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Powering DC Brushless Motors on Airplanes with Variable Frequency Systems

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Crane Aerospace & Electronics

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Ansoft Application Workshop

October 19, 2006 – Los Angeles, CA

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Introduction

- Background
- New Challenges for Electrical Motors on Airplanes
- Existing Power Conversion Approach
- Review of Technology Options for Powering Motors, which Meet Aerospace Power Quality Limits
- Conclusions

Background

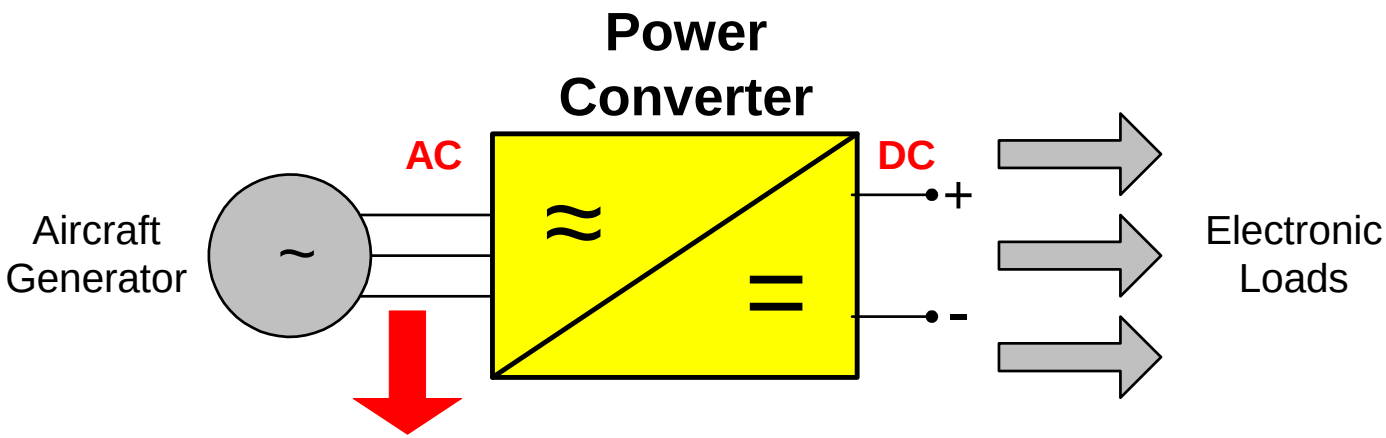
- Traditional constant frequency power sources (400 Hz) on airplanes are being replaced by variable frequency generators (typically 360-800 Hz)
- Pneumatic and hydraulic systems are being replaced with electrical devices – most of which are using electric motors
- More electrical equipment are being added to airplane – power quality become an issue

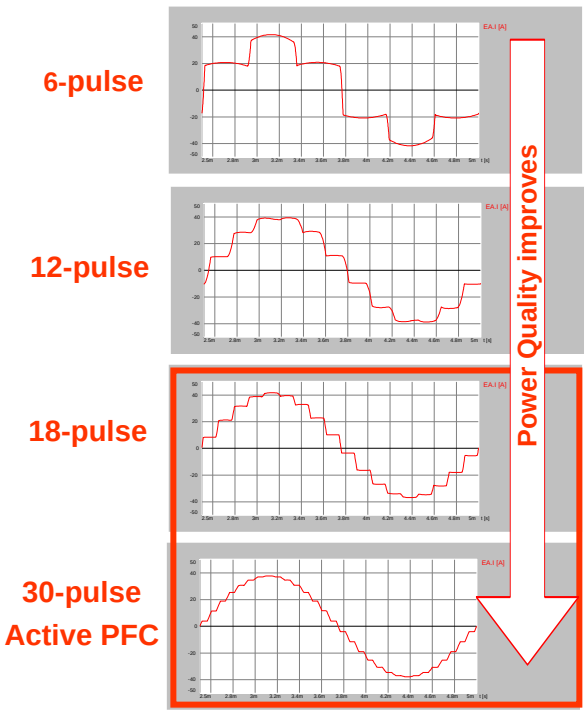
Challenges

This creates new challenges, which need to be resolved:

- **Challenge #1** - Inductive motors speed vary with frequency
  → solution: replace inductive motors with DC brushless motors
  - However, direct rectification of AC into DC generates high current distortion – exceeding acceptable power quality limits
- **Challenge #2** – find effective solution for converting AC into DC with good power quality

Power Quality





- Effect of power conversion is reflected back onto the aircraft AC bus
- Smoother the current waveform
  ---> the better the “Power Quality”
- 18-pulse, 30-pulse and active PFC approaches represents good power quality

Power Quality

- Power quality requirements from leading OEM's (examples):
  - Boeing: 787B3-0147
  - Airbus: AMD-24
- Recent, DO-160, Rev.E Document imposed power quality requirements for an aerospace products powered from an aircraft AC power system
- The most significant requirement is on restriction of individual harmonics generated by user equipment rated 35 VA or more
- Harmonic limits requirement makes direct rectification obsolete
  - Practically, all motor drivers, which are using direct rectification need to be replaced or upgraded

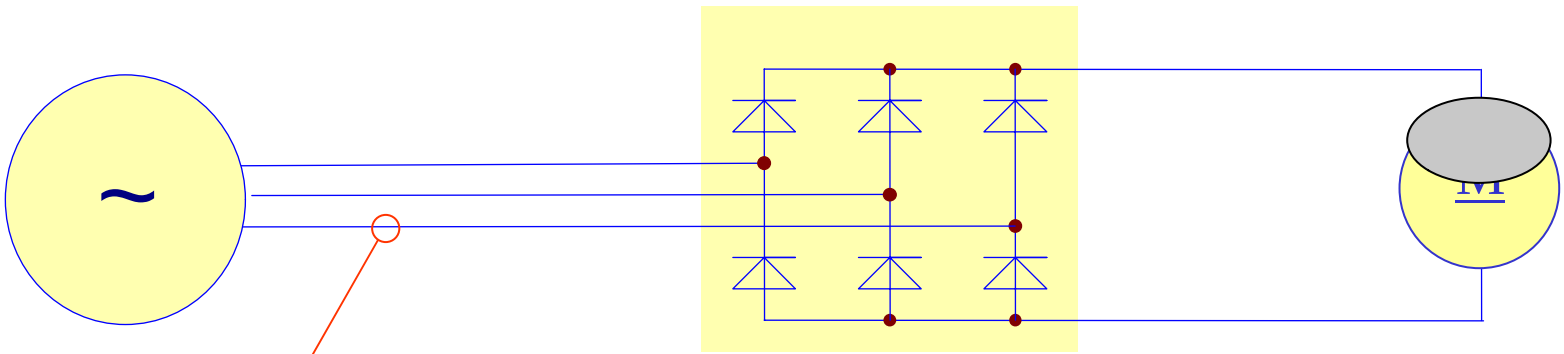
DO-160E Current Harmonics Limit

Each current harmonic, up to 40th harmonic has specified limit

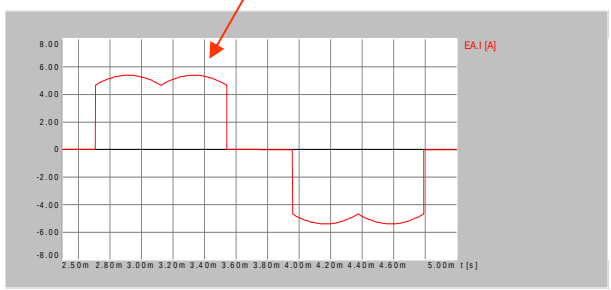
Harmonic Order	Limits
3^{rd}, 5^{th}, 7th	$0.02\ I_1$
Odd Triplen Harmonics (h = 9, 15, 21, ..., 39)	$I_h = 0.1\ I_1 / h$
11^{th}	$0.1\ I_1$
13^{th}	$0.08\ I_1$
Odd Non Triplen Harmonics 17, 19	$0.04\ I_1$
Odd Non Triplen Harmonics 23, 25	$0.03\ I_1$
Odd Non Triplen Harmonics 29, 31, 35, 37	$I_h = 0.3\ I_1 / h$
Even Harmonics 2 and 4	$I_h = 0.01\ I_1 / h$
Even Harmonics > 4 (h = 6, 8, 10, ..., 40)	$I_h = 0.0025\ I_1$

Existing Approach

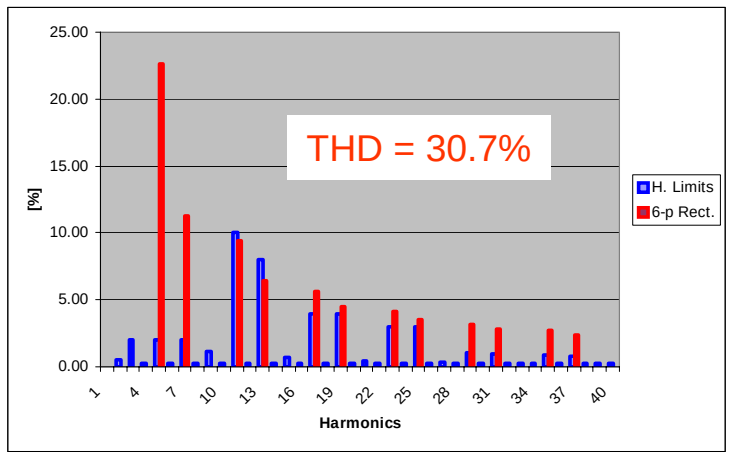
- Traditionally, 6-pulse rectification provides DC power for motors
- However, input current harmonics acceded DO-160E limits
- New - more advanced technology - is required to convert AC into DC



Current waveform



Harmonics

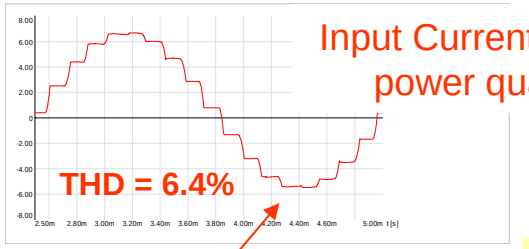


Technology Options

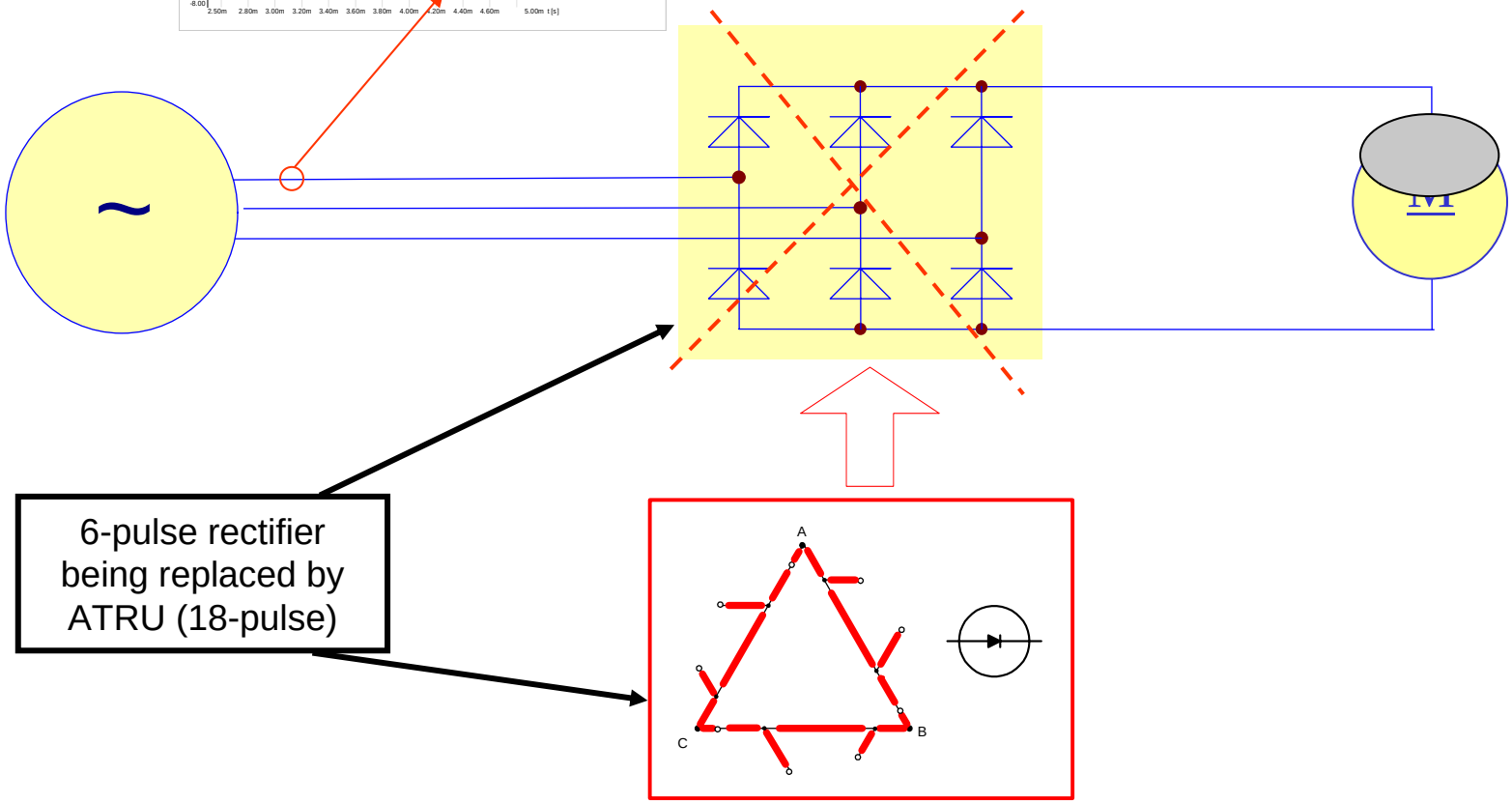
Following power conversion technologies are capable to meet new power quality requirements:

- Multiphase power conversion (passive conversion)
- High frequency switch mode conversion (active conversion)
- Other harmonics correction techniques, based on:
  - Harmonics injection
  - Active filter implementation

Multiphase Power Conversion

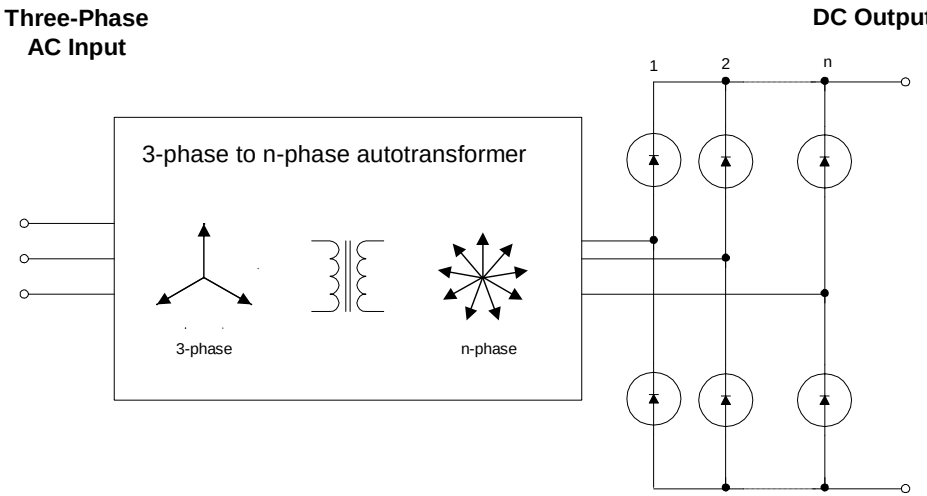


Input Current meets power quality

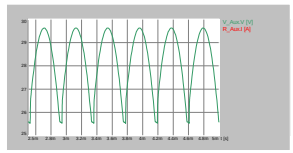
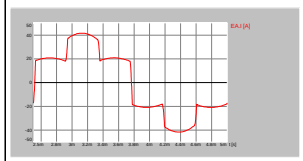
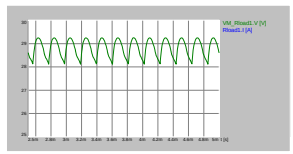
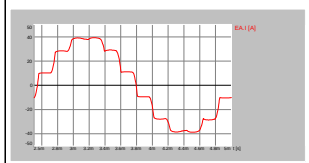
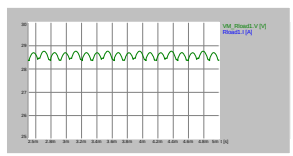
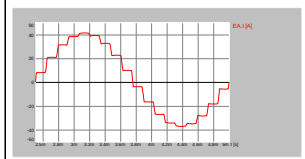
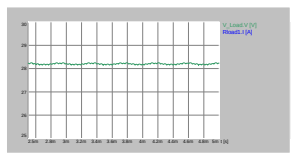
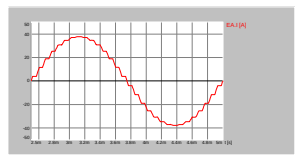


6-pulse rectifier being replaced by ATRU (18-pulse)

Multiphase Power Conversion



- Output Voltage: 270 Vdc nominal (with 115 Vac input); passive regulation
- Meets Input Current Harmonic Limits
- Power Factor: 0.980-0.990
- Efficiency: 96-98%
- Simplicity: low parts count, no needs for energy storage components (C or L)
- Several Products in manufacturing (power range: 1-200 kW)

Design Approach	Output Voltage Ripple [%p-p]	Input Current THD [%]
6-pulse	14 	28-33 
12-pulse	3.4 	9-14 
18-pulse	1.52 	6-9 
30-pulse	0.55 	2.5-3.5 

Multiphase Power Conversion - Hardware Examples

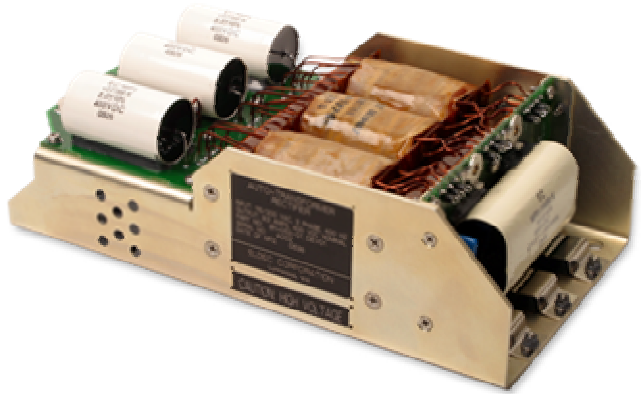
135 kW Converter - 230Vac/540Vdc
(liquid cooled)

30 kW Converter -115Vac/270Vdc
(Forced air cooled)

80 kW Power System - 115Vac/270Vdc
(Liquid cooled)

Multiphase Power Conversion - Hardware Examples

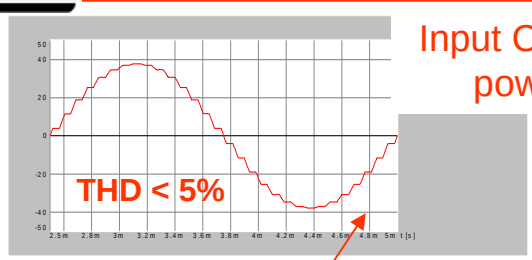
15 kW Converter - 230Vac/540Vdc



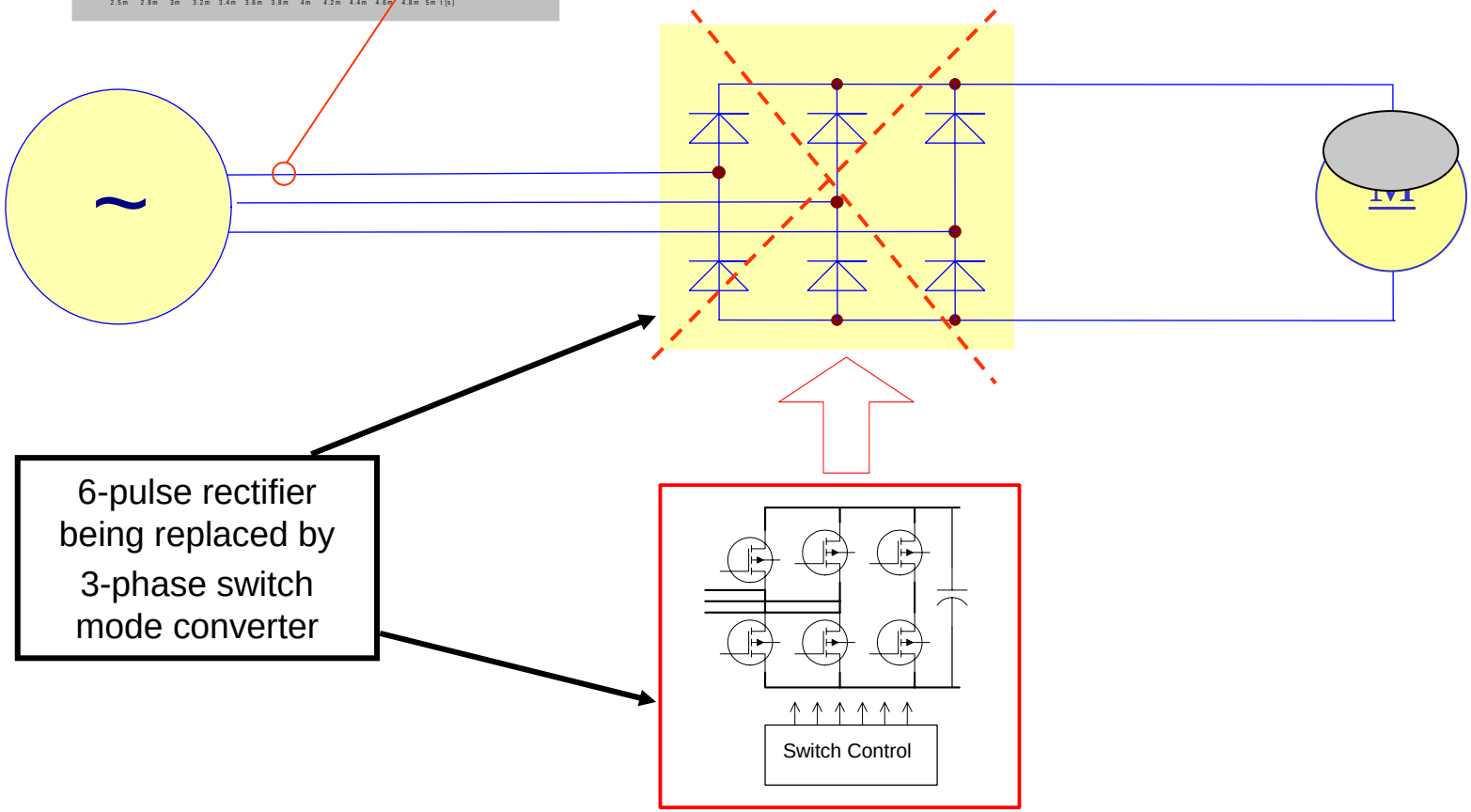
4 kW Converter -230Vac/270Vdc

1 kW Converter -115Vac/270Vdc

High Frequency Switch Mode Conversion



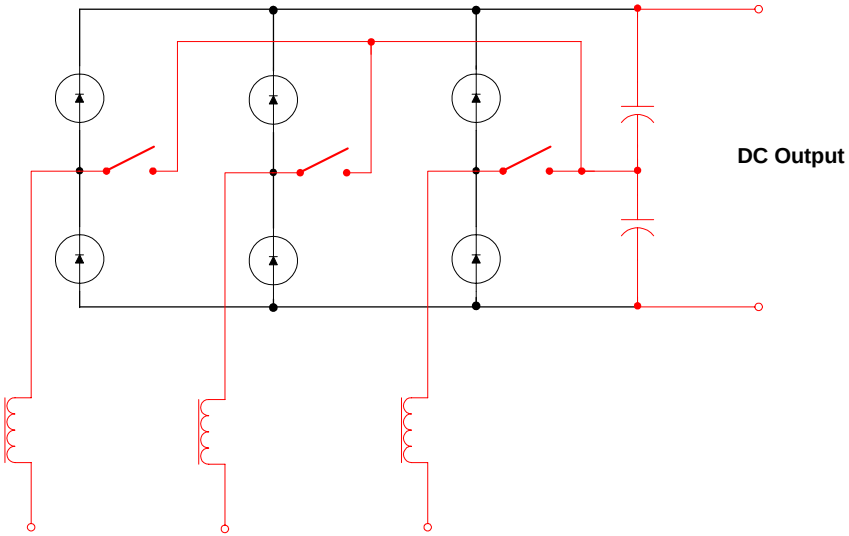
Input Current meets power quality



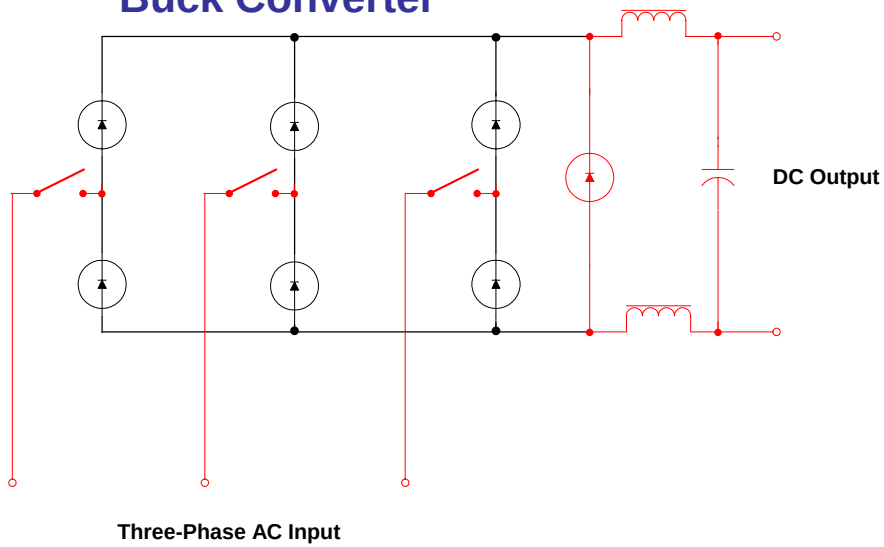
High Frequency Switch Mode Conversion

Two practical solutions, based on:

Boost Converter



Buck Converter



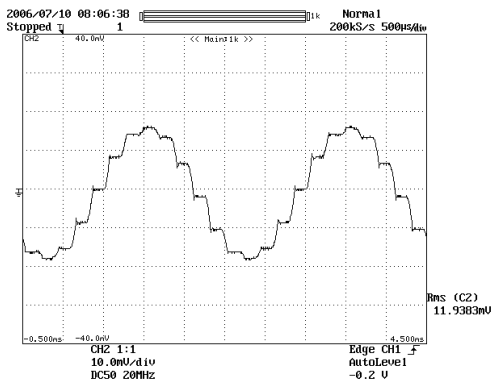
- Regulated DC Output Voltage:
  - 320 Vdc minimum - for boost converter
  - 230 Vdc maximum - for buck converter
- Meets Input Current Harmonic Limits

- Power Factor: 0.994-0.998
- Efficiency: 95-97%
- Soft Start Circuitry
- Demonstration Hardware Developed and Tested (one for each approach)

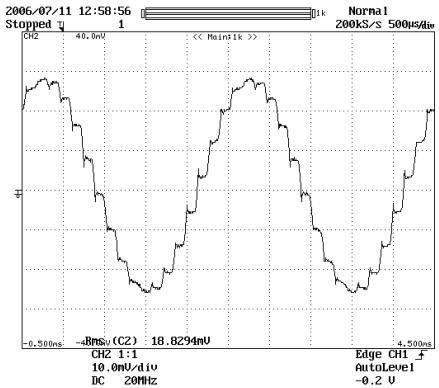
Performance Summary of AC/DC Converters

Parameter	Design A Passive (12-pulse)	Design B Passive (18-pulse)	Design C Passive (30-pulse)	Design D Active (Boost)	Design E Active (Buck)
Output Power	4.5 kW	1.6 kW	8.6 kW	15 kW	5 kW
Input Voltage (nominal)	230 Vac	115 Vac	115 Vac	115 Vac	460 Vac
Output Voltage (nominal)	270 Vdc	270 Vdc	320 Vdc	400 Vdc	460 Vdc
Power Quality Meeting DO-160E ….Current THD Current Waveform	 Yes 11% Picture A	 Yes 6.4% Picture B	 Yes 3.3% Picture C	 Yes 3% Picture D	 Yes 3% Picture E
Power Factor	0.986	0.992	0.998	.990	.990
Output Ripple	15 Vp-p	12 Vp-p	7 Vp-p	3 Vp-p	10 Vp-p
Efficiency	95%	96%	97%	97.5 %	96 %
EMI Filter	No	Yes	No	Yes	Yes
Size	6” x 4.6” x 3”	7” x 2.6” x 2”	9” x 6” x 3.4”	11” x 15” x 3”	13.7” x 3.6” x 4”
Weight	5.5 lb	3.1 lb	10.2 lb	20.8 lb	6.7 lb

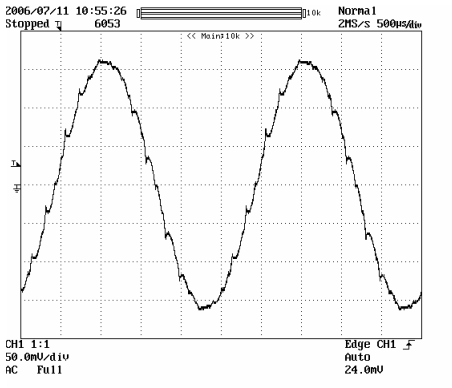
Input Current Waveforms of AC/DC Converters



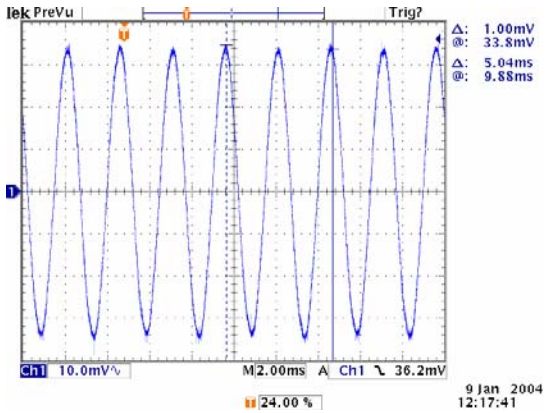
A) Passive, 12-pulse



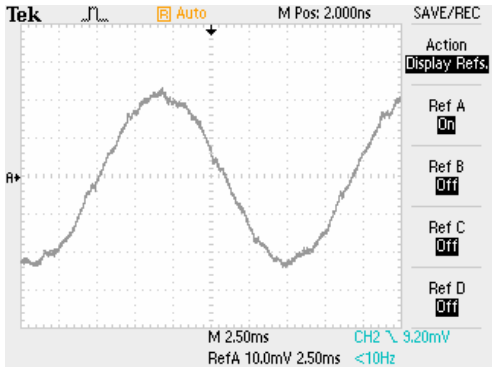
B) Passive, 18-pulse



C) Passive, 30-pulse



D) Active, Boost



E) Active, Buck

Comparison between Passive and Active Approaches

- Both approaches are converting 3-phase AC power into DC power
- Both approaches are capable to obtain 150-600 Vdc output with 115 Vac or 230 Vac input
  - For passive approach output voltage is set by adjusting transformer turns ratio
  - Active approaches can regulate at any set voltage except 230-320 Vdc range (without additional DC/DC converter)
- Both approaches achieve compatible power quality:
  - Low input current harmonics (THD: 3-7%)
  - Individual harmonics meeting aerospace power quality standards (DO-160, rev. E)
  - High power factor (0.980-0.998)
  - Low output ripple (can be set to any level by output filter size)
  - High efficiency (95-98%)
- Both approaches can be air or liquid cooled

Comparison between Passive and Active Approaches

	Passive Approach (ATRU)	Active Approach (Boost/Buck Converter)
Advantages	• Simplicity No need for energy storage devices or control • High reliability Typical MTBF is 250,000 hours • Robustness – accepts high overloads • Lower weight at 400 Hz applications Weight example (completed unit): * 4 kW – 7 lb * 15 kW – 13 lb • Lower cost	• Precise output voltage regulation • Output voltage can be adjusted • Built in softstart • Built in overcurrent protection/current limiting • The same unit can operate at 400Hz or 60Hz • Significantly lower weight at 60 Hz
Disadvantages	• No output voltage regulation Input voltage variations are passed to the output, plus about 4% voltage drop from no load to full load Additional DC/DC converter is needed to obtain full voltage regulation • Presence of inrush current - basic design Additional circuitry is needed to shape input current	• Lower reliability • High energy storage capacitor needed (Aluminum electrolytic) • No overload capabilities • Higher cost • Gap in output voltage setting Additional DC/DC converter is needed to obtain voltage between 230 Vdc and 320 Vdc

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Conclusions

- Demands for electrical power on today's airplane are increasing
- Traditional, constant frequency power systems are being replaced by variable frequency
- DC brushless motor become the motor of choice on new airplanes
- Power conversion equipment is effecting aircraft DC bus
- New power quality requirements are being established in the aerospace industry
- New power conversion technologies are needed to fully meet recent power quality requirements – creating new challenges
- Two group of technologies, capable to meet new power quality requirements, are emerging: passive and active approach
- When unregulated DC voltage can be tolerated, multiphase conversion has a good fit in aerospace applications

More Information

- Crane Aerospace & Electronics (ELDEC Division) specialize in design and manufacturing of power conversion equipment for aerospace applications
- Standard available products:
  - TRUs: 115Vac/400Hz, 3-phase to 28Vdc - up to 300 Amps
  - Regulated TRUs: 115V/400Hz, 3-phase to 28Vdc - up to 400 Amps
  - ATRUs: 115V or 230V, variable frequency, 3-phase input to DC output - up to 200kW
  - Aircraft Battery Chargers
  - Power Conversion Units
- Information: ELDEC web side: *www.eldec.com*
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