Bidirectional DC-DC Converter Systems Sustained with Power Component Methodology

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Overview - Bidirectional Converter Systems Sustained with Power Component Methodology

- **Definitions**
  - The Power Component Approach
  - Classifications of Power Train Function
- **Some example applications**
  - Powering airborne and underwater autonomous vehicles
  - Automotive
    - Power Harvesting Using Regenerative Braking
    - Power Distribution in the chassis
  - Domestic Hybrid Grid
  - *Smart Factory 4.0* Concept
- **Interim Observations**
- **New Power Functions to Follow**
- **References & Acknowledgements**
- **Summary and Acknowledgements, Audience Questions**

Definitions #1 - Power Component Methodology

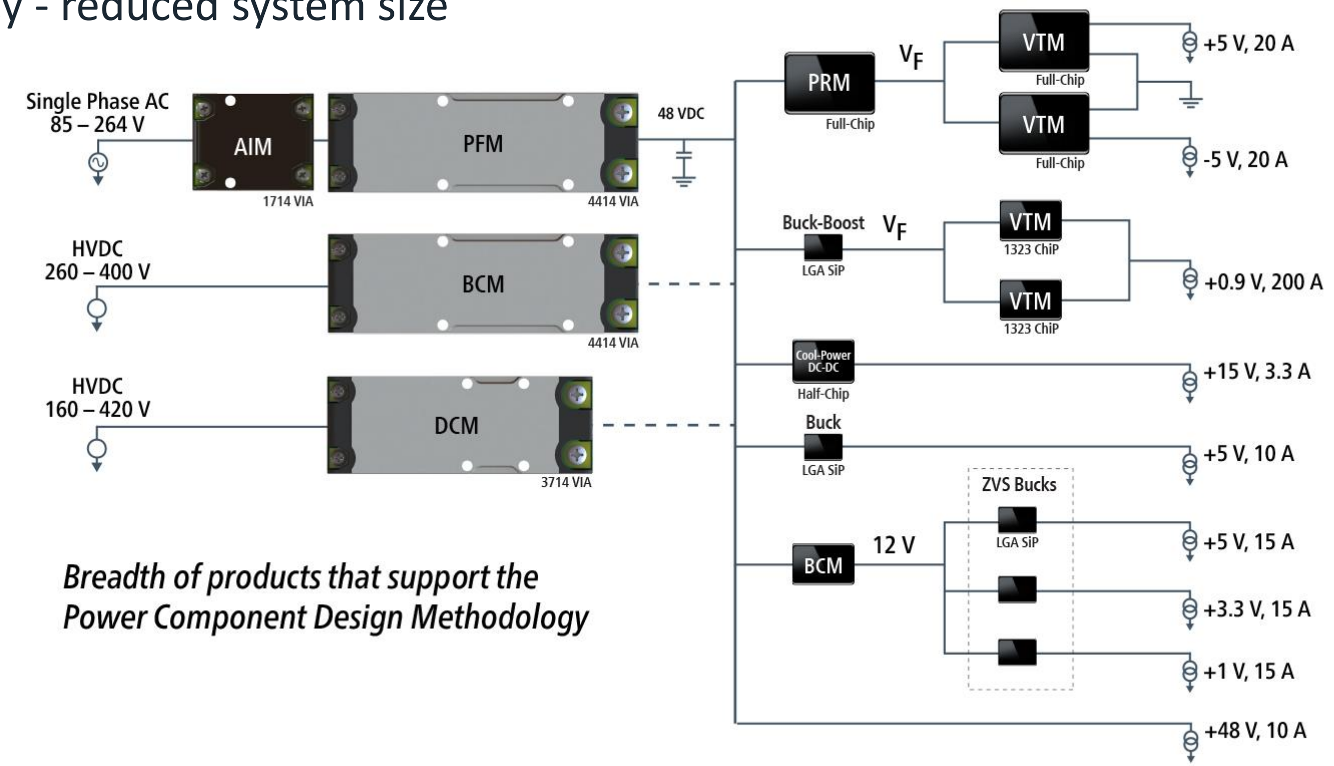
Optimized Approach to Power Design

Advantages

clever partitioning offers interchangeabilty – increased power density – scalability - elimination of redundant conversion stages - reduced power losses leading to higher efficiency - reduced system size

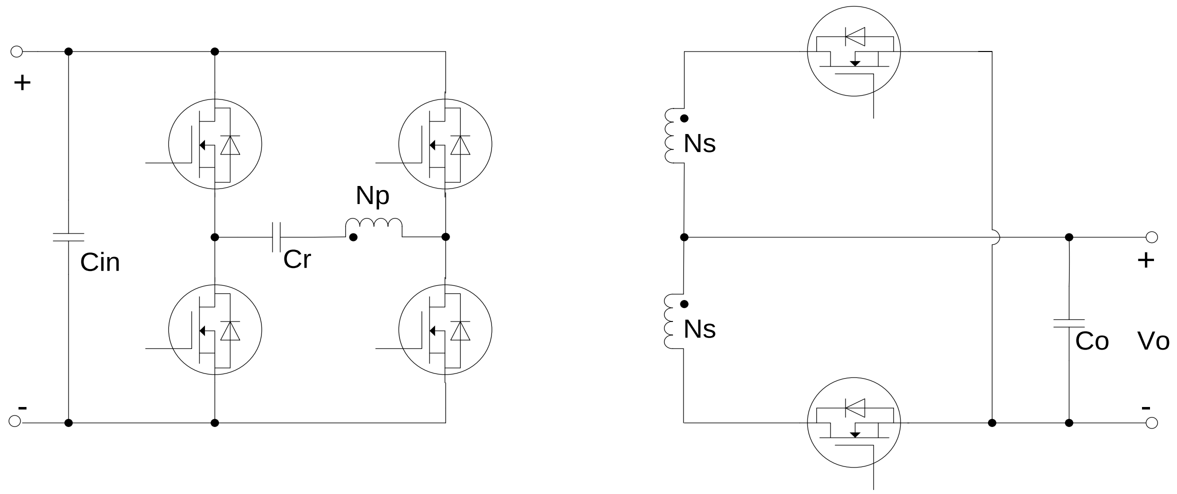
Point of Load Power

Front End Power



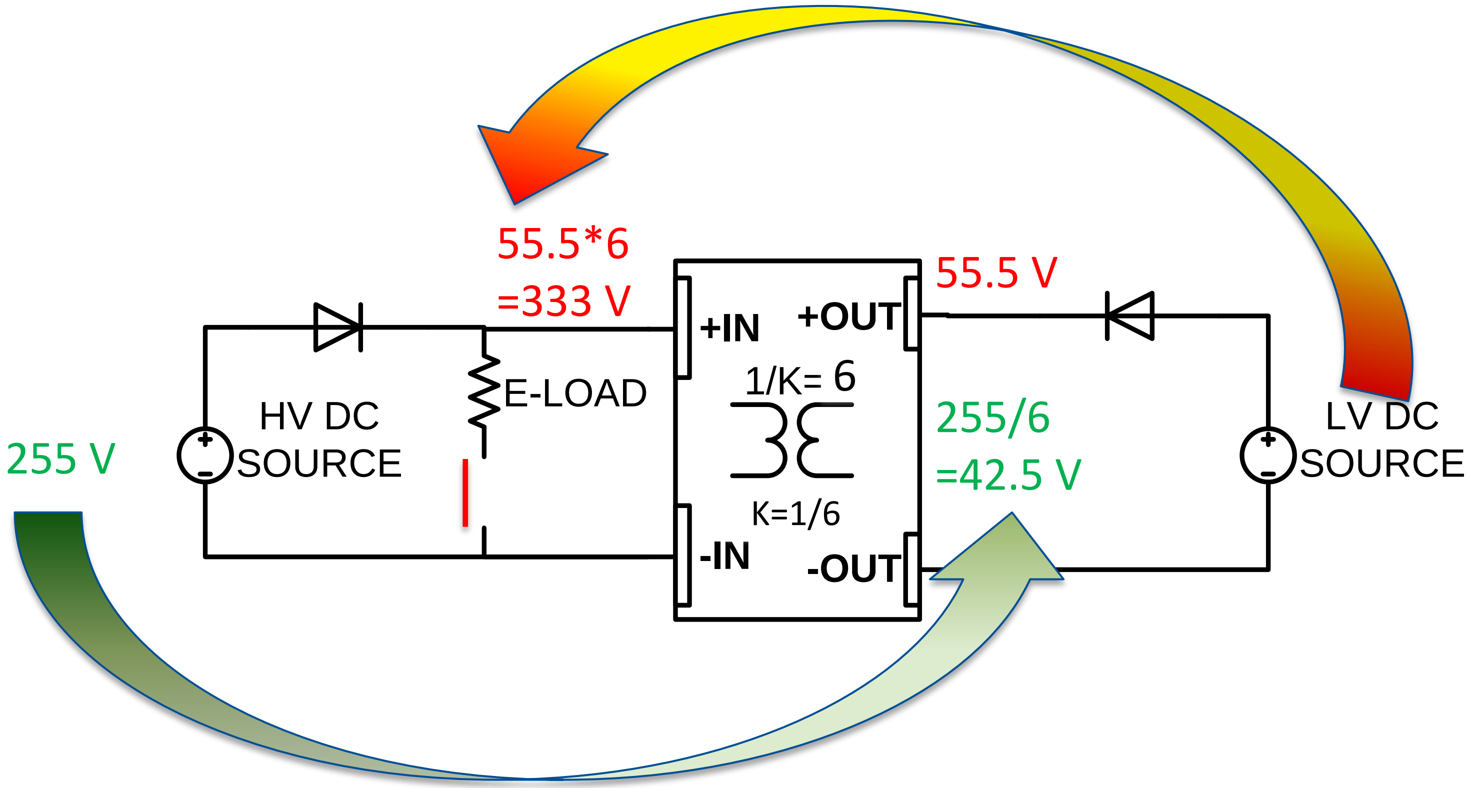
Breadth of products that support the Power Component Design Methodology

Sine Amplitude Converter Fundamentals



- **SAC consists of a series resonant Full bridge primary with a center tapped secondary using rectifier MOSFETs**
- **Resonant topology – magnetic parasitics are characterized and used to determine optimum timing for ZVS switching of primary and secondary power FETs**
- **Not shown - A primary referenced controller feeds isolated drive signals to each FET**
- **No feedback is required**
- **Once the part is activated, power flow is determined by source that "drives" a particular power port**

Experimental Test Setup for Reverse Operation



Theory is simple: Start up the BCM HV port, with LV port energized

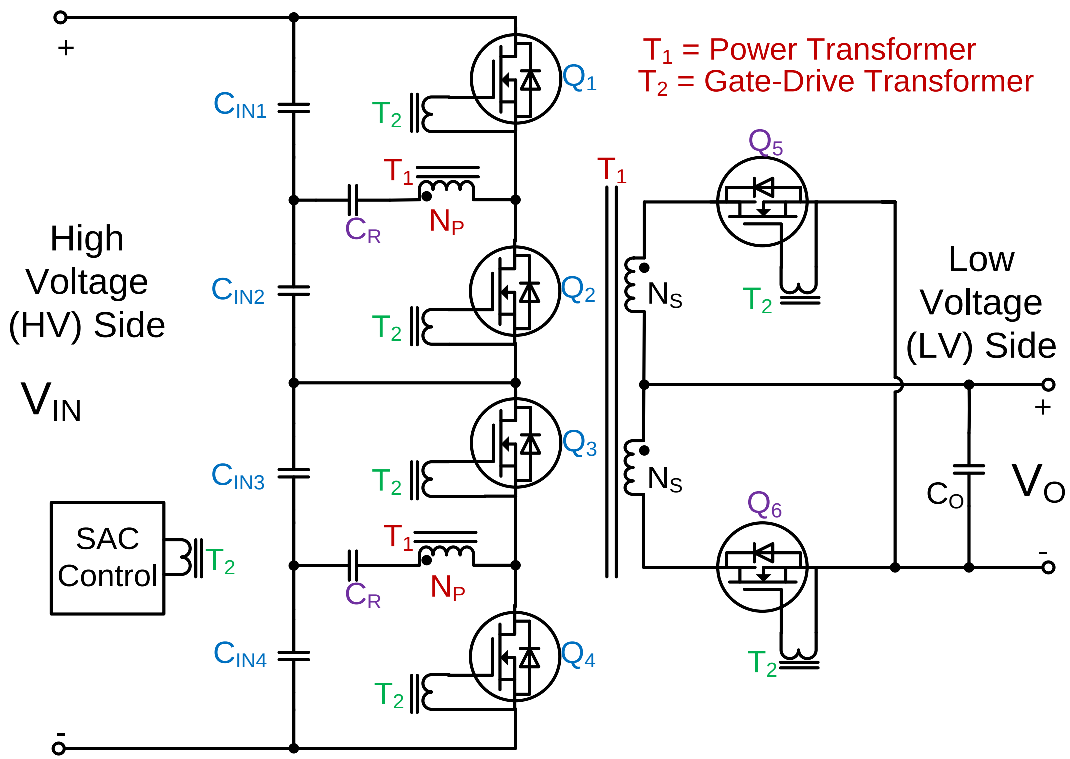
SAC Action Illustrated by Experiment

Reverse flow experiment running in the steady state. Source on top left was used to start a 300W rated VI.Chip BCM with secondary priming source pre-applied (55.5V) Primary load draws 0.9675A at 325.33V so K factor is ~ 5.9.

Limitations of the traditional SAC

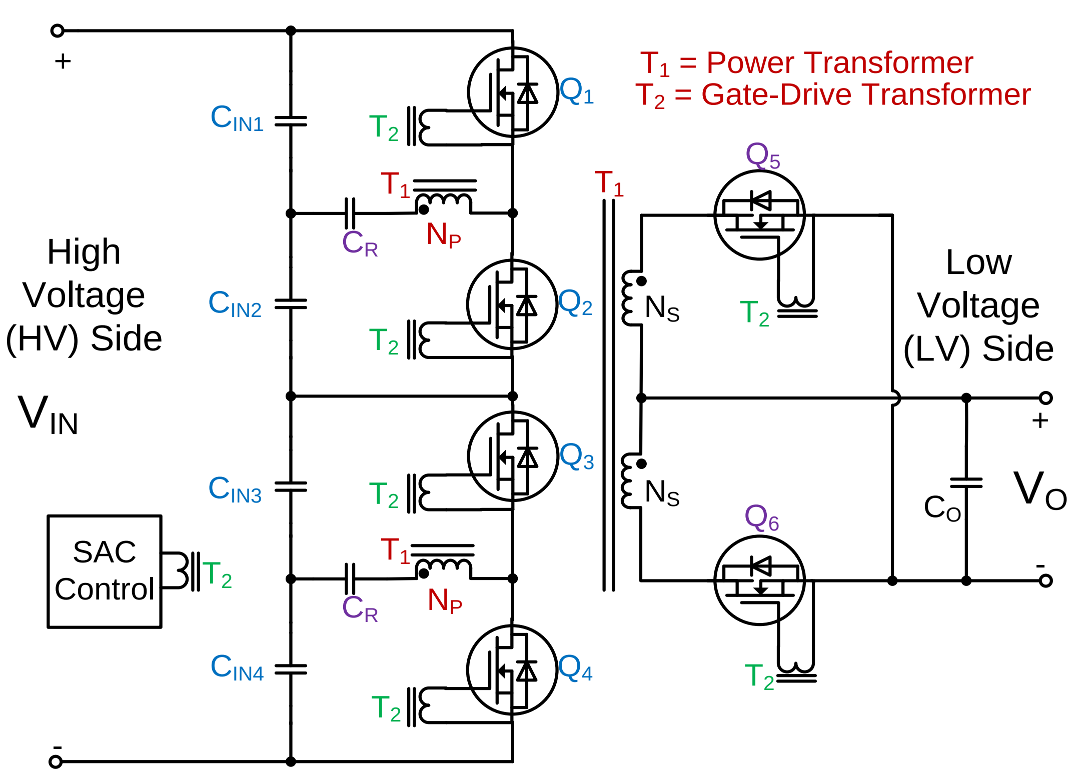
- Power limited
- Low voltage ratios
- Low standoff voltages limit application of high voltage
- What’s needed is a converter scheme that can deal with higher transformation ratios which implies that port voltages can be extended to higher levels
- Needs to be coaxed into starting
- This is the point at which the architecture of the SAC can be refined

Solution : A New Bidirectional DC-DC Converter



- **This lends itself to 384 V DC distribution schemes where no high efficiency solution was available**
- **Uses a planar transformer design**
  - Lower transformer losses
  - Transformer coupled high frequency galvanic isolation
  - Enhanced reliability
- **Primary circuit – HV Side – Input side**
  - Stacked half bridge
  - Low voltage MOSFETs
  - Lower conduction losses
- **Secondary circuit – LV Side – Output side**
  - Center tap with synchronous rectification

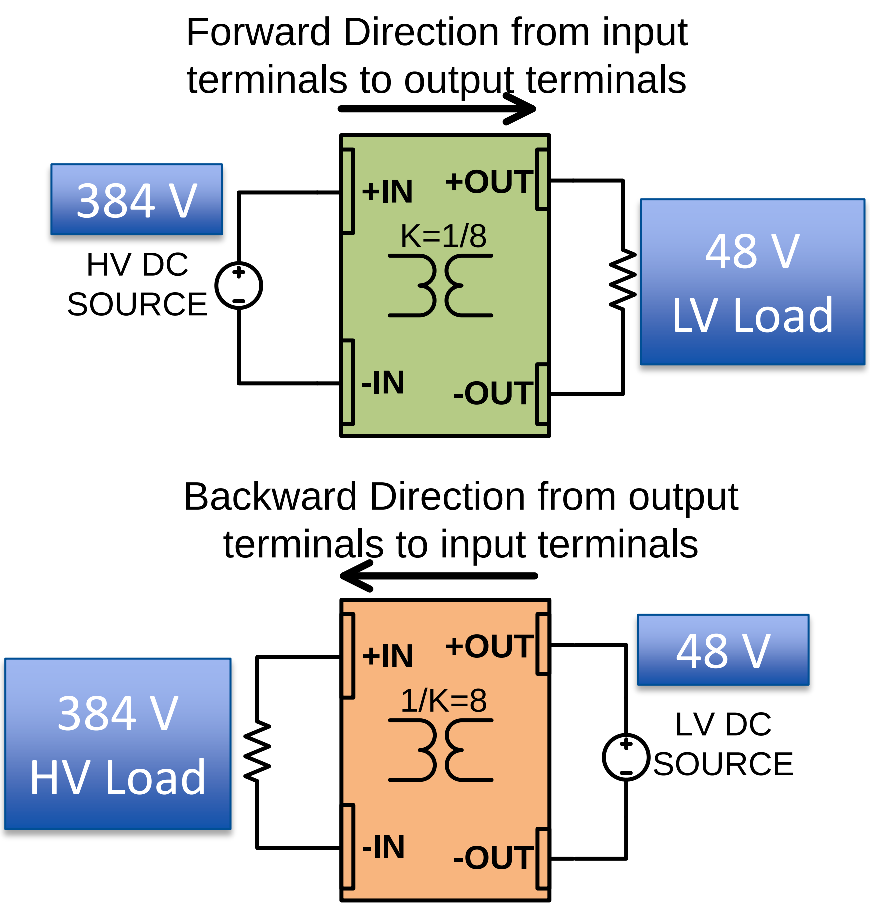
A New Bidirectional DC-DC Converter



$$\frac{V_{OUT}}{V_{IN}} = \frac{I_{IN}}{I_{OUT}} = K$$

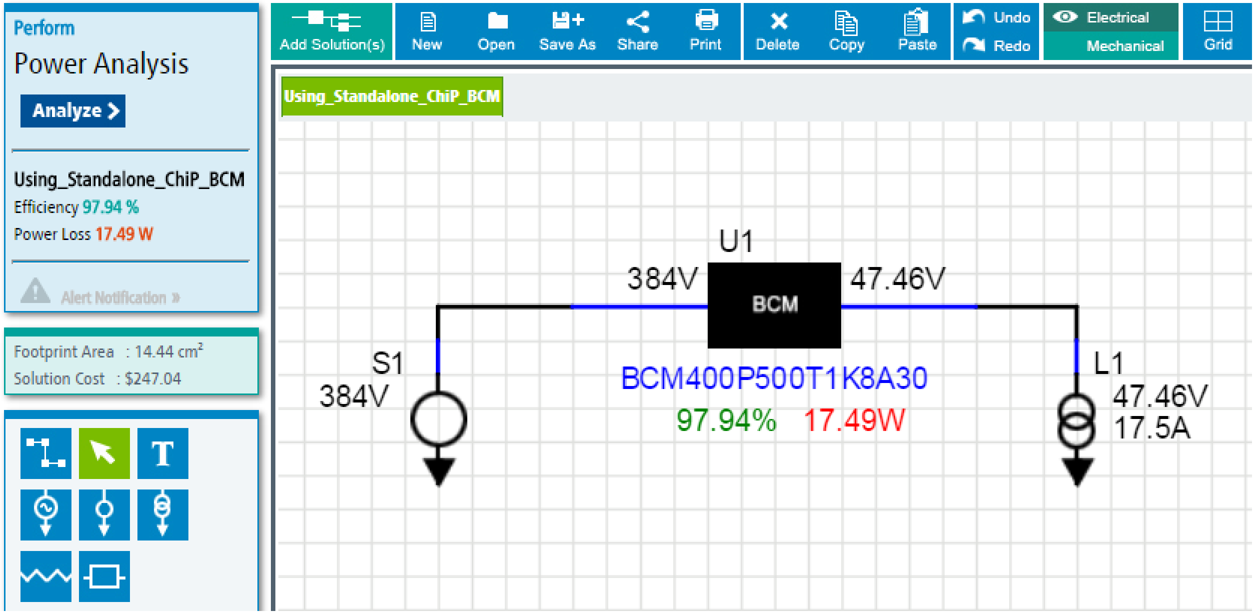
- **Resonant sine amplitude converter (SAC) control**
- **ZVS and ZCS soft switching**
- **1.1 MHz fixed high switching frequency**
  - Lower switching losses from light load to full load
- **Open loop control**
  - Bidirectional fixed ratio DC-DC conversion
  - Reason the new BDC operates in bidirectional mode is because of the MOSFETs in SAC control topology
- **DC transformer**
  - Voltage and current matching in DC-DC applications

Circuit Implementation Example K = 1/8



- **Forward mode: 384 V to 48 V**
  - Step down DC-DC conversion like Buck
  - BDC starts up in forward direction
  - Normal start up
- **Reverse mode: 48 V to 384 V**
  - Step up DC-DC conversion like Boost
  - Higher Voltage Gain
  - SAC cannot start up in backward direction
  - Everything starts from HV side
    - Reverse operation starts when $V_{OUT} > V_{IN} * K$
  - System where everything starts from LV side
    - First start BDC in forward mode using startup circuit satisfying following condition
    - $V_{OUT} > V_{IN} * K$

Simulation of New BDC with K =1/8

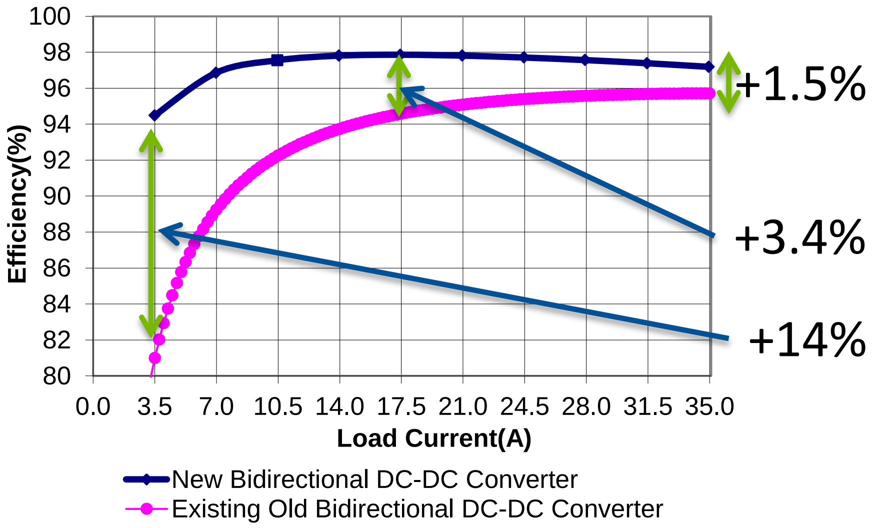


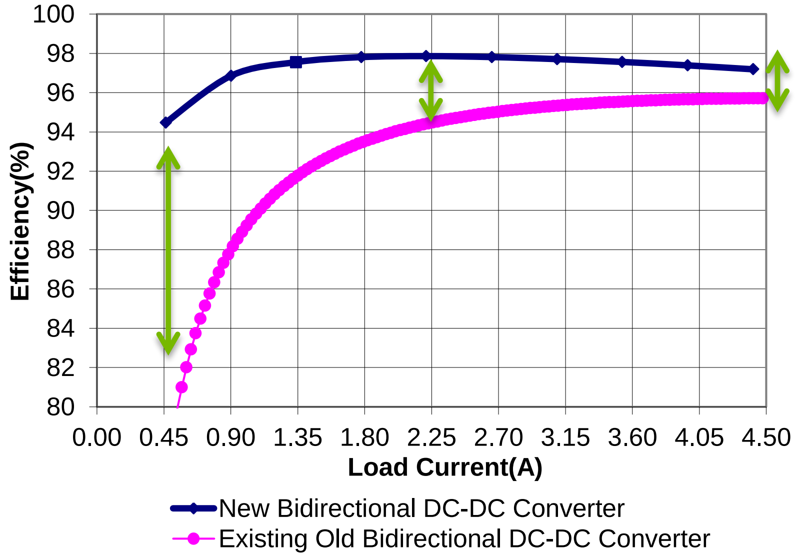
› Efficiency = 97.94% in forward direction at 384 V HI side voltage and 17.5 A LO side current

Board level Implementation for Experimental Results

- This is the board - used for testing of 384 V to 48 V bidirectional conversion.
- New BDC is under the catamaran heat sink, Airflow ~ 1000 LFM
- Full load Current Rating
  - 35 A refer to LO side
  - 4.5 A refer to HI side
- Maximum Power Level for 384 V to 48 V conversion
  - 1650 W

Actual Experimental Results – Measured Efficiency vs. load

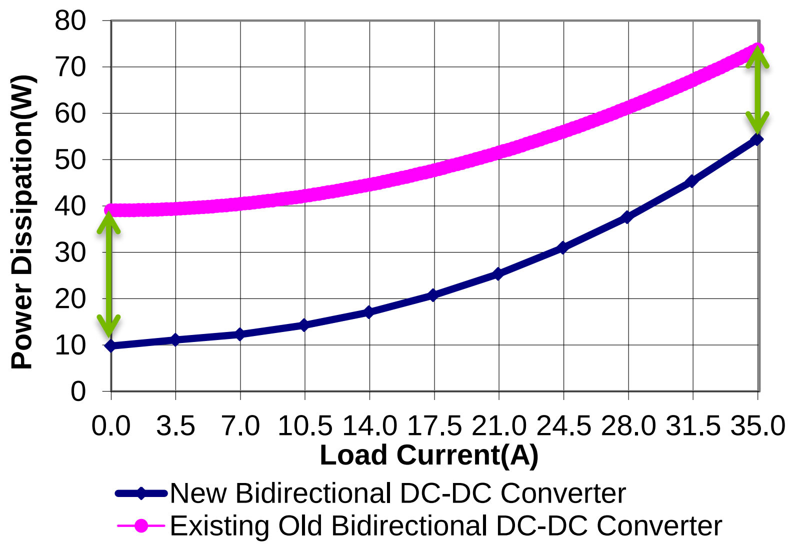


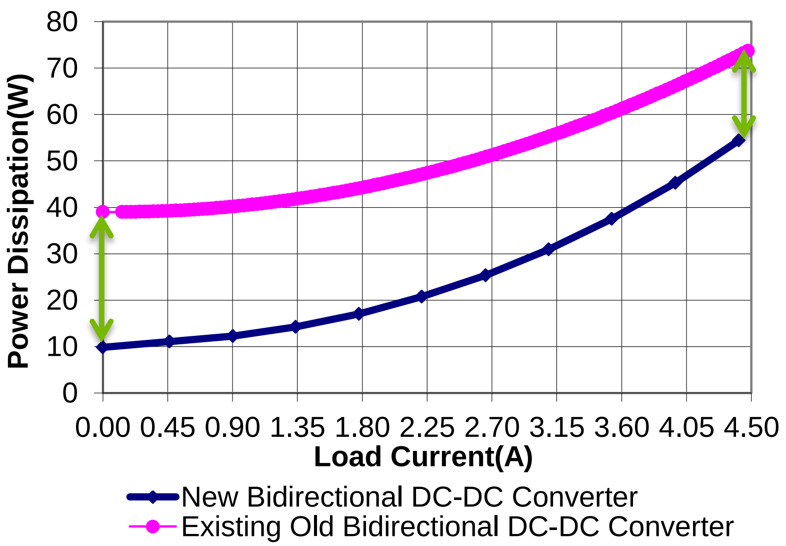


- Measured efficiency in forward direction
- 384 V input source
- K=1/8
- 48 V output at no load

- Measured efficiency in reverse direction
- 48 V input source
- 1/K = 8
- 384 V output at no load

Experimental Results – Measured Power Loss vs. load

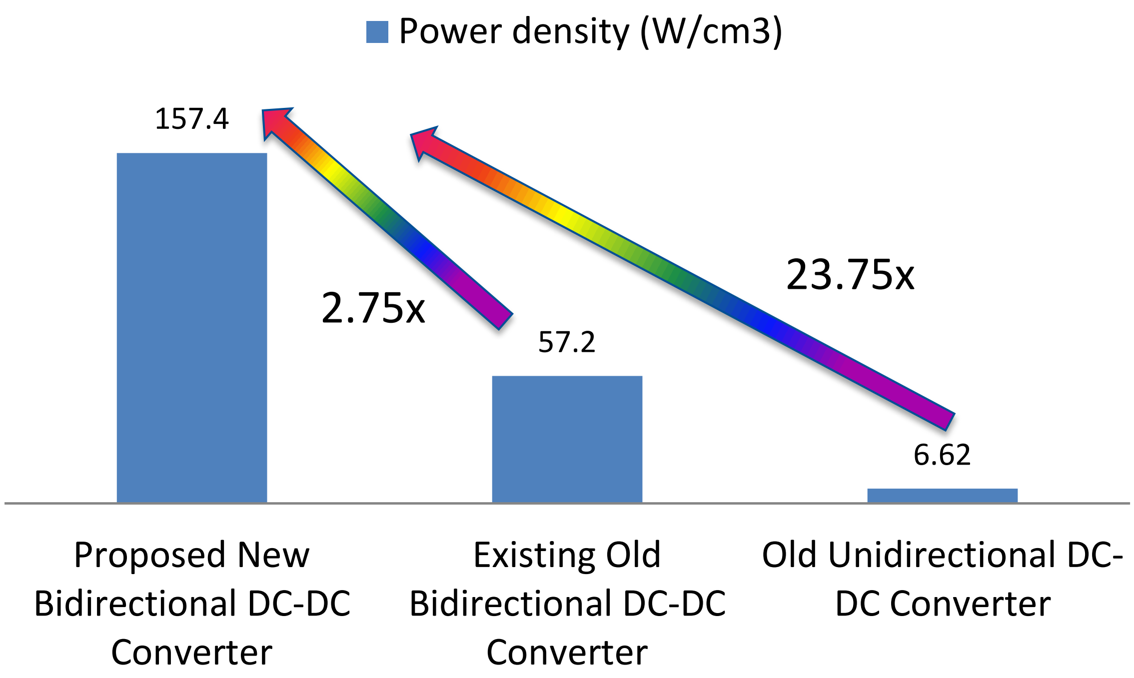




- **Measured power loss in forward direction**
- **35 A load or 4.5 A load**
- **Power level ~ 1650 W**
- **New BDC**
  - % Total power loss = 3.33%
- **OLD BDC**
  - % Total power loss = 4.55%

- **Measured power loss in reverse direction**
- **35 A load or 4.5 A load**
- **Power level ~ 1650 W**
- **New BDC**
  - % Total no load power loss = 0.61%
- **OLD BDC**
  - % Total no load power loss = 2.42%

Power Density Comparison



Comparison - Performance Gain of New BDC

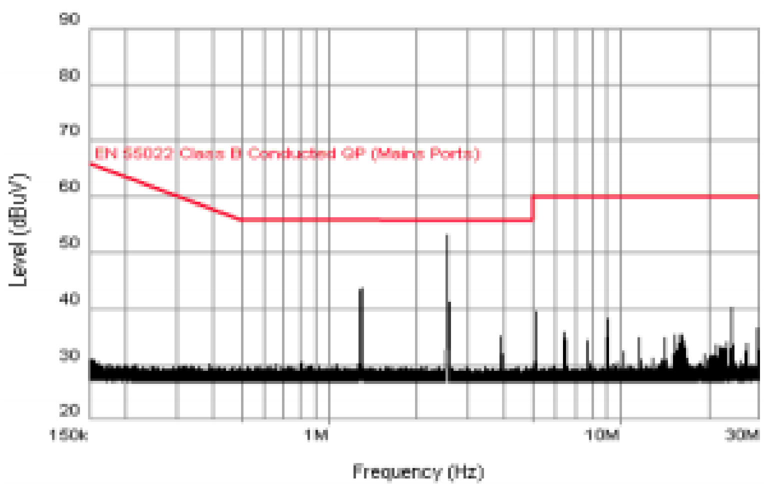
Parameters	Existing Old BDC	New BDC	Gains of New BDC
Number of converters	6	1	Less number of converters
Input Voltage Range (V)	360 to 400	260 to 410	Wider input voltage range
Switching frequency (MHz)	1.75 MHz	1.1 MHz	Lower core losses
Efficiency at 10% load (%)	81	94.5	13.5% better
Efficiency at 50% load (%)	94.4	97.8	3.4% better
Efficiency at 100% load (%)	95.7	97.2	1.5% better
Output resistance (mΩ)	28.3	22.6	Lower resistive losses
No load power dissipation (W)	39	10	Lower no load losses, almost ¼
Volume (cm^3)	28.86	10.48	Occupy less PCB space
Power density (W/cm^3)	57.2	157.4	2.75 times more
Weight (g)	84	41	Weight is half

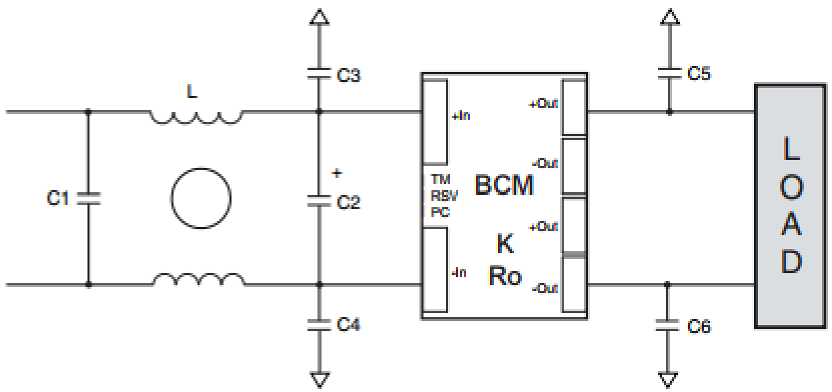
Power Component Design and Conducted Emissions

- **With hard-switched converters the noise artefacts tend to be wideband and more difficult to suppress**
- **Strategies for noise control involve**
  - **Synchronizing and holding the spectral artefacts to given frequencies**
  - **Smearing the noise across the frequency spectrum**
  - **Suppressing the noise spectrum**

- **Parts that utilize quasi- or fully-resonant power train topologies that are ZCS / ZVS or both tend to produce less wideband noise, simply due to the nature of the type of switching used.**

Using discrete component filtering for CE



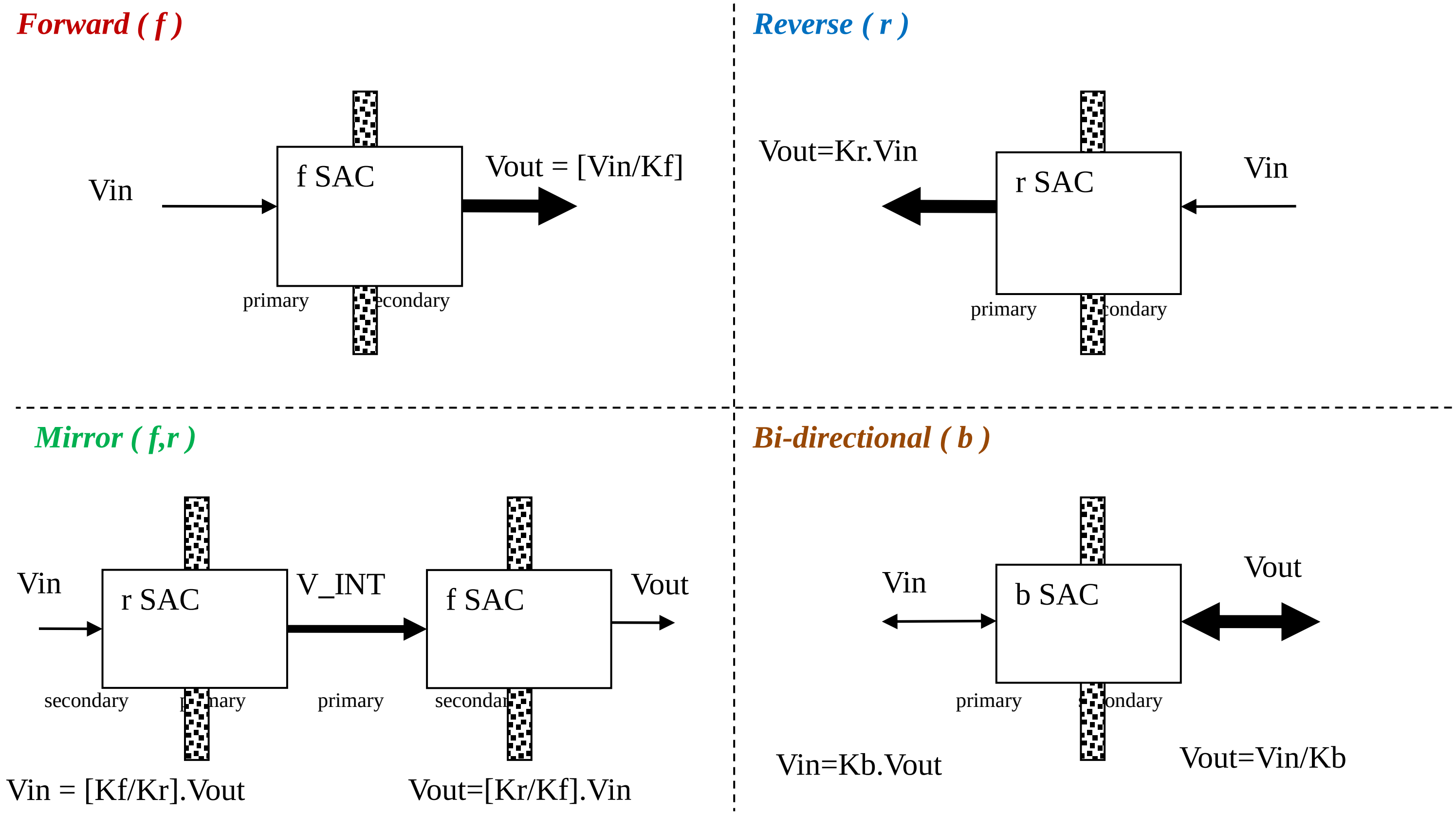


C1:	2.2 µF, 'X2' Type
C2:	10 µF, 100 V Electrolytic
C3, C4, C5, C6:	4.7 nF, 'Y2' Type

With high switching frequencies and a galvanic isolation barrier it is possible to return HF/VHF common mode noise currents back to the noise source with simple discrete filters

Four Power Converter Classes

Are all these DC converter systems characterized as being linear and time-invariant?



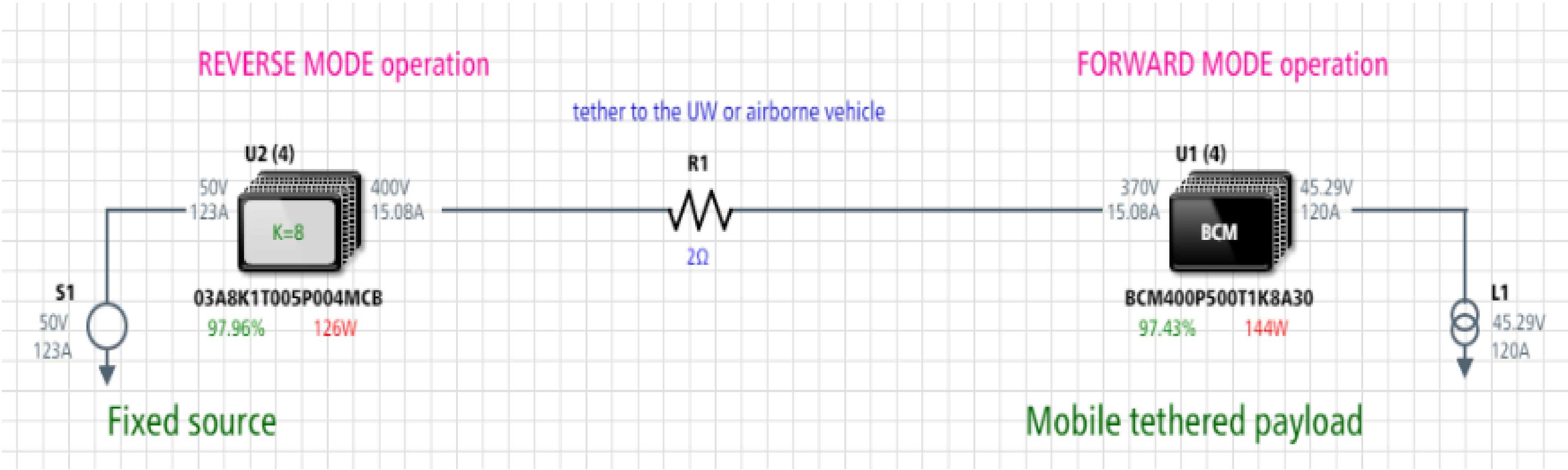
UAV: Unmanned aerial vehicles Tethered & Untethered

- **Application Features**
  - The need for several different payloads
  - Power plant is moved out of the UAV to save weight
  - Electrical power must now be carried in the lightest wires available
  - Lightweight wire is current limited, so the voltage on the tether needs to be high for a given amount of power on the cable in the tether.

  - Sometimes power has to be routed through sophisticated mechanical connection schemes which are unable to carry high currents

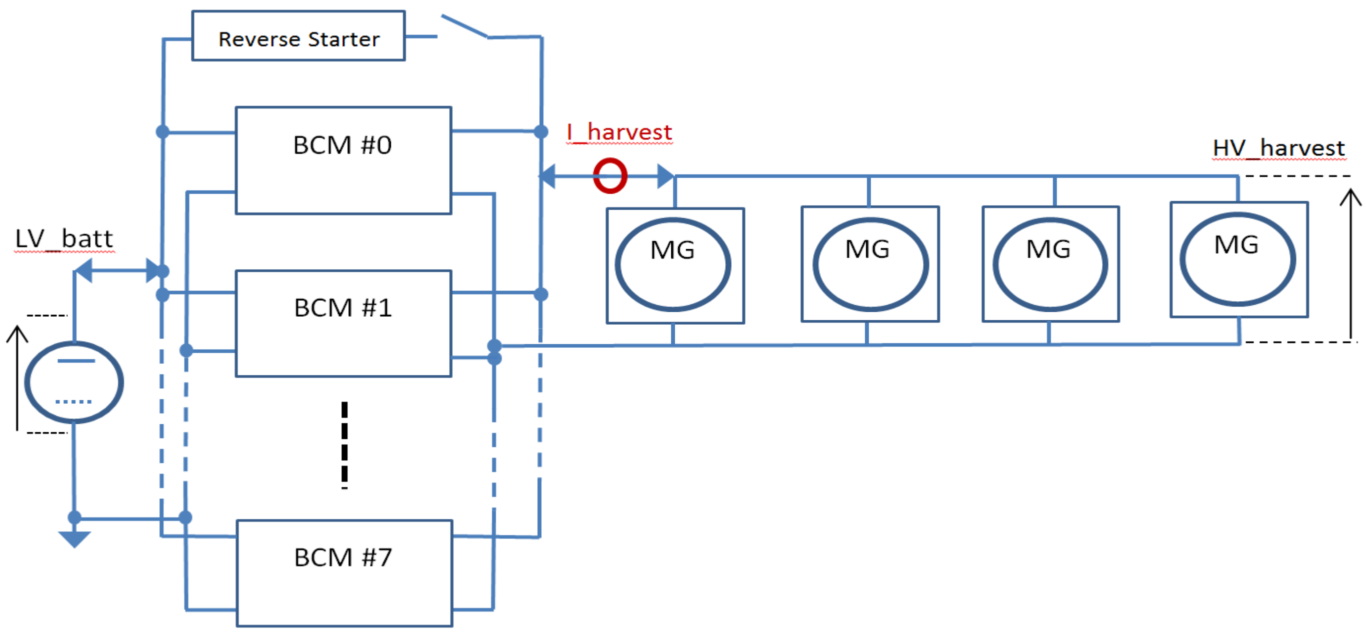
Mirror Topology for AUV and UAV Applications

- Fixed power unit generates a low line voltage
- A reverse SAC boosts this voltage and feeds it into the tether
- Power losses are lowered with high Kr (transformation ratio associated with U2)
- Voltage from the tether is stepped down in voltage, current multiplied in exact proportion at the load by the SAC
- Vicor Whiteboard™ rendering below shows a working example of a Mirror Topology used to implement this architecture



Regenerative Braking

- This unregulated power train needs an external controller to time the various energy transfers
- Motor/Generator units convert kinetic → ← electric energy
- Energy collected from the 400V harvest bus ends up being stored in the LV battery
- 48V and 12V batteries and/or super capacitors can be used as energy stores



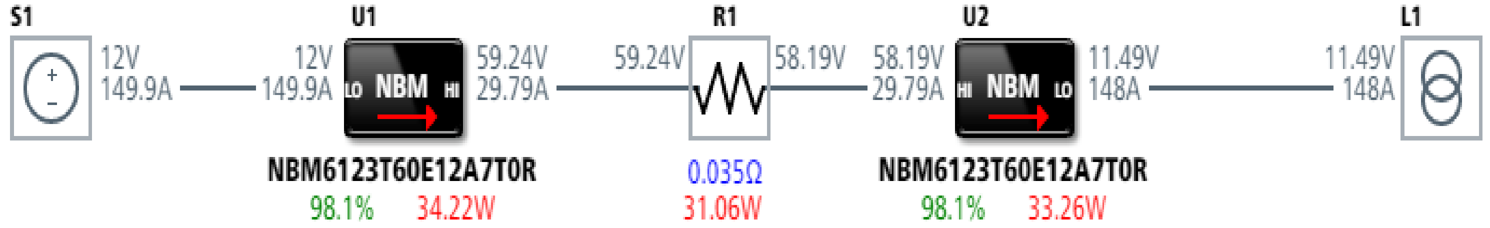
Improved DC Distribution for Autos

Carry lower current at higher DC voltages to Points of Load

- Lower weight of copper used in busses as compared with conventional 12V bussing
- Bidirectional power flow system of single- or multi-node NBMs possible

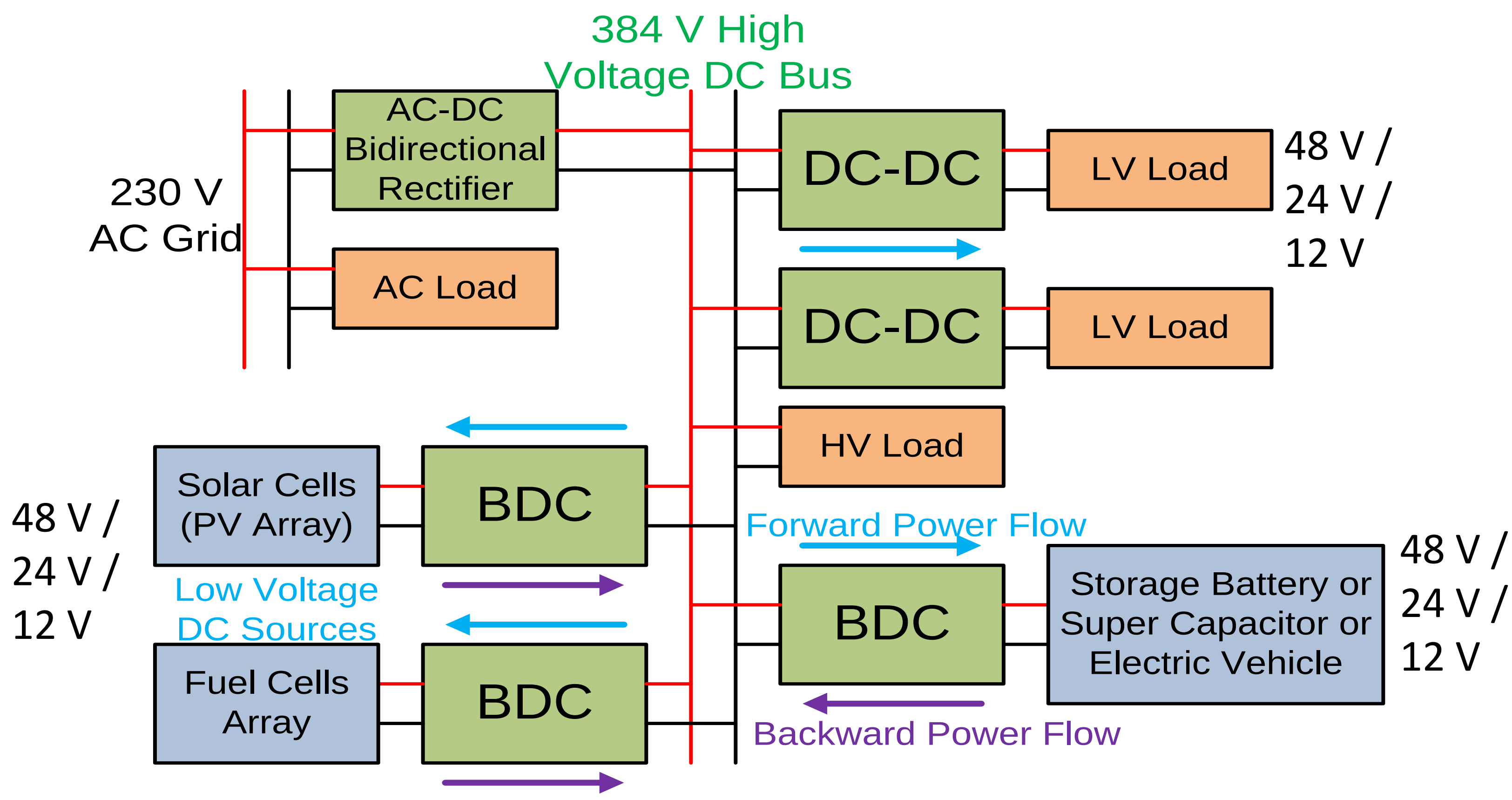
Options are open to use combinations of

- super capacitors for fast delivery in full or partial arrays with or without chemical batteries
- batteries with different terminal voltages, chemistries, structures and connections



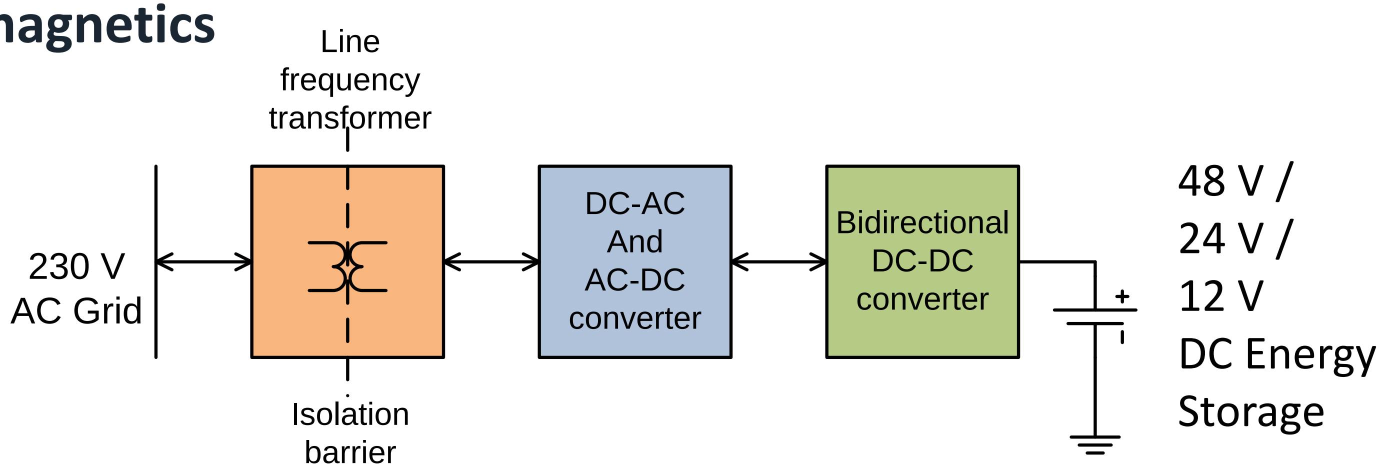
Non-isolated BCM facilitated automotive HV bus

Domestic Hybrid Grid Featuring Bidirectional Conversion



Smart Factory 4.0 - Introduction

- **Initiative brings more automation into factory and warehouse environments speeding distribution of raw materials and finished products through these locations**
- **Autonomous robotic palettes and handling systems must be able to draw on and transfer electric energy as needed from local and remote sources**
- **This application is well served with bidirectional high frequency switched SMPs as opposed to big, bulky and less efficient AC line magnetics**



Smart Factory 4.0 – Combining Information and Machines in the Industrial Space

- **Scheduling, delivery of goods to workstations controlled with IoT**
- **Goods moved in warehouse and factory areas with autonomous machines such as the Kiva robot**
- **24V motors are used in the systems to lift, move and rotate the pallettes**
- **Batteries / Super capacitors charged from mostly off-peak AC**
- **Load Balancing at National System Grid level. The need to convert power from different sources identical to the auto BD bus example**

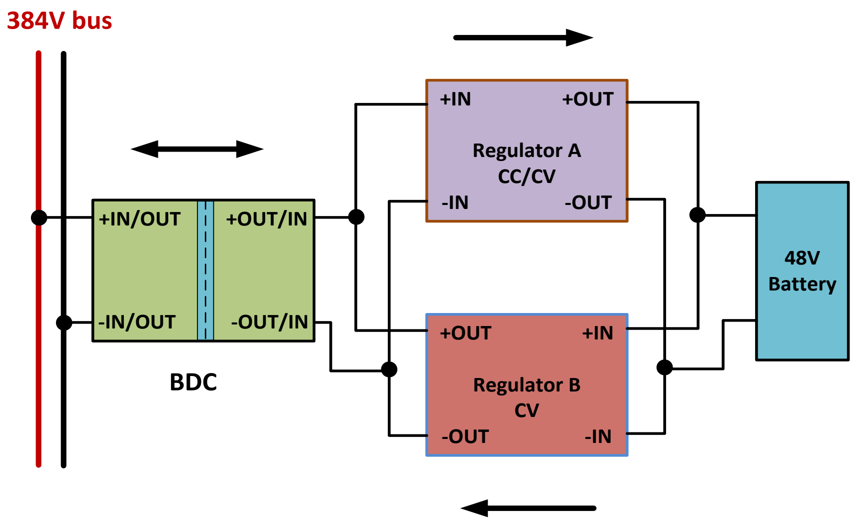
Interim Observations

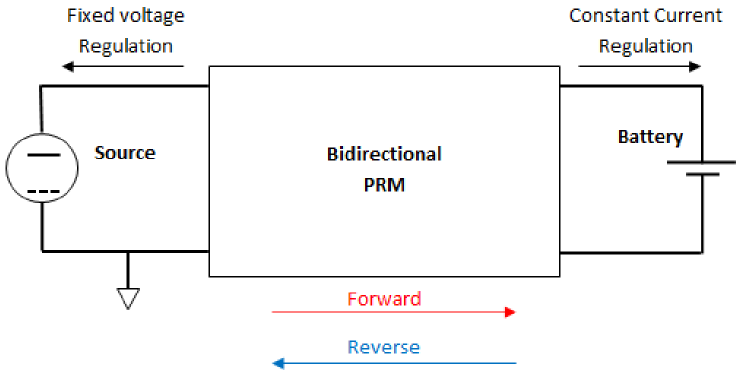
- **Sine amplitude converter engines naturally compatible with bidirectional power converter systems**
- **Many bidirectional systems can be implemented without regulators**
- **Controllers, microprocessors can be used to exert control over power component based bidirectional converters**
- **Regulation is seen as necessary at critical nodes in complex bidirectional systems**
- **It is clear that a bidirectional regulator is needed. It**
  - should have digital interfacing and control
  - reduces costs
  - simplifies power flow changes
  - improves hardware utilization (streamline the system)

New Power Functions to Follow

› The SAC exhibits the flexibility of digital systems to change direction of power flow in a power train suited to bidirectional usage.

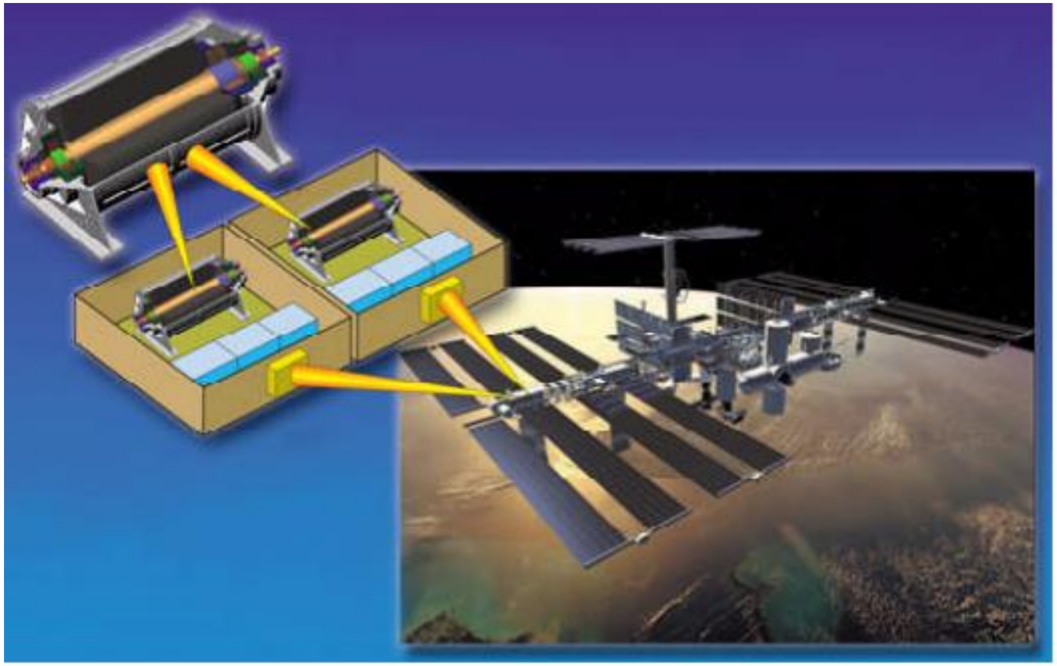
› New Power Components will exhibit the ability to change power flow implicitly without the need to consider which port needs excitation for startup.





Summary

- Fundamental principles and number of examples have been presented showing typical applications
- Bidirectional power conversion is a vital part of future systems where alternative source, energy storage and load management are critical. The more remote an application, the more important this aspect of power design becomes.



References and Acknowledgements

- An Isolated Step-up DC-DC Converter Using Series Connect Sine Amplitude Converters 978-1-4799-6735-3/15/$31.00 ©2015 IEEE
- A New Bidirectional DC-DC Converter for Fuel Cell, Solar Cell and Battery Systems APEC 2016

- Presentation materials originally contrived by Mr Ankur Patel, Applications Engineer, Vicor Corp. featured in slides throughout this presentation
- Pictures in slide 17 accredited to NASA Glenn Research Center