National Aeronautics and Space Administration

Investigation into High Power Converter Topologies

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Agenda

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Introduction

- The NESC commissioned NASA Glenn Research Center (GRC) to perform a study of high-power DC-DC converter topologies
- Why perform the study?
  - Several past contractor-led converter development programs have been plagued with development delays and cost overruns due to:
    - Poor initial design decisions
    - Complex requirements driving designs
  - Better inform government engineers about strengths and weaknesses of various topologies, learn about new topologies/design strategies
  - Allow NASA to be better prepared for upcoming high power/high voltage power conversion systems work, such as Lunar and Martian surface missions, high power electric propulsion, as well as terrestrial systems, such as electrified aircraft
  - Contractors often do not have the option to restart poor decisions – allows NASA to be better informed at the start of programs

Task Overview

- Phase I: March-September 2021
  - Performed literature search to identify topologies
  - Selected candidate topologies
  - Evaluated strengths, weaknesses, robustness, potential applications
  - Performed preliminary simulations for each topology
  - Populated spreadsheet with initial findings
  - Developing a database comparing performance, efficiency, mass, volume, component stresses
  - Writing final report summarizing findings – much more detailed than this presentation

Investigation Team

- Kristen Boomer
- Art Birchenough
- Luis Piñero
- Xavier Collazo-Fernández
- Pat Hanlon
- Greg Tollis
- Corey Rhodes
- Matt Granger
- Bob Scheidegger

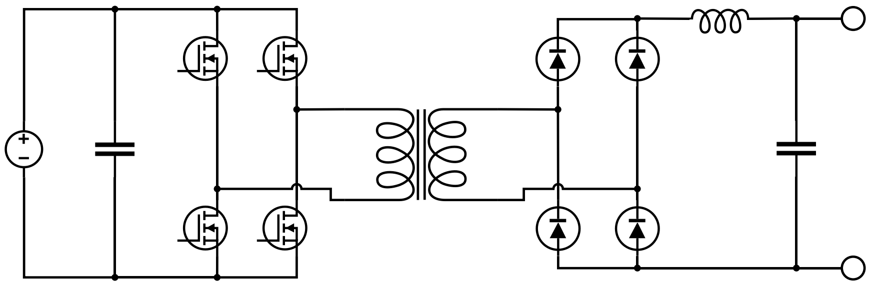
Assumptions and Design Considerations

- Focused on isolated DC-DC converter topologies for high power applications
- Baseline topology is PWM full bridge with parameters (module level):
  - Input Voltage: ≤150VDC
  - Output Voltage: 200VDC
  - Power: 1kW
- Max rated FET voltage 250V, max rated diode voltage 600V (before derating) due to available space-qualified parts
- Identified competing topologies to evaluate pros/cons against baseline
- Modules can be stacked in series or parallel or internally paralleled to increase power level and/or output voltage
- Studied one DC-AC topology in detail due to interest for aeronautics applications

Topologies Studied

- PWM Full Bridge
- Phase-Shifted Full Bridge
- Weinberg Current-Fed
- Cascade Current-Fed
- Resonant LCC, LLC
- Neutral Point Clamped (DC-AC Topology)

PWM Full Bridge Converter



A full bridge voltage fed converter, by a large input capacitor, feeding a full bridge rectifier through an isolating transformer, followed by an L-C output filter.

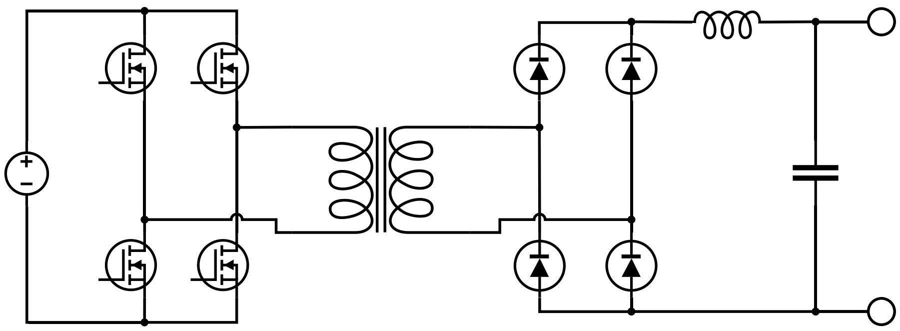
The converter typically uses peak current control to prevent transformer saturation and provide fast response to input or output transients.

Vin	<150V, range +/- 10-20% for 250V derated FETs
Vout	~200V for derated 600V diodes
Power	1kW modules
Efficiency	~95%
Switching Frequency	50kHz upper limit

Pros
- Well-understood, readily available components
- Flight-qualified control ICs
- Operates over wide output range
- Linear transfer function – easy to parallel
- Good efficiency

Cons
- Operating frequency limited by output diode speed
- Significant voltage spikes on rectifiers, which must be fast recovery
- Susceptible to shoot through

Phase-Shifted Full Bridge Converter



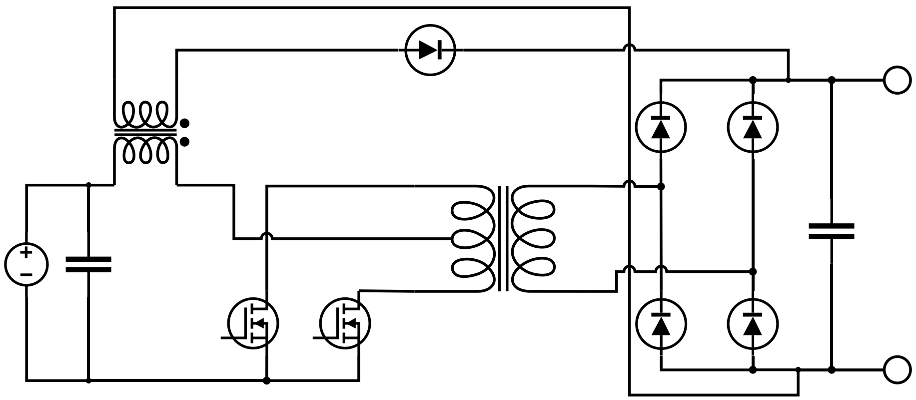
- Similar to PWM full bridge converter but modulation done by phase-shifting the legs of the bridge
- Circulating current on top and bottom MOSFETs allows energy stored in the leakage inductance to charge/discharge MOSFETs output capacitance and achieve zero voltage switching (ZVS).

Vin	<150V, range +/- 10-20% for derated 250V FETs
Vout	~200V for derated 600V diodes
Power	1kW modules
Efficiency	95-96%
Switching Frequency	50-100kHz

Pros
- Zero voltage switching
- High efficiency
- Easy to synchronize and parallel

Cons
- Susceptible to shoot-through
- Potentially higher conduction losses on MOSFETs from circulating current
- Only one phase-shift modulation chip available
- Switching frequency limited by output diode losses

"Weinberg" Converter



A push-pull converter, fed by an input inductor, feeding a full bridge rectifier through an isolating transformer into an output filter capacitor

The converter typically uses peak current PWM control and can operate at either greater than or less than 50% duty cycle

Vin	<60V for derated 250V FETs
Vout	~400V for derated 600V diodes
Power	500W (for 2 FETs)
Efficiency	~95%
Switching Frequency	50kHz upper limit

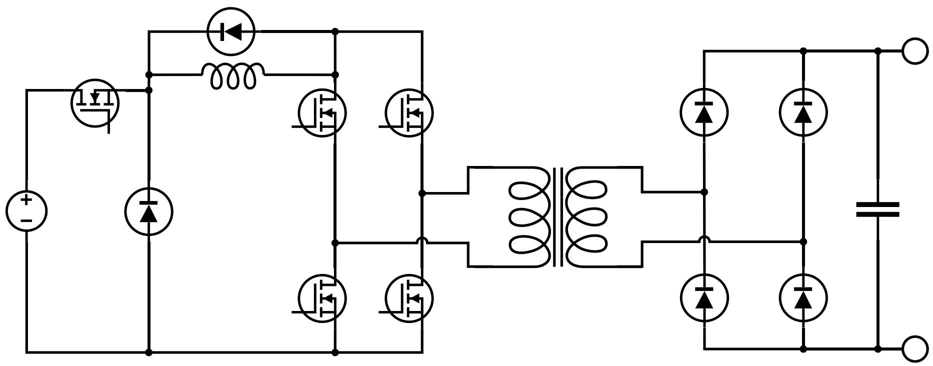
Pros

- Shoot-through tolerant
- Operates over wide output range
- Good efficiency

Cons

- Better suited for lower input voltage
- High voltage stresses on FETs and auxiliary "flyback" diodes
- Operating frequency limited by FET switching losses
- No existing IC control chips, so controller must be custom-designed

Cascade Current-Fed Converter



A buck converter stage, whose output inductor is the input inductor of a current fed full bridge converter a full bridge rectifier through an isolating transformer, followed by an output filter capacitor.

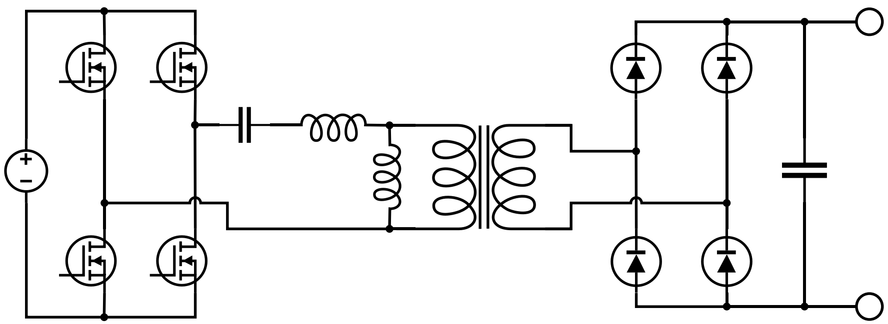
This design features the simple control of a buck converter, the FET voltages are well controlled as in the full bridge converter, and the minimal diode voltages stresses of a current fed converter.

Vin	<150V, range +/- 10-20% for derated 250V FETs
Vout	~400V for derated 600V diodes
Power	1kW modules
Efficiency	Low-to-mid 90s%
Switching Frequency	50kHz upper limit

Pros
- Shoot-through tolerant
- Operates over wide output range
- Linear transfer function
- Flight-qualified control ICs plus some additional parts
- Low peak stresses on all converter components

Cons
- Higher parts count
- Operating frequency limited by FET switching losses
- Additional switching stage reduces efficiency

Resonant Converters



Full-Bridge LLC Converter

- Power is regulated by controlling the switching frequency near the natural frequency of a resonant tank circuit
- Most designs use three resonant elements (LLC or LCC)
- Compatible with half or full-bridge arrangements
- Can achieve ZVS for the primary switches and ZCS for the secondary side rectifiers
- Good option where high power density is critical

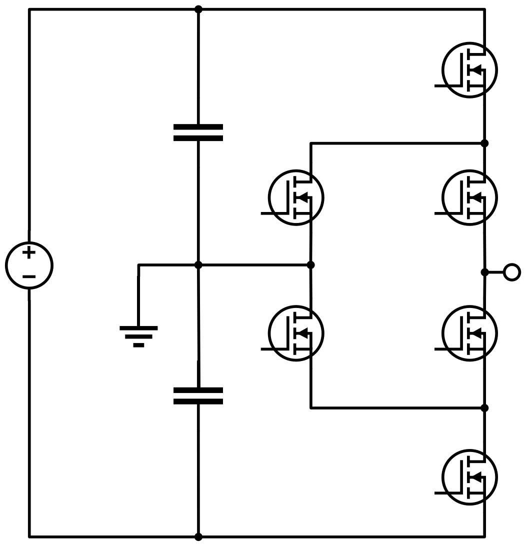
Vin	<150V with derated 250V FETs
Vout	~400V for derated 600V diodes
Power	1kW modules
Efficiency	95-98%
Switching Frequency	>200kHz possible

Pros:
- Efficient, high frequency designs for high power density
- Voltage stresses on semiconductors are minimized
- Transformer parasitics can be utilized for resonant circuit

Cons:
- Designs are difficult to optimize
- Controller implementation is more complex than PWM
- Difficult to parallel and synchronize multiple modules

Applications:
- LLC – Most efficient, but narrow input/output voltage range
- LCC – Used in high step-up, wide input/output voltage range applications

Neutral Point Clamped Multilevel DC-AC



- Enhancement to full bridge topology to allow high voltage operation with low voltage parts
- Additional benefit of three-level output provides lower AC current ripple

Vin	Up to 1kV Parts see 500V due to multilevel
Vout	Up to 700Vrms, l-l
Power	NASA designs up to 1.4MW
Efficiency	98-99%
Switching Frequency	20-60 kHz

(For Aero, 1.2kV SiC FETs typically used)

Application: Electric Aircraft Motor Drives

Pros

- Lightweight multilevel strategy
- High voltage capability
- Reduced EMI
- Good AC quality

Cons

- Increased complexity
- Reduced reliability
- Susceptible to neutral ripple

Topology Comparison

	PWM Full Bridge	Phase Shifted Full Bridge	Weinberg	Cascade Current Fed	Resonant (LLC or LCC)
Module Power	1kW	1kW	500W	1kW	1kW
Vin max	150V	150V	60V	150V	150V
Vout max	200V	200V	400V	400V	400V
Switching Frequency	<50kHz	50-100kHz	<50kHz	<50kHz	>200kHz possible
Efficiency	95%	95-96%	95%	<94%	95-98%
Controls	Simple	Moderate	Complex	Simple	Complex
Series/Paralleling	Simple	Simple	Simple	Simple	Complex

<u>Compared to PWM Full Bridge:</u>

- Phase-Shifted Full Bridge offers a slightly higher efficiency, but somewhat more complex controls
- Weinberg is a lower input voltage topology with more complex control (custom, no flight-qualified controller ICs)
- Cascade current fed has a more complex power stage with simple control, but lower efficiency
- Resonant offers high frequency operation (reduced mass) and higher efficiency, but more complex controls

Controls

- In addition to choosing a power topology, control methods impact the performance of the converter
- Both contractor and NASA-designed projects have experienced converter performance issues due to choices in topologies and control schemes
- Resonant and Weinberg topologies require custom control solutions
- Analog vs Digital Control
  - Traditionally, analog control has been implemented due to its speed and historically available parts, but it is inflexible
  - Digital control has been on the rise due to its flexibility and lower parts count, but speed is not as good as analog
  - Hybrid control systems with analog inner control loop and digital outer loop may be an optimal solution

Findings

- In the topologies studied, there was not a single standout as the “best” topology, as each has similar overall performance
- Efficiencies for all DC-DC topologies are low-to-mid 90s
  - GRC has previously designed high input voltage SiC DC-DC converter with 98% efficiency but parts are not yet space qualified
  - DC-AC with SiC and no magnetics is 98%
- The topology choice affects which parts see the highest stress
  - The PWM and phase-shifted full bridge topologies have low stress on the switching devices, but higher stress on the secondary rectifier diodes
  - Current-fed topologies have the most stress on the switching devices but are shoot through tolerant
    - May be alleviated by the addition of a buck input stage on the cascade current-fed topology, but the efficiency suffers
  - Resonant topologies are lighter weight, more efficient, and have low stress on the switching devices and secondary rectifier diodes, but require more complex control, making it more difficult to optimize converters

Forward Work

- Complete Phase I report by 10/31/21
- Proposed Phase II: Eighteen-month effort to build studied converter topologies
  - Focus on resonant topologies and cascade current-fed since NASA has less experience with these topologies
  - Compare hardware results to simulations
  - Work on resonant converter controls and paralleling
  - Digital controls implementation
  - Evaluate DC-AC topologies to narrow trade space

Summary

- As NASA pursues ambitious high-voltage, high-power space and aeronautics missions, there is a need to identify converter technologies that enable these missions
- NASA GRC studied several isolated DC-DC converter topologies and one DC-AC converter topology
  - Identified strengths and weaknesses of each topology
  - Evaluated performance of each topology, including parts stresses, efficiency, robustness
  - Performed simulations of each topology
  - Identified potential applications
- Currently wrapping up final report to complete Phase I of study
- Proposed a Phase II effort to build topologies of interest to evaluate performance in hardware and gain experience and understanding of how topologies perform for NASA applications