AMC 1210 is a 4 channel 2nd order modulation filter
- The ΔΣ bit stream from the AMC3336 is filtered by the AMC1210 to be read by a µC using serial SPI



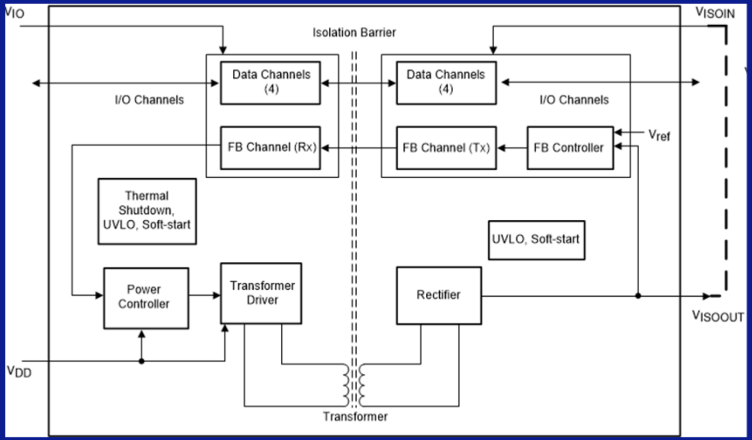
AMC3336 Modulator [3]



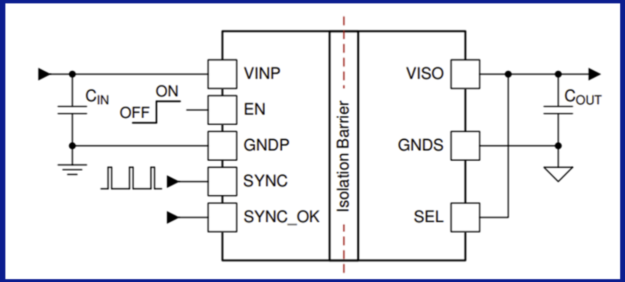
AMC1210 2nd Order Modulator Filter [4]

Isolation Devices

- TI’s ISOW7742-Q1 is a digital isolator with 2 transmits / 2 receive channels with DC
- The ISOW7742-Q1 features an internal power isolator
- The UCC12050 is a DC/DC isolator with a 3.3-5 V output range



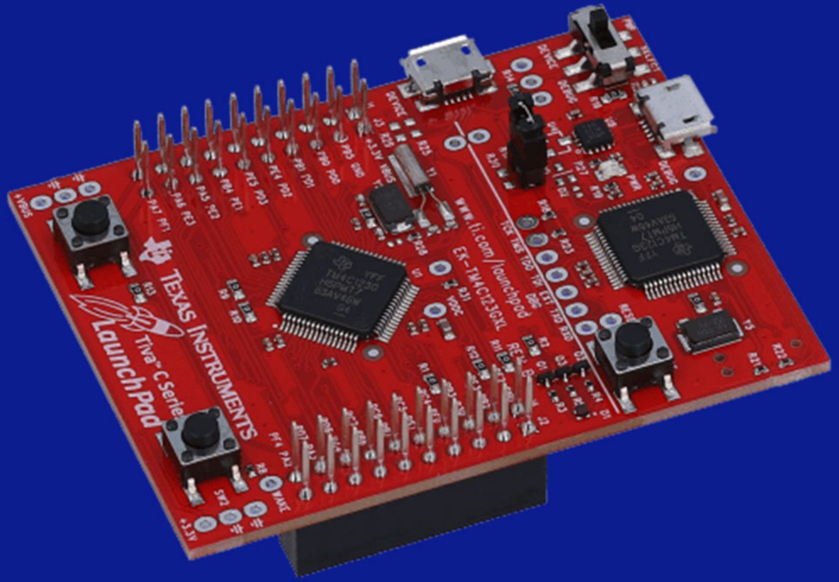
ISOW7742-Q1 Digital Isolator [5]



UCC12050 Power Isolator [6]

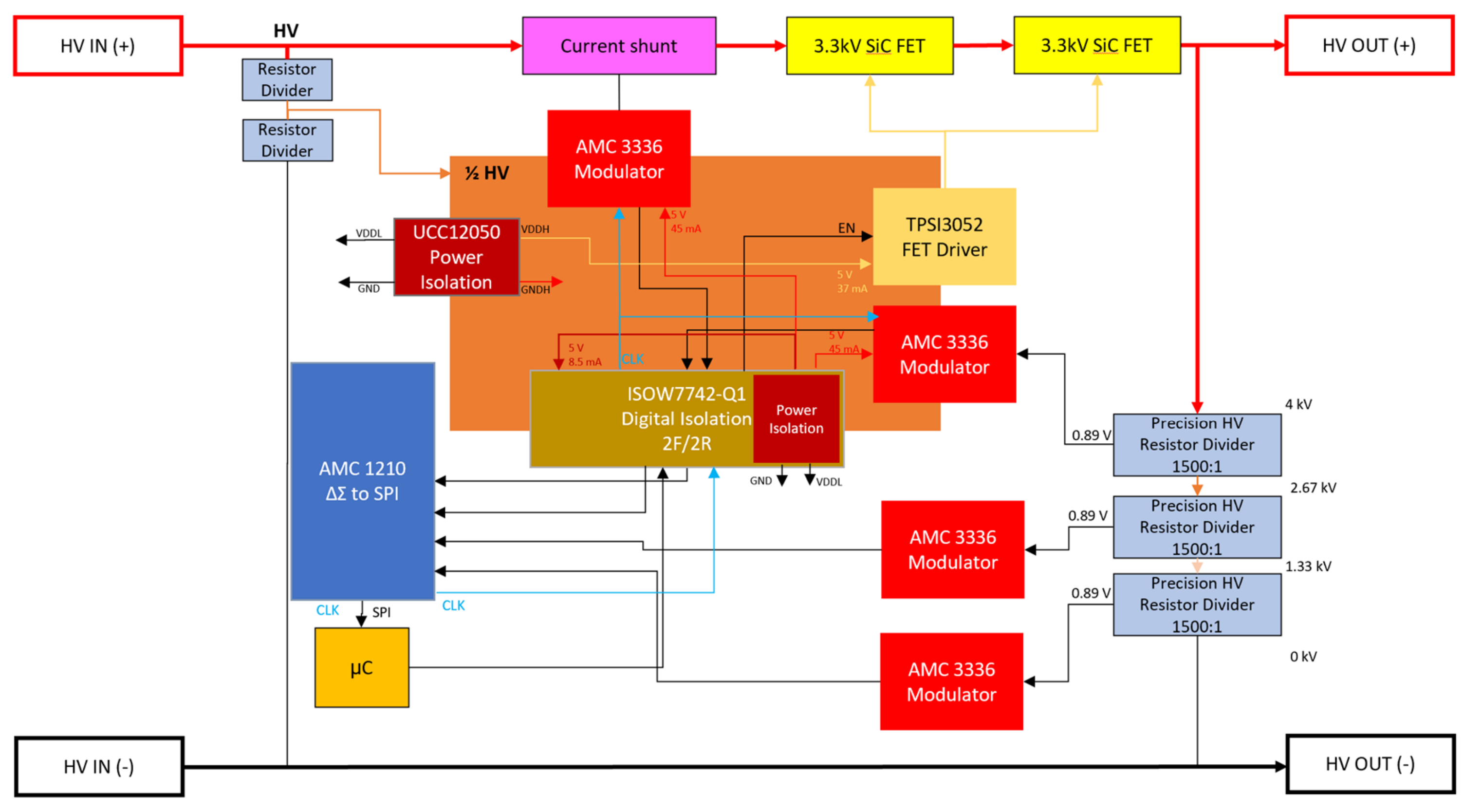
Microcontroller Interface

- Automated test equipment will interface with the prototype tester resource via SPI
- To simulate this interface, a Texas Instruments TM4C123GH6PM microcontroller will be used
- This microcontroller is available on the EK-TM4C123GXL evaluation board (shown on the right) for convenient prototyping
- This microcontroller operates at 80 MHz and features 4 SPI/SSI modules, sufficient for our application



Texas Instruments EK-TM4C123GXL Evaluation Board [7]

HV Control Block Diagram



Next Steps

- Integrate the HV board with the UMR-AA-4000P DC/DC converter loop and validate the design’s performance
- Finalizing the design of the final prototype and set of required ATE signals
- Characterize the final prototype and set the final parameters
- Implement on an ATE

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  - Dr. Alexander Johnston
  - Tyler Scoggin

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- [4] Texas Instruments, “Quad Digital Filter for 2nd-Order Delta-Sigma Modulator datasheet (Rev. D)”, [Revised May 2009]
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