[Insert Cool Name]:

Bidirectional PV-to-Bus Converters for Differential Power Processing in Automotive Applications

Ian Stewart

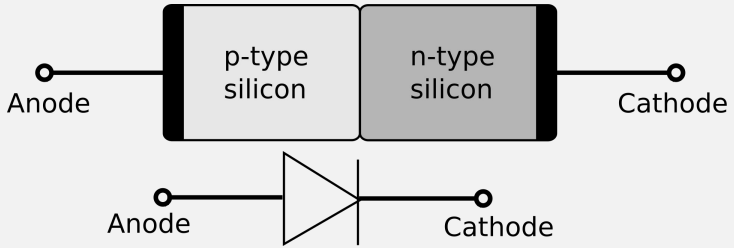
Agenda

1. Introduction
2. Background & Motivation
3. Differential Power Processing
4. Converter Design
5. Conclusion

Introduction

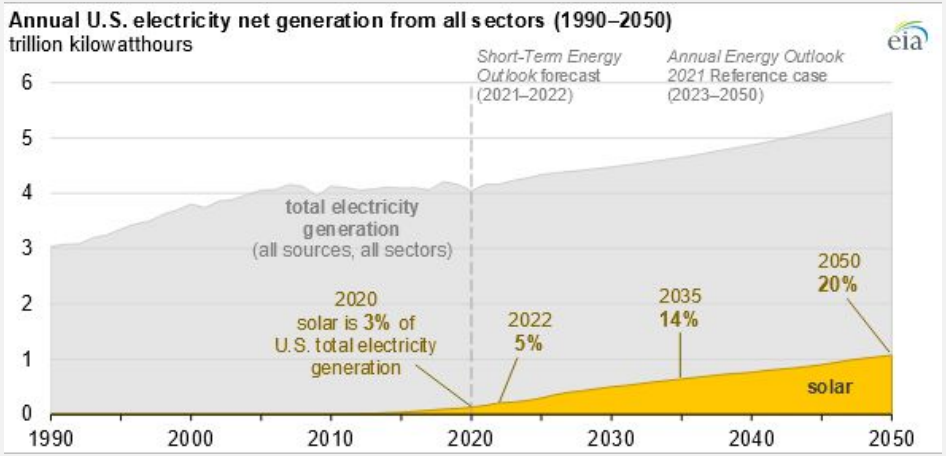
Photovoltaics

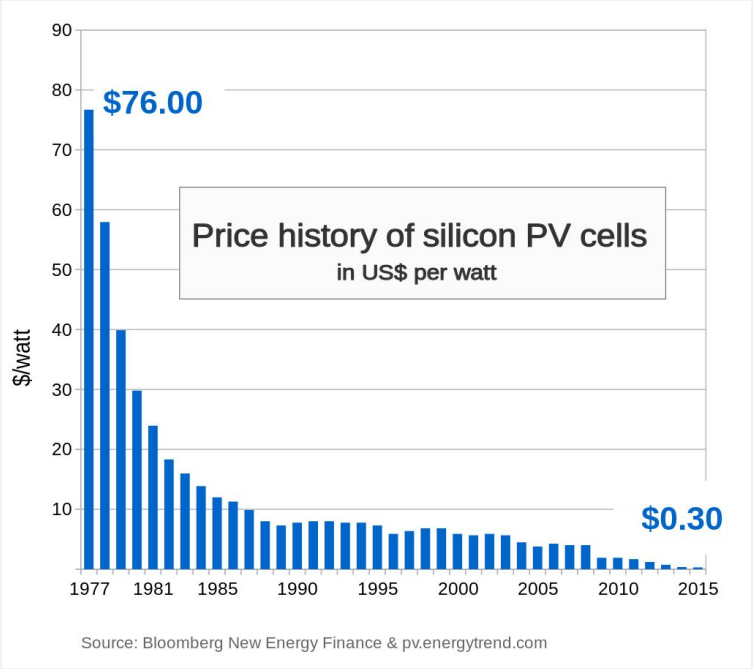
- Process of converting light into electricity, often light from the sun
  - Generally uses semiconductor electron generation
- Modern mass-production solar cells are generally made of Silicon
  - Creating doped P-N Si junctions is cheap, easy to manufacture
  - Crystals are grown, doped, and then the ingot is cut into wafers
- Higher-performance cells use other technologies
  - Generally significantly more expensive (>1 order of magnitude)
  - Significantly more fragile



Solar Power

- Solar Power rapidly gaining traction
  - Cost rapidly decreasing
  - Efficiency increasing
    - Approxing theoretical maximum





Automotive Uses

- Solar power can also be useful to vehicles
  - Even before EVs, used to keep A/C running while parked
  - With the rise of EV popularity, can be used to increase range
- Cars have been made that operate on solar power for decades
  - First street-legal solar car registered in the UK in 1976
  - Many solar-powered racing cars built in the years since
- In the near future, solar panels will likely be an option on many cars
  - Lightyear, Aptera, Sono, Squad commercializing around solar
  - Tesla, Hyundai, and more adding panels to supplement EVs

Automotive Challenges

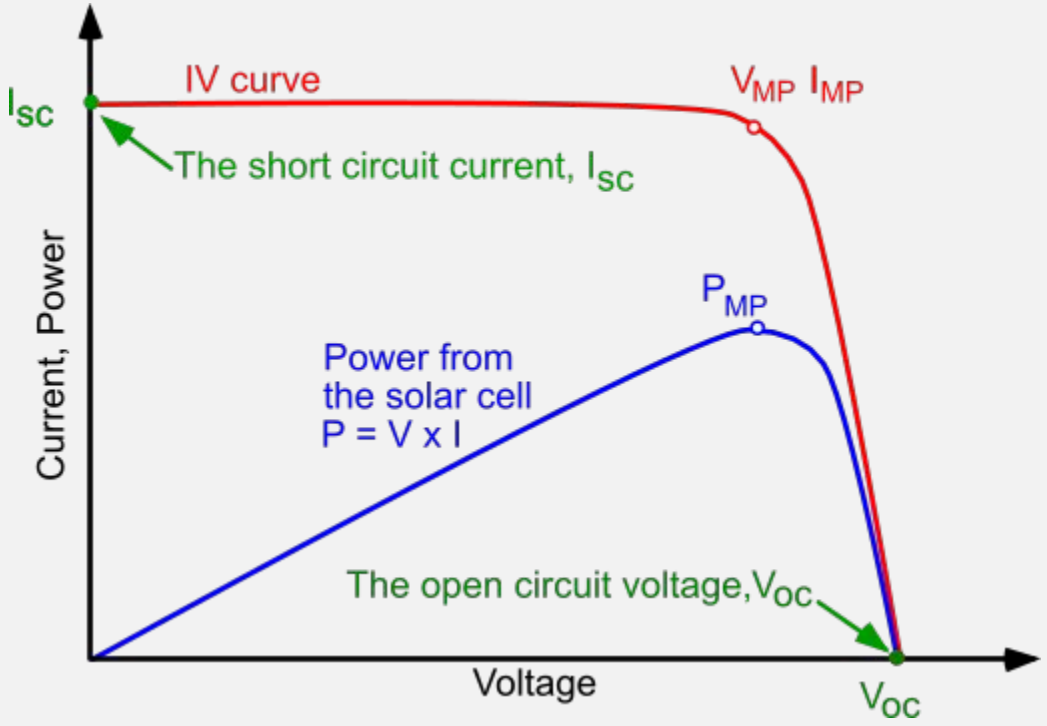
- Remains unlikely most people will ever drive fully on solar power
  - Can work for small cars commuting in sunny areas, but
    - Silicon solar cell theoretical max efficiency is under 34%
    - Standard car sizes have considerable power requirements
      - Drag, rolling resistance, comfort features, autonomy
    - Cars have aerodynamic curvature and are shaded
- However, reducing reliance on fossil fuels is of vital importance
  - Any range increase from solar power is a reduction on the grid
- As such, seek to maximize power generation from solar cells

How Embedded Systems Can Help

- Power produced by a solar array subject to a number of loss factors
  - Base Efficiency - nominal efficiency of the cells being used
  - Cosine Loss - difference in normal vector of cell and sunlight
  - Thermal Loss - cell efficiency decreases with temperature
  - Shading Loss - cell generation decreases if sunlight blocked
  - Remember, cells in series are affected by each other's losses!
- Arrays also do not necessarily operate at their most efficient point
  - Specific voltage/current combination will produce max power
  - However, cells don't magically operate at this point on their own
- These are areas that embedded systems can help address

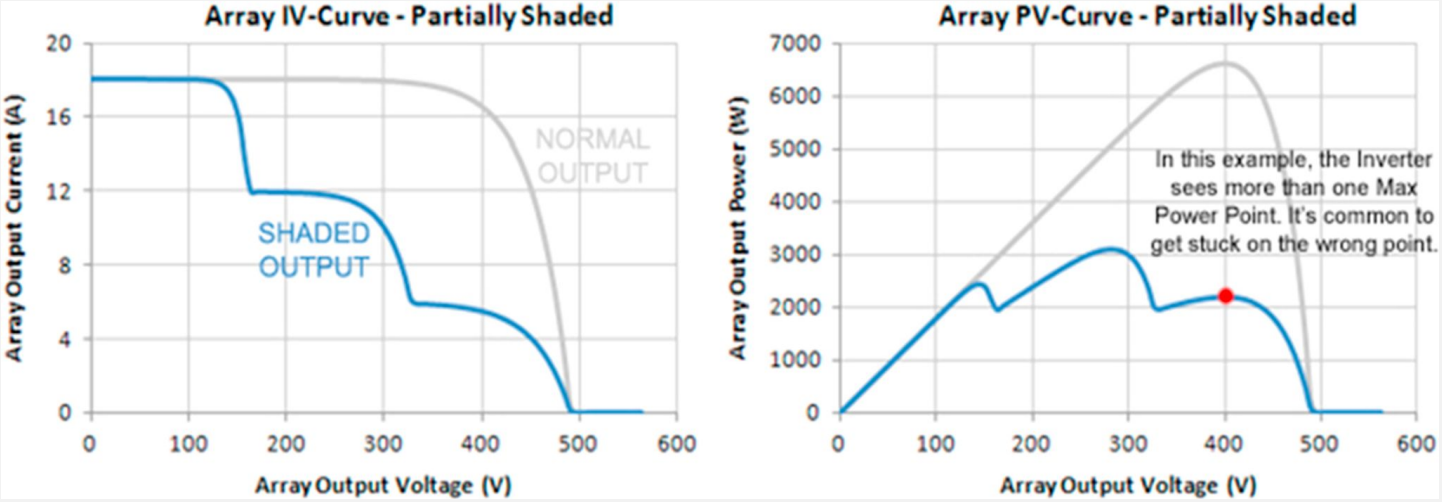
Background & Motivation

Solar Cell Maximum Power Point



Maximum Power Point Tracking

- Commonly, we use an embedded system to track the MPP
  - With a single solar cell, this is convex - perturb and observe
  - When multiple cells exist, local maxima may exist
    - This is particularly damaging to efficiency with shading

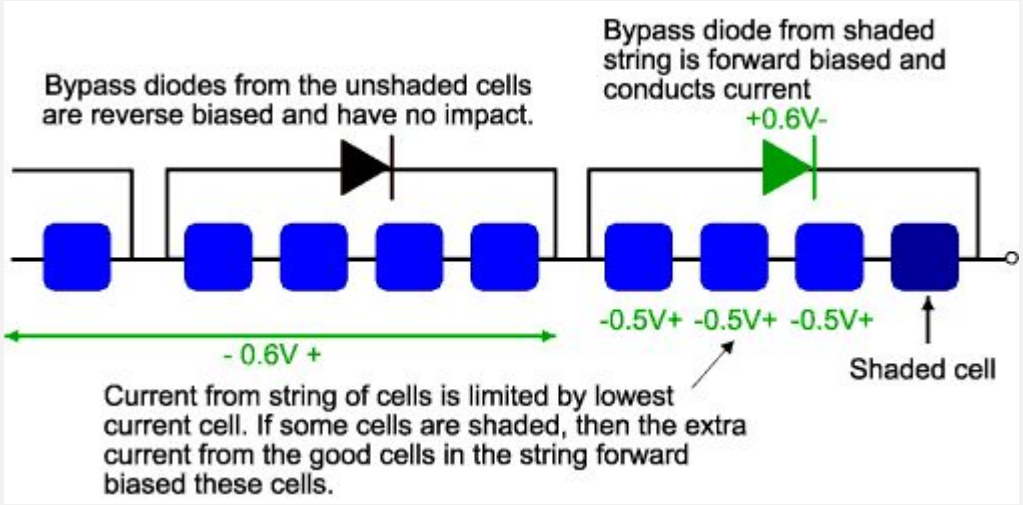


How To Address This

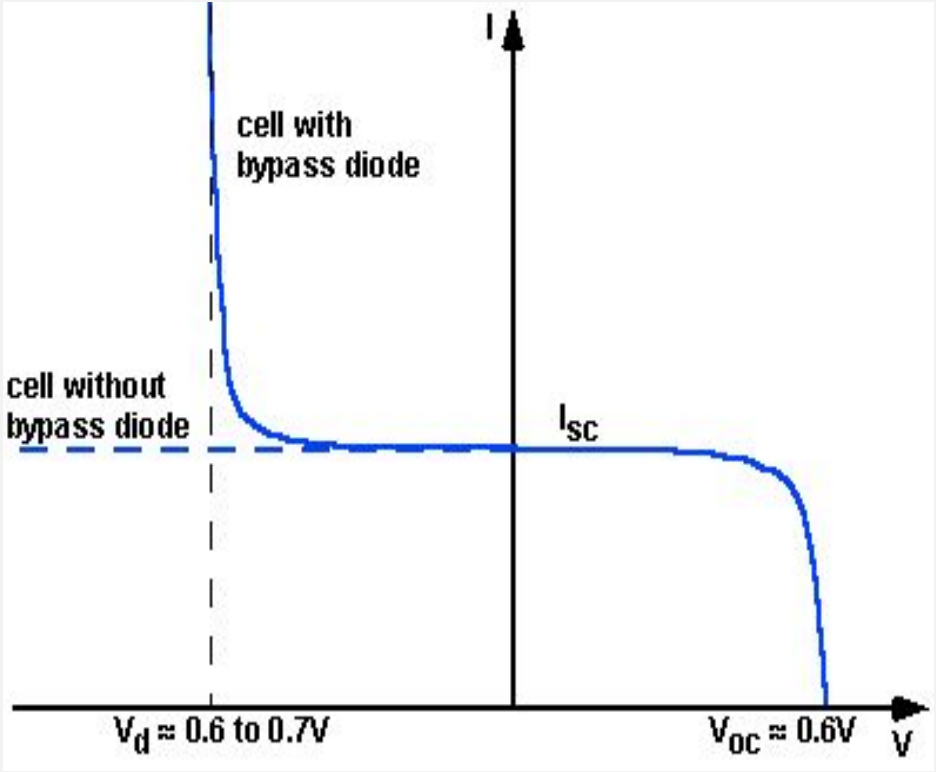
- Tempting to utilize other methods to track maximum power point
  - Other algorithms can be used to improve tracking accuracy
  - Global sweeps can be performed to characterize IV curve
    - Very easy to guarantee operation at maximum power point
    - Do not generate optimal power while sweep is performed
- Only useful as long as the IV curve does not change
  - IV curve will change constantly on a moving car
- More efficient use of resources to just improve the power curve!

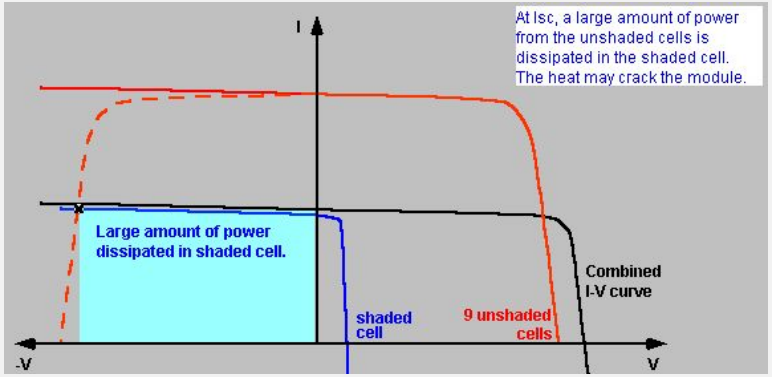
Improving the Power Curve?

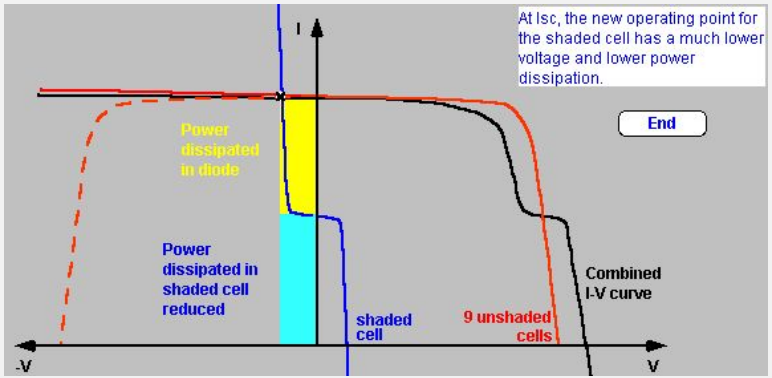
- Necessitates understanding why shading causes local maxima
  - Generally due to bypass diode activation
    - Diodes placed along cell to prevent reverse bias damage



Bypass Diode Effect on IV Curve







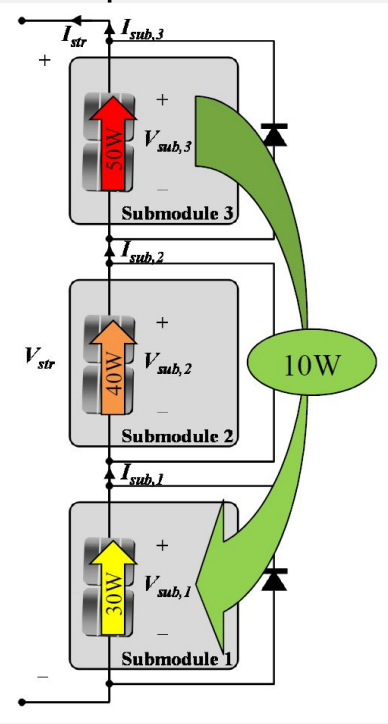
What To Do About It

- Obviously, the ideal would be for the cells to just… never be shaded
  - Clearly impractical when on a moving automobile
- However, we live in reality, and must deal with the downsides of that
- Note these issues are generally caused by shared operating point
  - If each cell could operate at its own MPP, would be no issue
    - Giving each cell a MPPT is prohibitively expensive
      - MPPTs are generally the driving cost for small arrays
  - Must find a different way to diversify operating points

Differential Power Processing

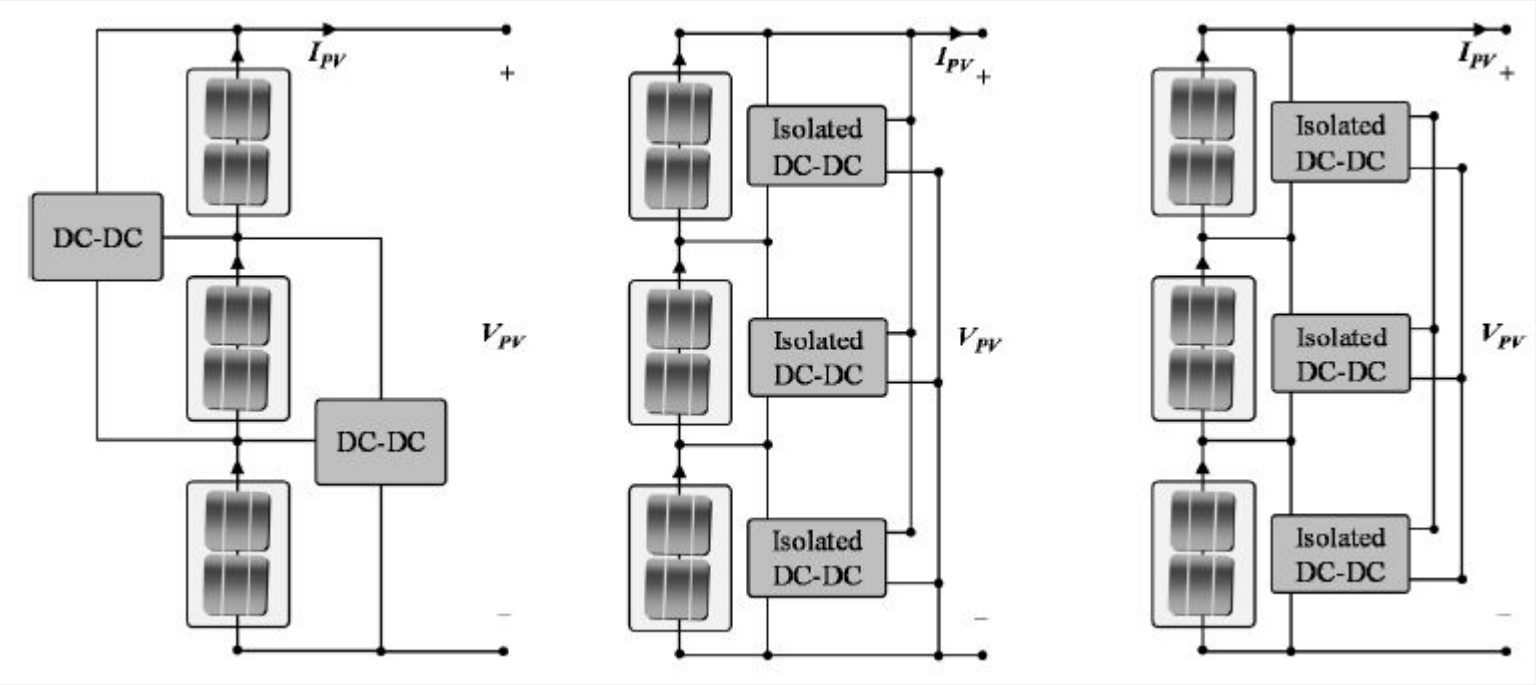
Differential Power Processing

- Take current from one part of the array and move it to another part
  - Now all parts of the array can operate closer to MPP
- It is not immediately obvious that this is possible
  - Current can not be directly siphoned
  - Instead, power must be converted across the array
- There are in fact several ways to do this
  - Commonly bidirectional converters are utilized
  - Sometimes, a capacitive ladder is used instead
    - Relatively cheap to produce and easy to control
    - Requires encapsulating components into array



Bidirectional Converter Methods

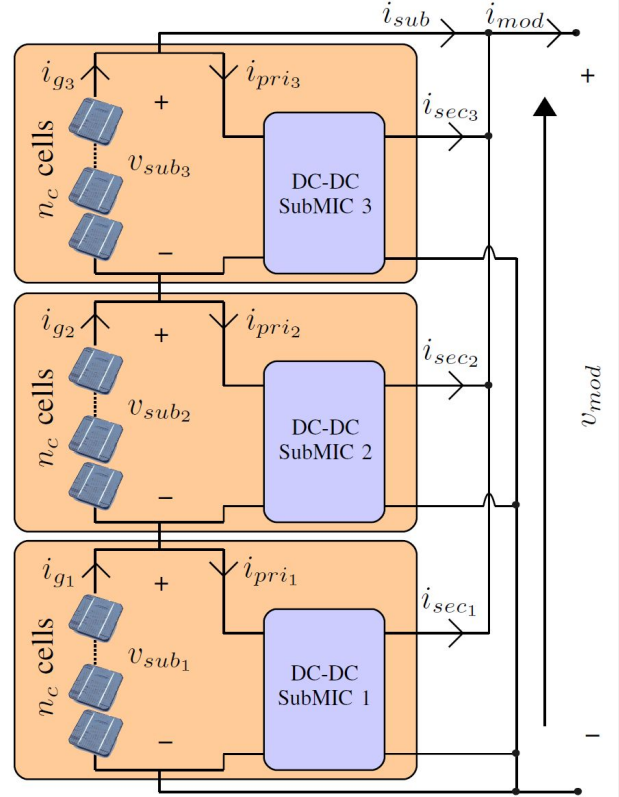
- There are several topologies that may be utilized

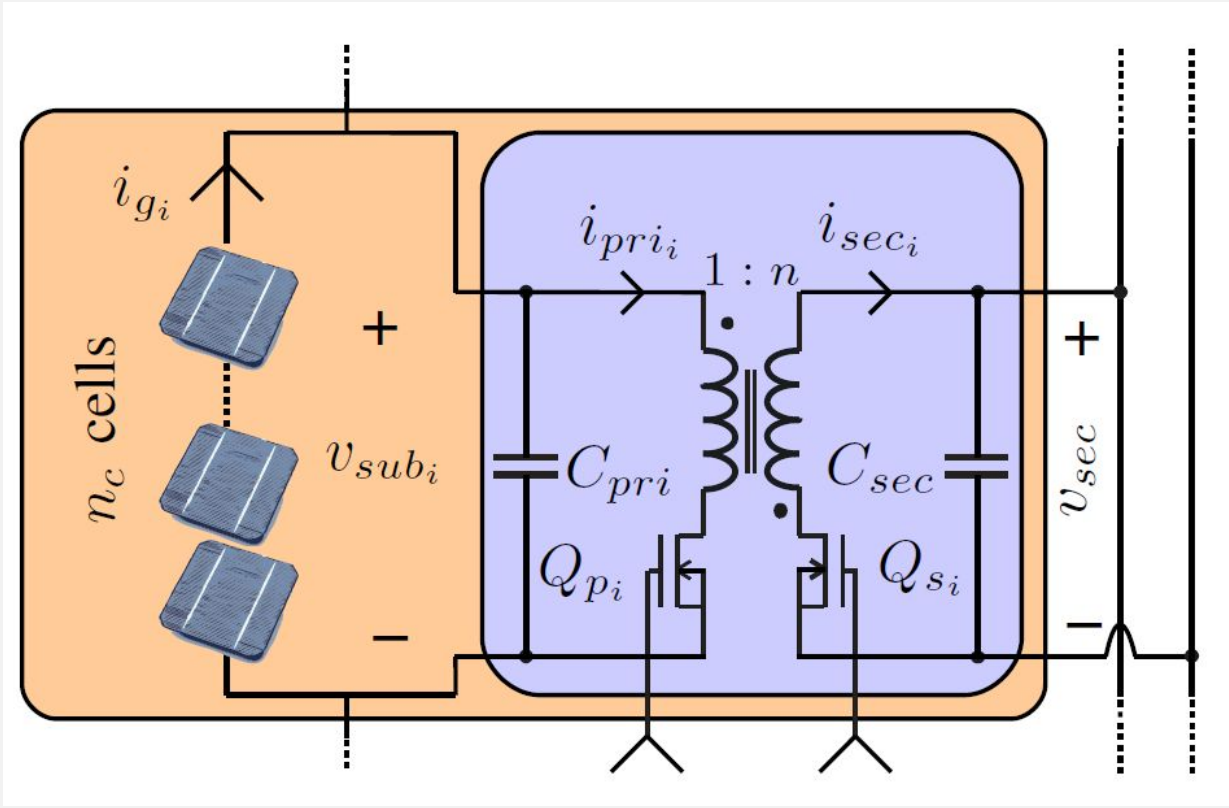


Status of the Literature

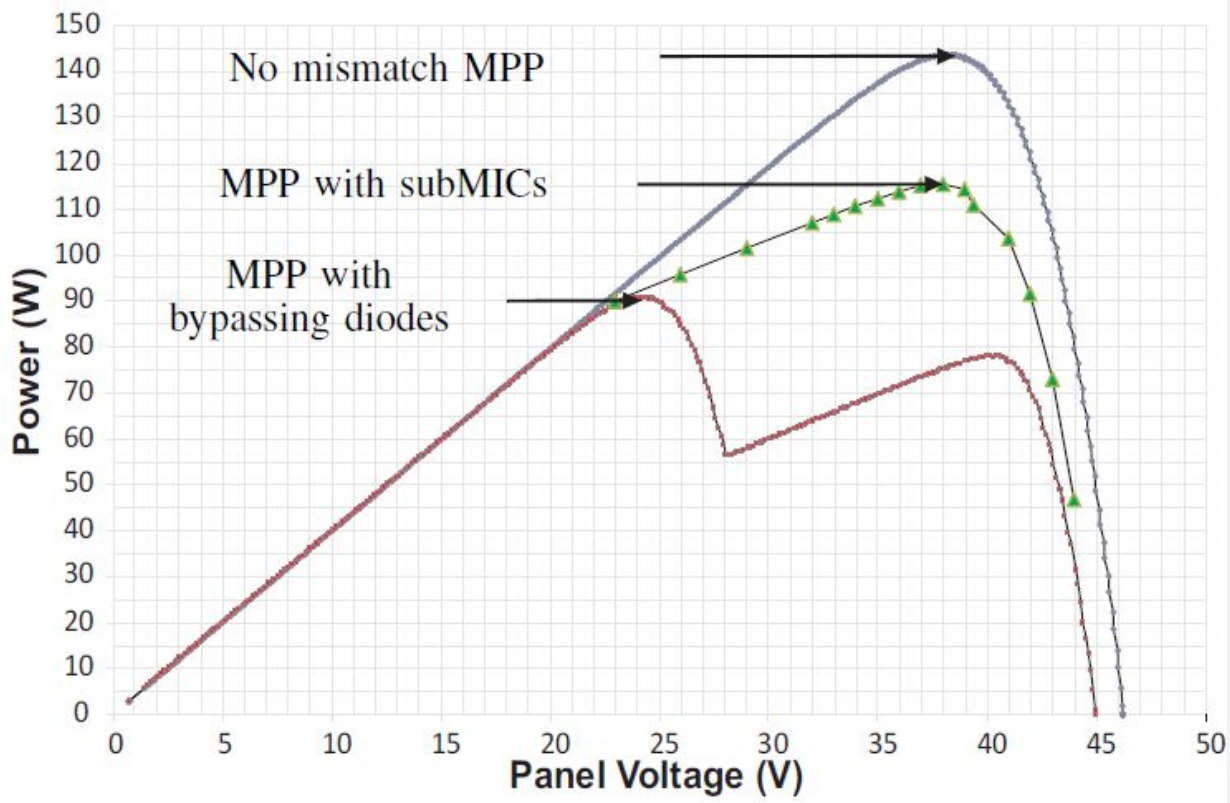
- Significant research has been conducted on PV-to-Isolated-Bus
  - This is more efficient than shuffling topologies
  - Easily expandable and much more easily controllable
    - Each converter needs only maintain its own MPP
      - Technically nonideal - losses acceptable for many uses
      - As no central control is required, can easily add more
- However, PV-to-Bus (nonisolated) is more ideal for automotive usage
  - Unlike commercial/residential panels, system cannot expand
  - Increased efficiency is worth the trade-off of system complexity
- Research focuses on the grid, PV-to-Bus is virtually unexplored

Basic Operating Principle





Desired Outcome



PV-To-Bus Implementation

- As mentioned, this has been shown to work in PV-to-Isolated Bus
  - PV-to-Bus has additional control, implementation challenges
- Voltage of entire array can often be many times that of each string
  - Requires components with much higher voltage ratings
    - Reduced impact in automotive environments
      - Still roughly 5-10x as opposed to 1x with isolated bus
- To minimize processed power, central control is required
  - Track maximum power point of each string and full array
  - Dictate operating points for each individual converter
  - Decentralized control not easy due to fluctuating array voltage

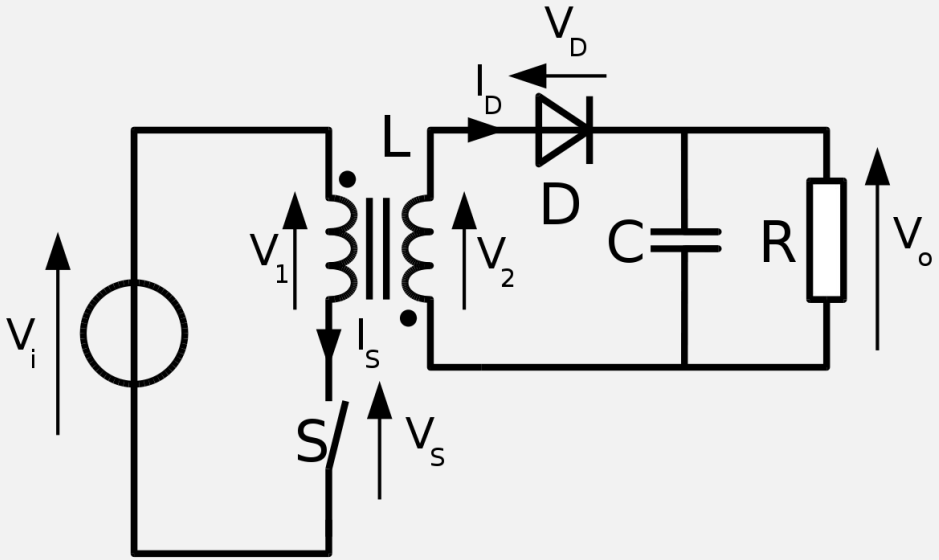
Converter Design

Prototype Circuit

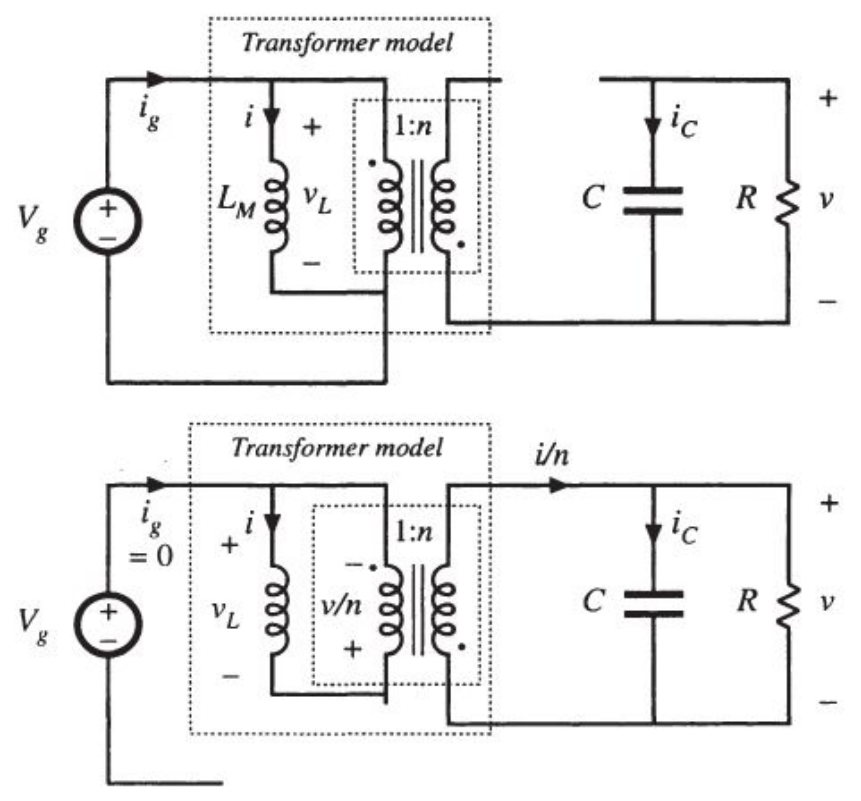
- PV-to-Bus requires highly-specialized design, so using a prototype
  - Will be representative of the voltages experienced on a real car
  - Can be modified down the line for different circumstances
  - Will enable experimental result gathering for proof-of-concept
- Implements voltage conversion, basic centralized control
  - Fine-grained control will be accomplished as later addition
    - Want to prove the basic idea works, then focus on details
- Will start with one such board, expand if results in line with theory

Flyback Converter Basics

- Flyback converters are basically isolated buck-boost converters
  - Isolation achieved through usage of a coupled inductor
    - Necessary due to converter laddering

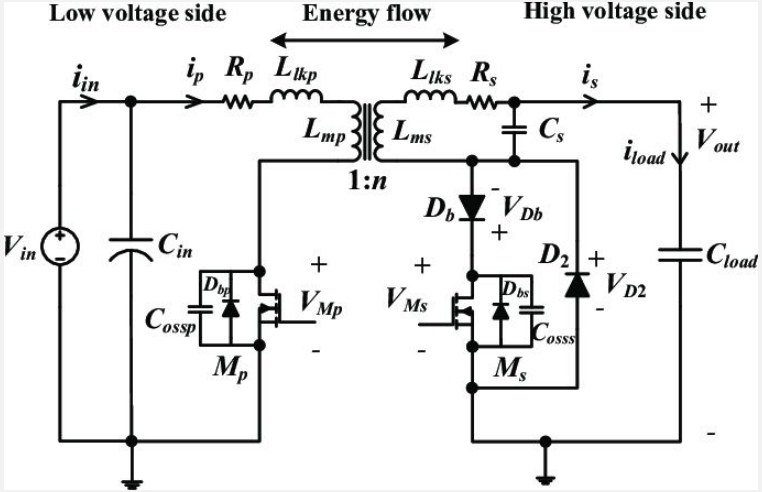


Flyback Circuit Operation



Bidirectional Flyback Converter Basics

- Bidirectional flybacks allow power to flow in either direction
  - Can boost power from string voltage to array voltage
  - Can buck power from array voltage to string voltage
  - Accomplished via replacing the diode with a second transistor



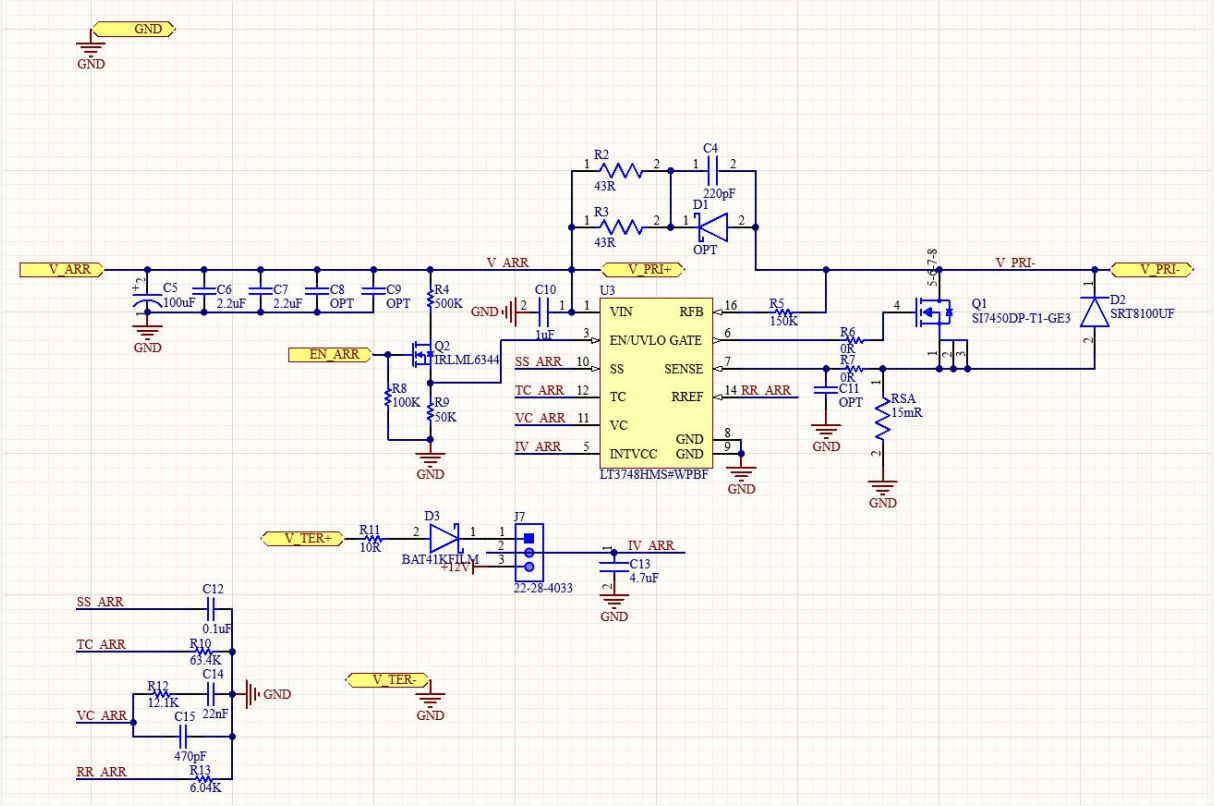
Flyback Design Considerations

- Power losses in circuit lead to inefficiency
  - Switching losses are dissipated in transistors, $\propto$ frequency
  - Copper losses are dissipated in wires/traces/windings
  - Core losses are dissipated in the transformer magnetic core
- Voltage ripple and stress
  - Need to spec components for maximum values attained
  - High ripple can lead to noisy, hard-to-control output
- Isolation barrier impedes sensing
  - Need knowledge of both sides' voltages to control converter
  - Must use a decoupled method to communicate across isolation

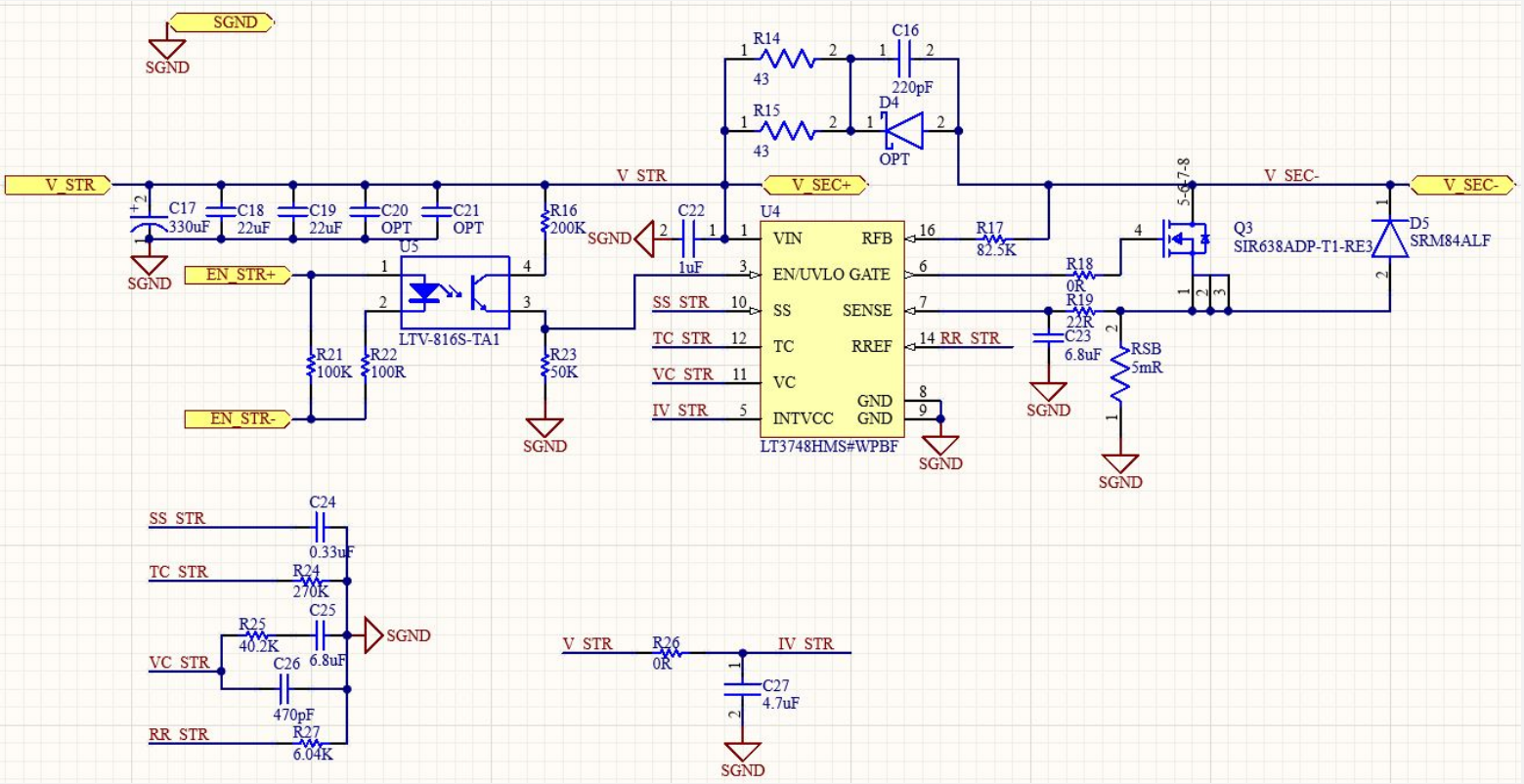
Prototype Realization

- 4-Layer PCB to ensure adequate return paths, noise filtering
- Utilizing STM32F405 microprocessor to enable control
  - Commonly-used microprocessor family, easy to implement
  - Allows for CAN communication, common on automobiles
- Currently using LT3748HMS#WPBF Flyback Controller
  - Automotive-grade component, wide voltage range (5-100V)
  - May replace with digital controller or custom circuit later
    - For proof-of-concept this is the fastest path forward
- Currently communicate across isolation barrier with photocoupler
  - Will need cross-barrier voltage sensing for final version

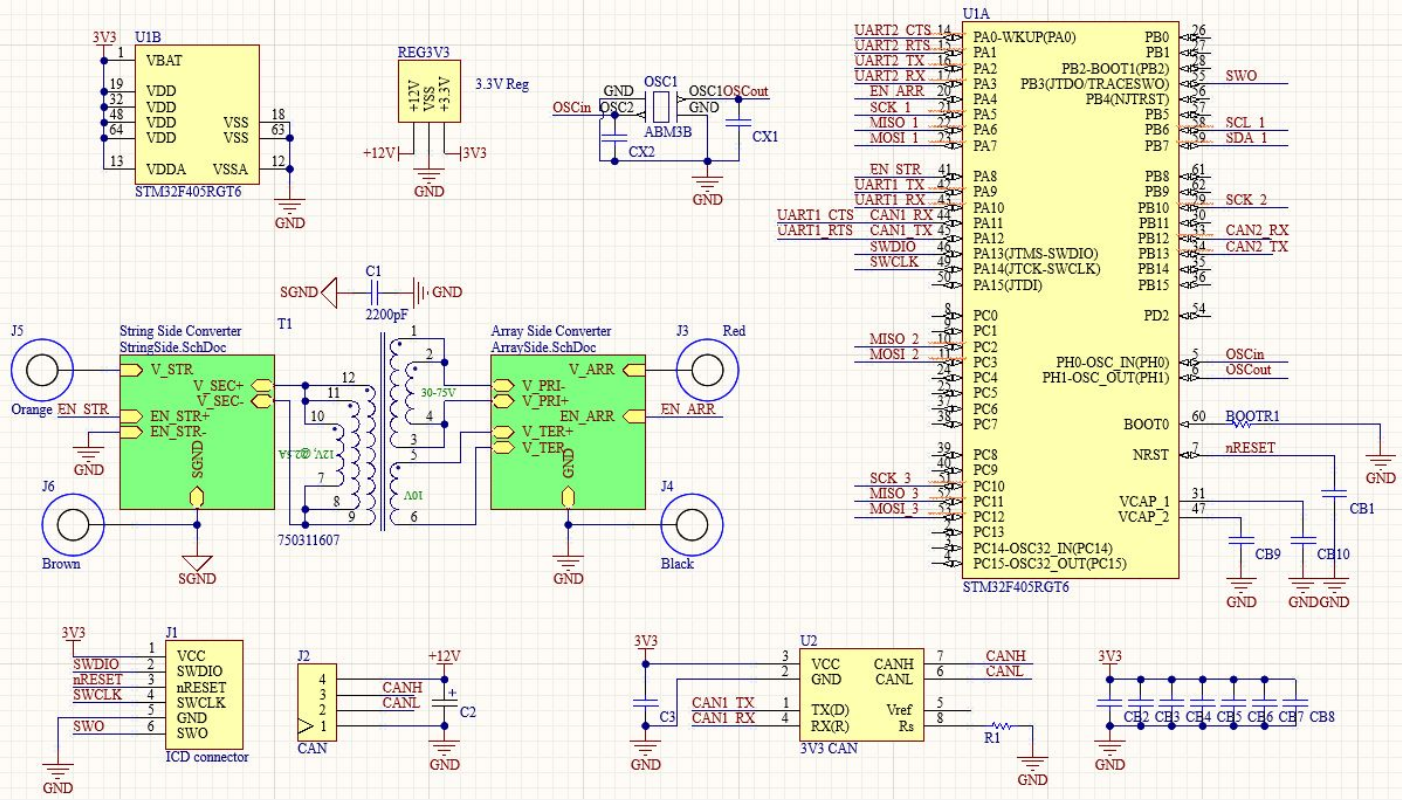
Array Side Schematic



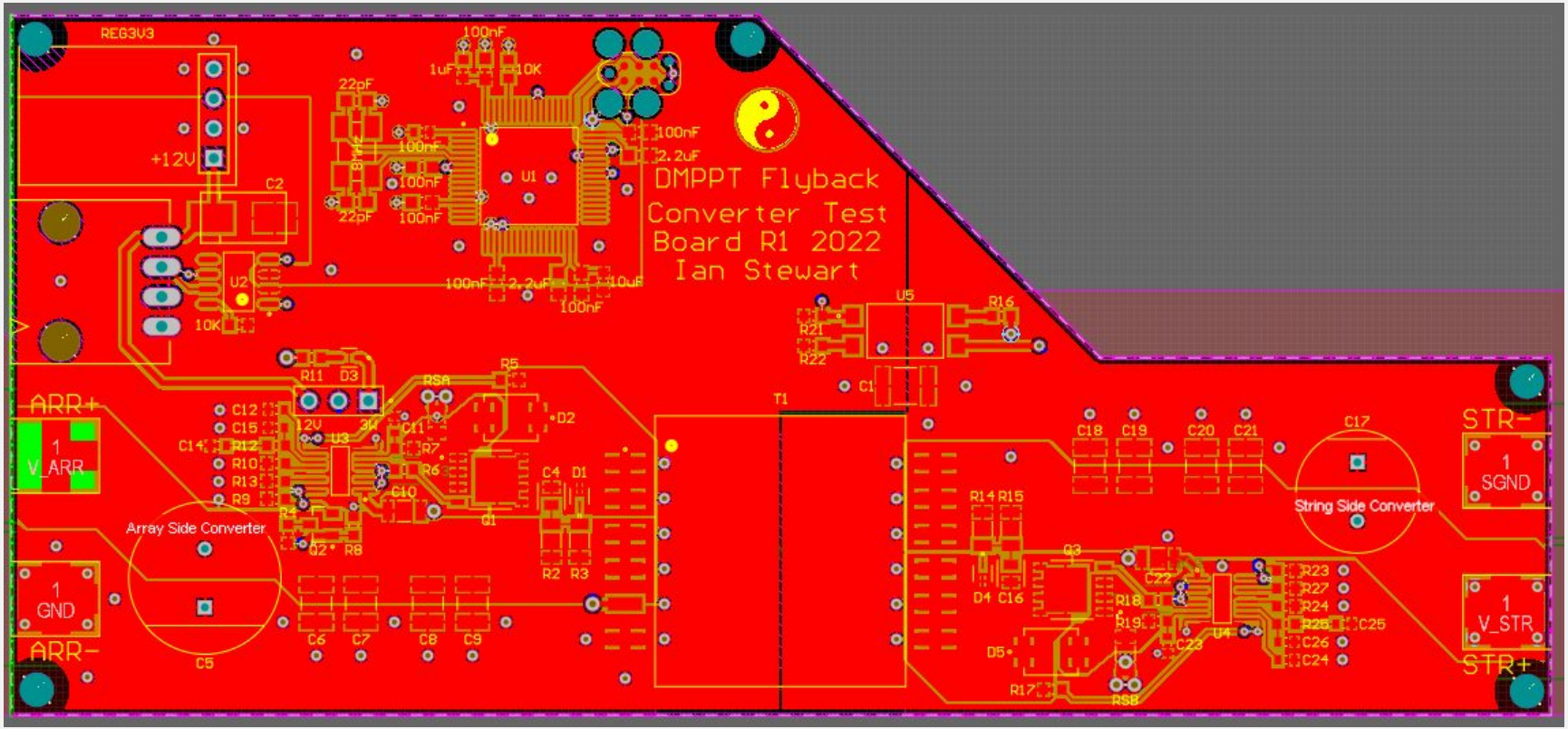
String Side Schematic



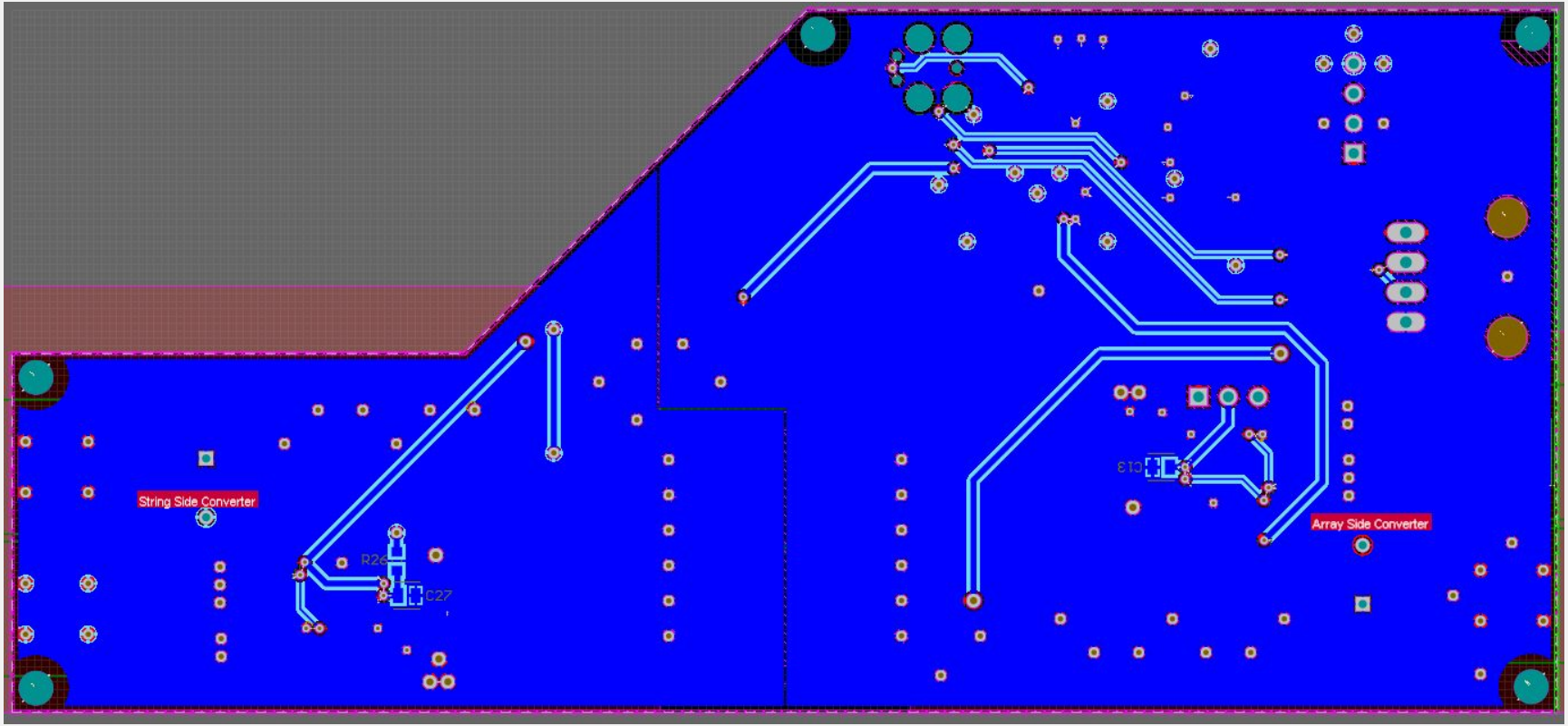
Central Controller Schematic



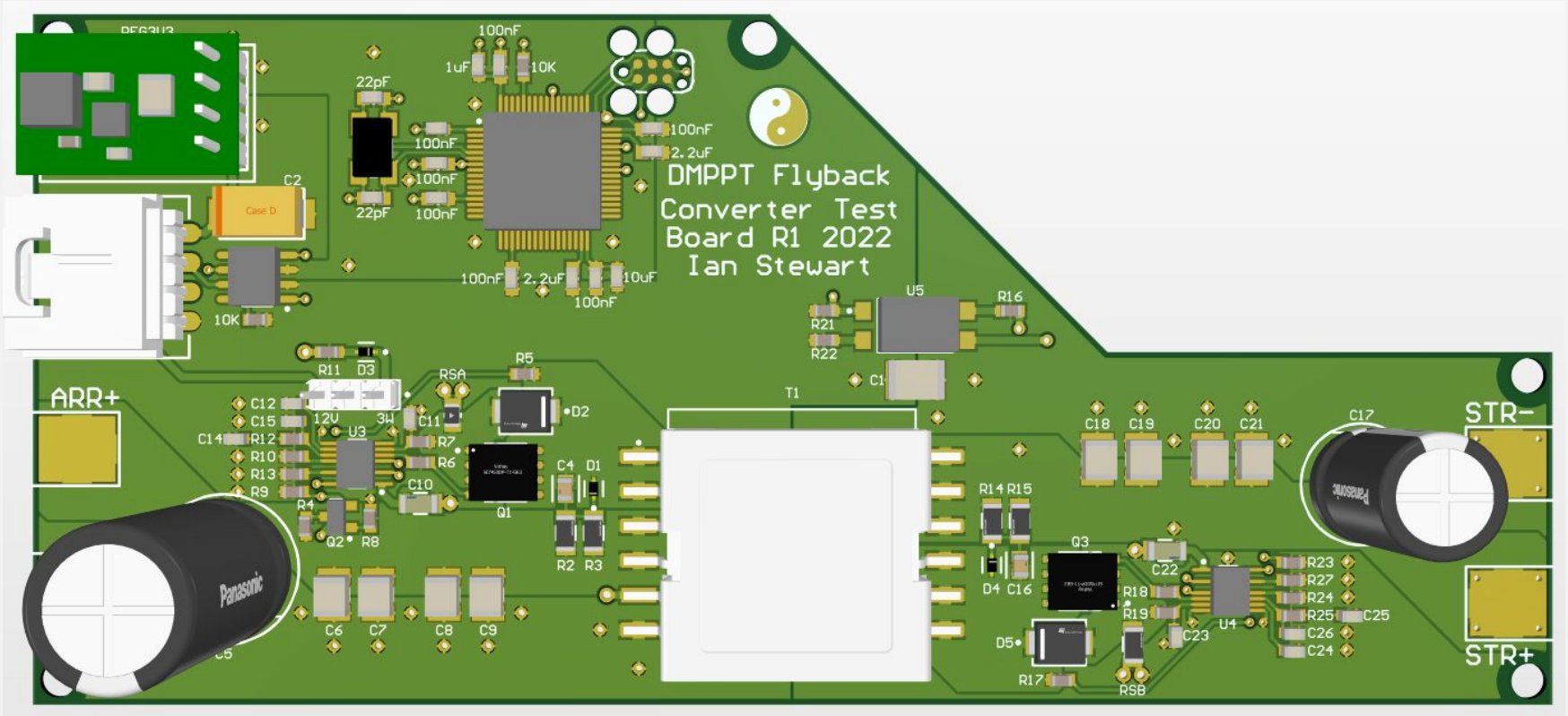
Prototype Board Top Layer



Prototype Board Bottom Layer



Prototype Board CAD



Conclusion

Project Overview

- Solar power has been gaining in marketshare for a long time
  - Likely to expand into automotive industry very quickly with EVs
- Automotive environment necessitates specialized design
  - Unlike anything research has done for use in other industries
- PV-to-Bus differential power processing is a promising topology
  - PV-to-Isolated-Bus has shown results in prior testing
  - Non-isolated bus offers highest efficiency
    - Extra complexity negligible in non-modular, single system

Current Status

- Prototype board design completed ~2 weeks ago
  - Components ordered, received and currently in-hand
  - Boards ordered, delayed in shipping - should arrive this week
- Once they're in, will manufacture and test these boards
  - Will ensure bidirectional flyback topology behaves as expected
    - Specifically, for reasonable voltages for this application
  - Will use findings to inform next steps regarding flyback control
- Based on shipping times, final report may only include prototype
  - Actual work will continue beyond the end of this course

Questions?