Power Conversion Technologies for Improved System Performance

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Introduction

- Background
- New Challenges for Power Conversion Equipment on Airplanes
- Review of Technology Options for Powering Motors that Meet Aerospace Requirements
- Implementing Modeling and Simulations for Design Optimization - Example
- Conclusions
- Summary of Hardware Performance

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 is being added to airplanes – power quality becoming an issue

Challenges

This creates new challenges, which need to be resolved:

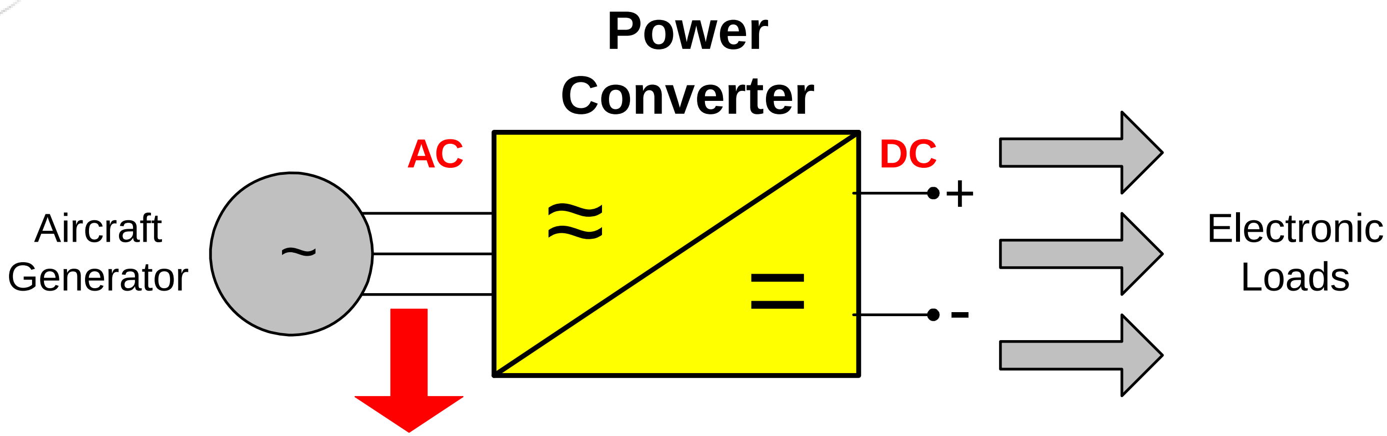
- Challenge #1 – Speed of inductive motors varies with frequency

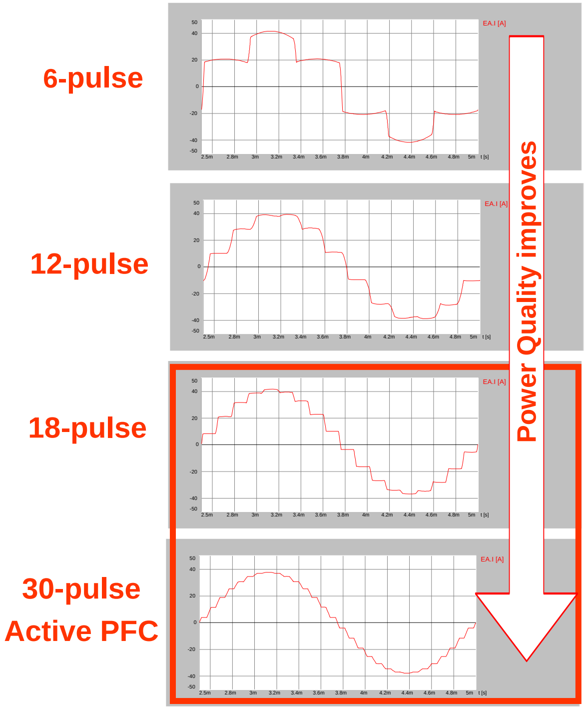
  → solution: replace inductive motors with DC brushless motors

  - 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
- The smoother the current waveform
  ---> the better the "Power Quality"
- 18-pulse, 30-pulse and active PFC approaches represent good power quality

Power Quality

- Power quality requirements from leading OEMs (examples):
  - Boeing: 787B3-0147
  - Airbus: AMD-24
- Recent, DO-160, Rev. F Document imposed power quality requirements for 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
- The harmonic limits requirement makes direct rectification obsolete
  - Practically, all motor drivers, which are using direct rectification need to be replaced or upgraded
  - Majority of traditional TRU units can not meet new current limit requirements – improved designs or larger filters are needed

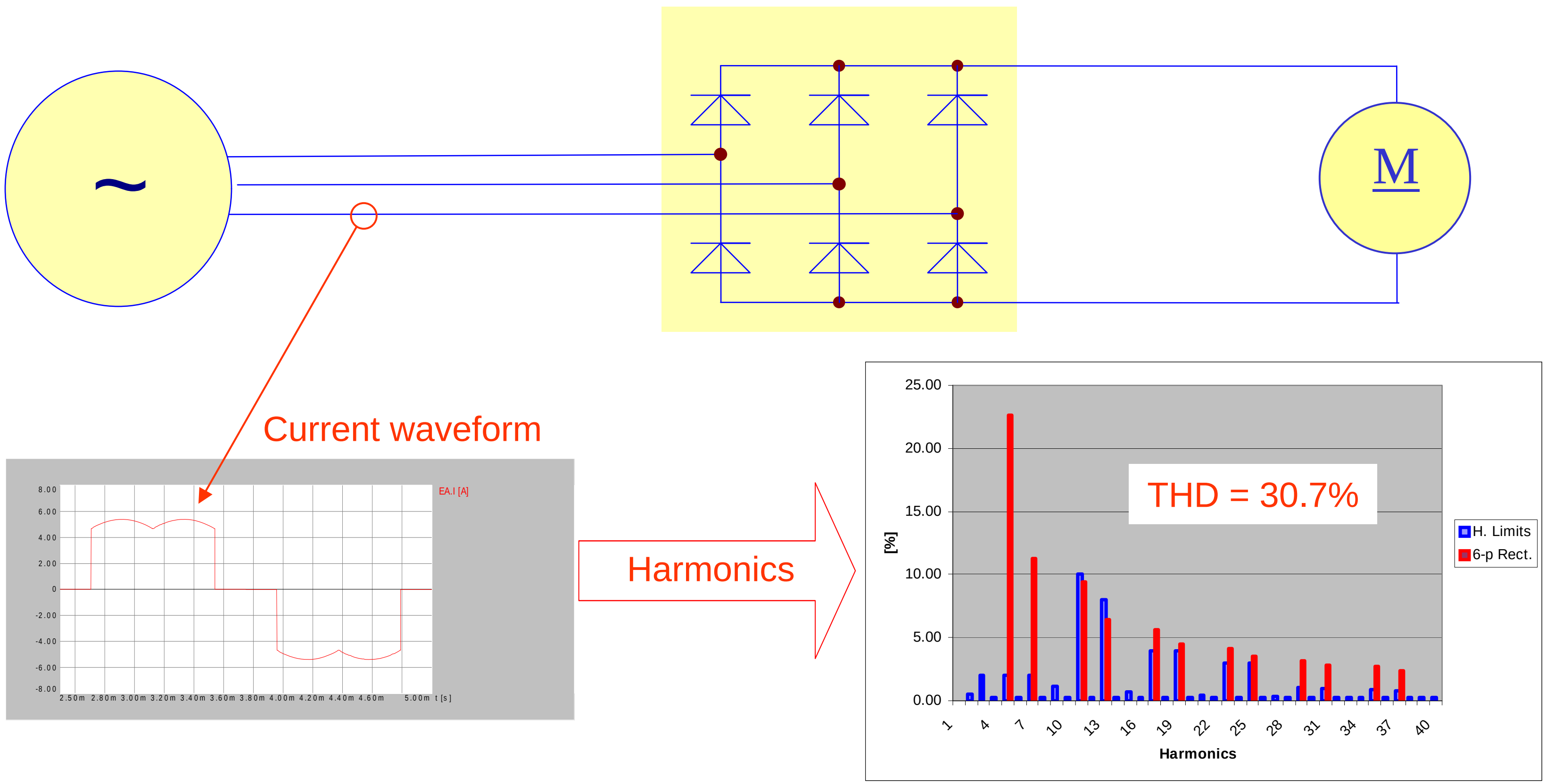
DO-160F Current Harmonics Limit

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

Harmonic Order	Limits
3rd, 5th, 7th	$0.02\ I_1$
Odd Triplen Harmonics (h = 9, 15, 21, ..., 39)	$I_h = 0.1\ I_1 / h$
11th	$0.1\ I_1$
13th	$0.08\ I_1$
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

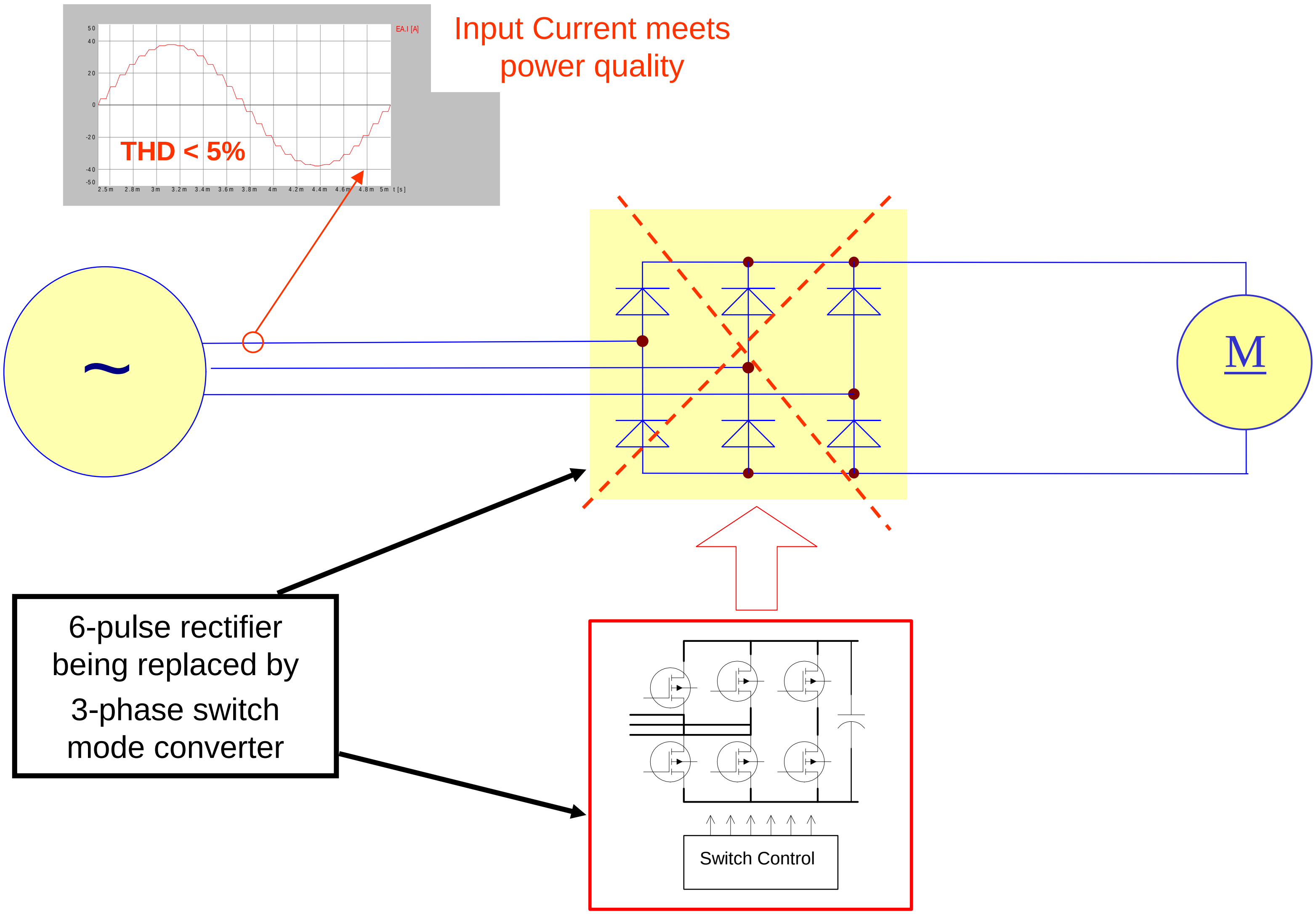
- Traditionally, 6-pulse rectification provides DC power for motors
- However, input current harmonics exceeded DO-160F limits
- New - more advanced technology - is required to convert AC into DC



Technology Options

- The following power conversion technologies are capable of meeting the new power quality requirements:
  - High frequency switch mode conversion (active conversion)
  - Multiphase power conversion (passive conversion)
  - Other harmonic correction techniques, based on:
    - Harmonic injection
    - Active filter implementation

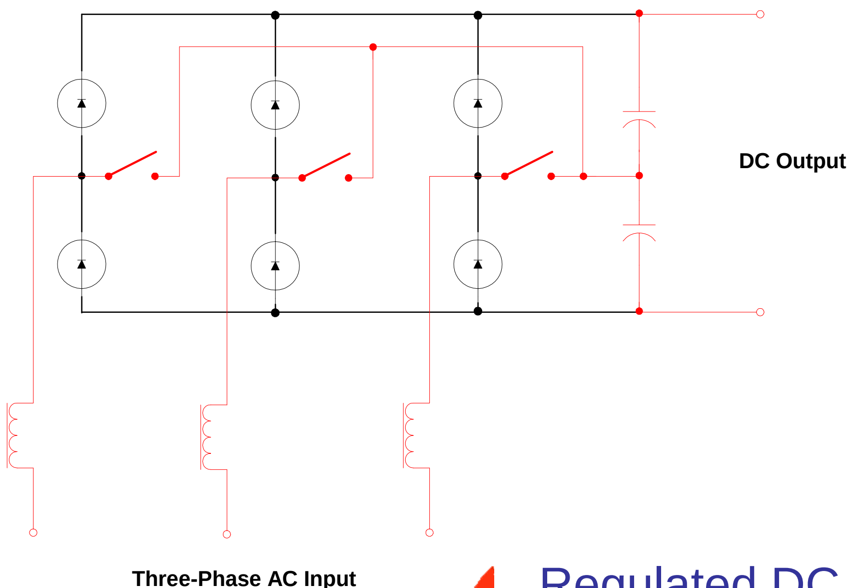
High Frequency Switch Mode Conversion



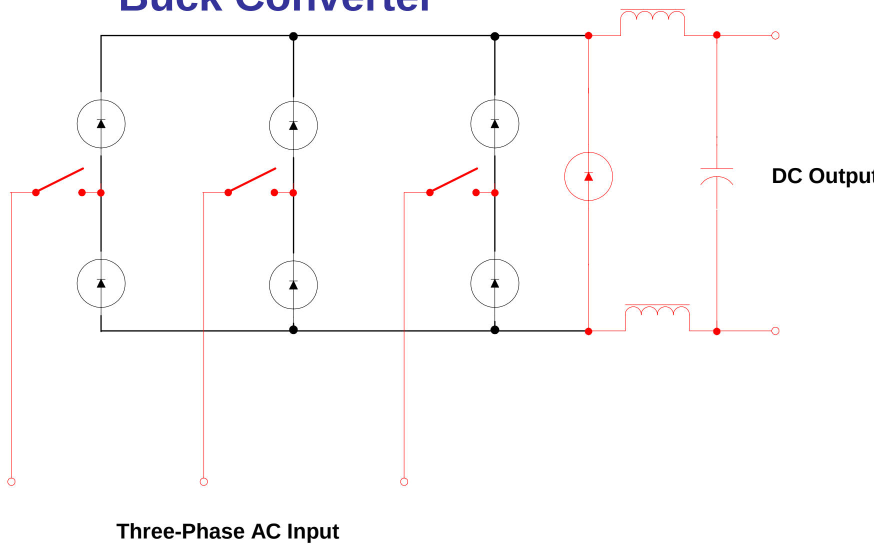
High Frequency Switch Mode Conversion

Two practical solutions, based on:

Boost Converter

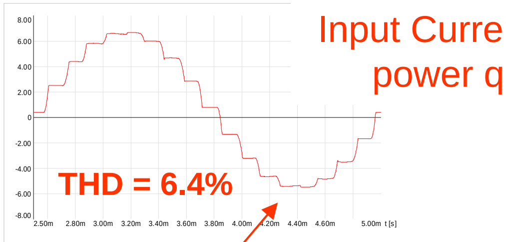


Buck Converter

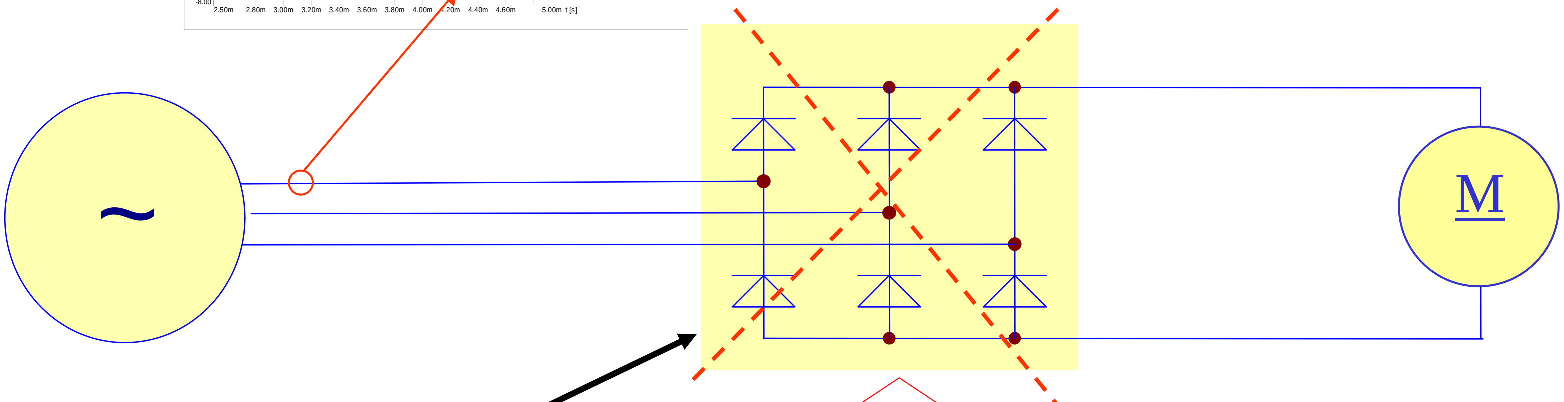


- Regulated DC Output Voltage:
  - 320 Vdc minimum (with 115 Vac input) - for boost converter
  - 230 Vdc maximum (with 115 Vac input) - for buck converter
- Meets Input Current Harmonic Limits
- Soft Start Ability
- Power Factor: 0.994–0.998
- Efficiency: 95–97 %

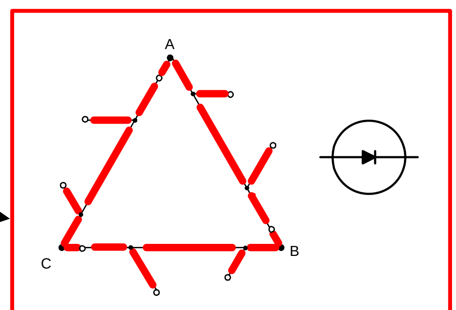
Multiphase Power Conversion



Input Current meets power quality



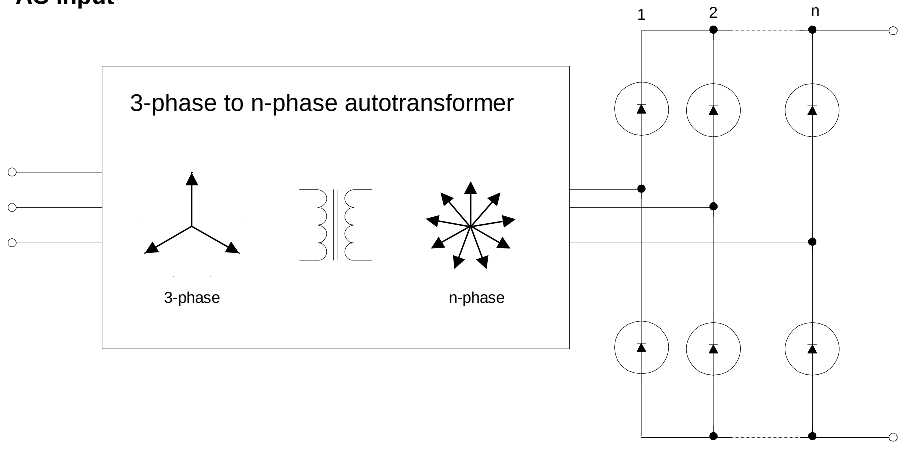
6-pulse rectifier being replaced by ATRU (18-pulse)



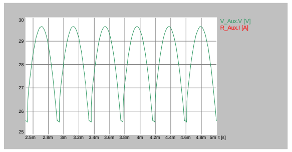
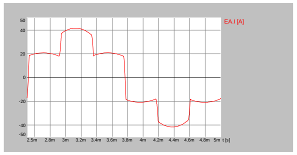
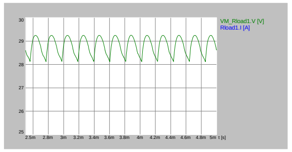
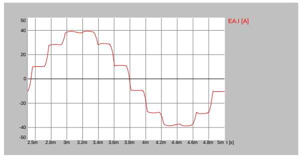
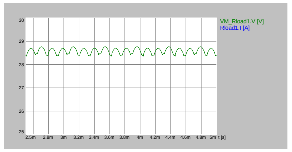
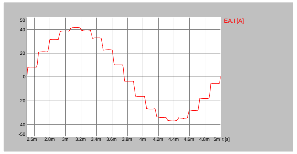
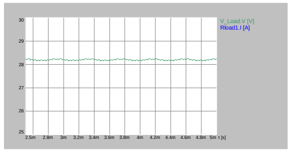
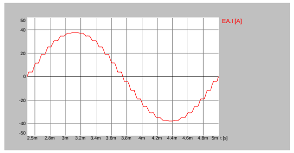
Multiphase Power Conversion

Three-Phase AC Input

DC Output



- 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 need for energy storage components (C or L)

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 

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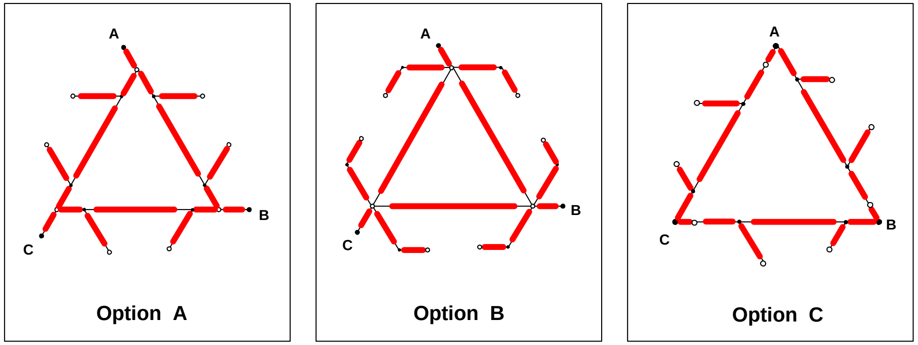
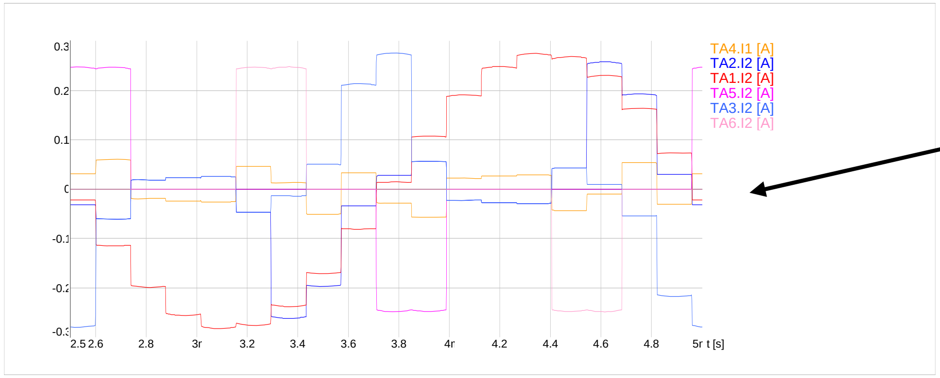
Design Example - Multiphase Power Converter

- 18-pulse autotransformer topology meets new harmonic limits – if designed correctly
- Some of available 18-pulse autotransformer options:



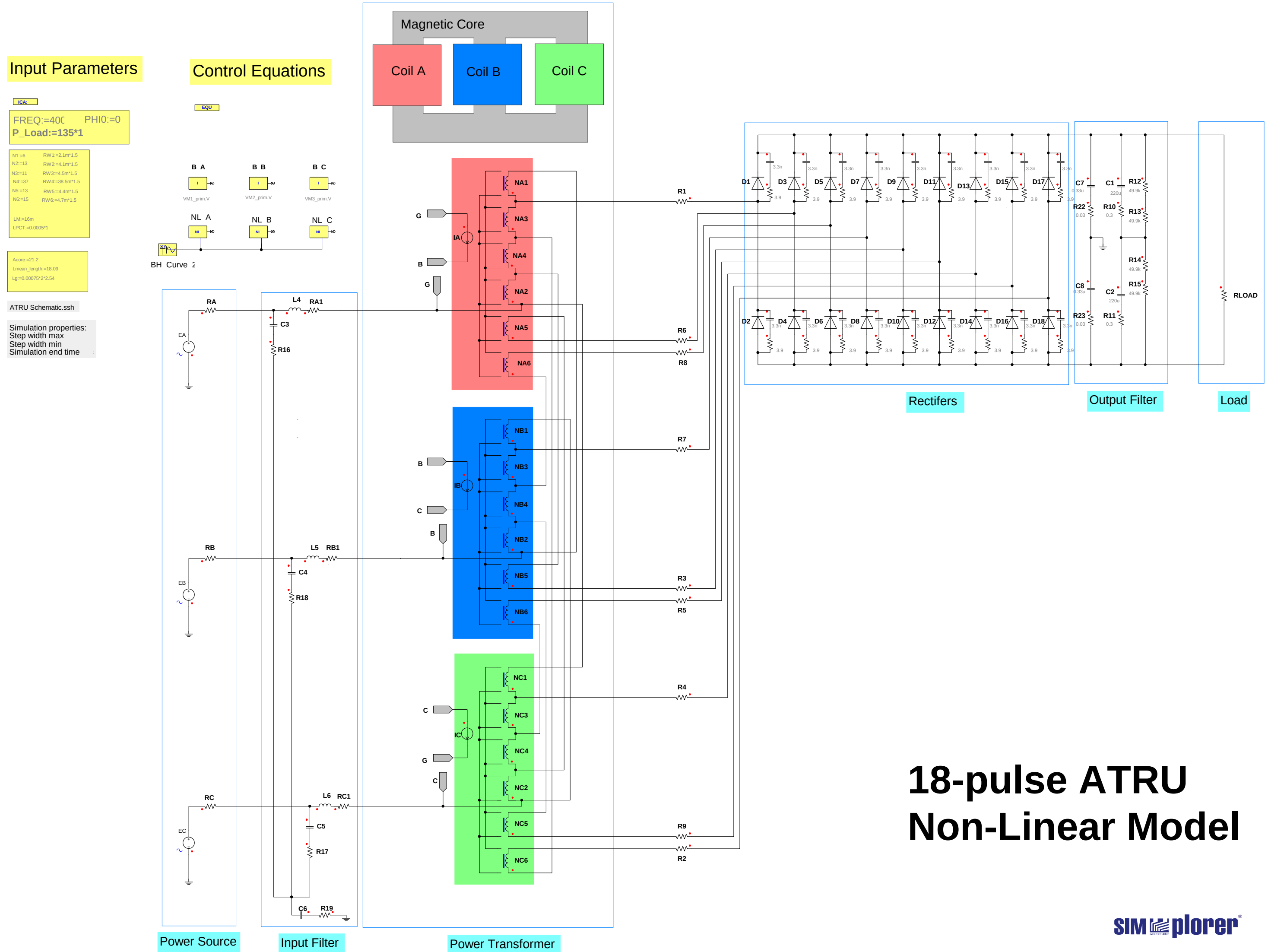
Autotransformer converts 3-phase input voltage into 9-phase output voltages (spaced 40 degrees from each other)

- It is almost impossible to analyze topology and optimize design without converter modeling and running simulations



Current waveforms in transformer windings become very complex

Design Example - Multiphase Power Converter



18-pulse ATRU Non-Linear Model

Design Example - Multiphase Power Converter

Transformer construction challenges:

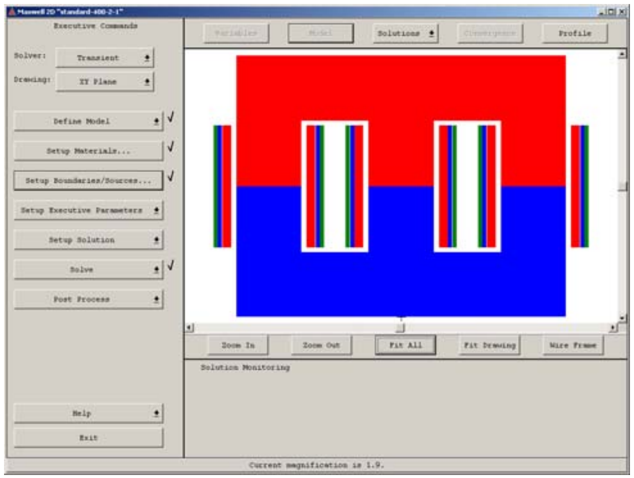
- Choosing winding material (copper, aluminum)
- Selecting conductor shape (round wire, square wire, foil)
- Defining and optimizing core geometry and aspect ratio
- Optimizing interactions between windings (leakage inductance, proximity effects)

- It is not practical to build and test each considered option
- Therefore, design iterations and optimizations need to be performed on computers

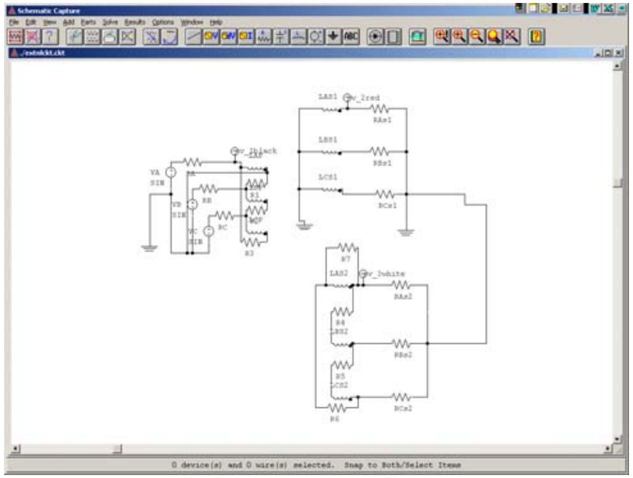
Design Example - Multiphase Power Converter

Transformer Construction Optimization:

Define core geometry
and winding configuration



Convert geometry
and materials into
electrical parameters



Simulate
performance

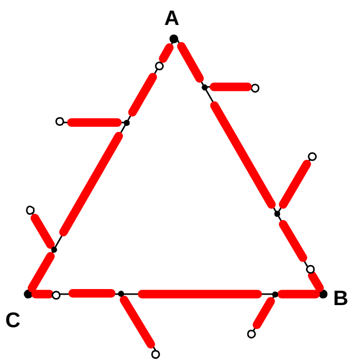
Core Losses
Winding Losses
Leakage Inductance
Regulation

Adjust and optimize

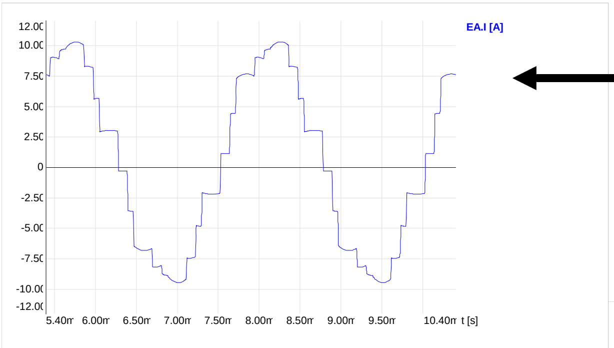
Design Example - Multiphase Power Converter

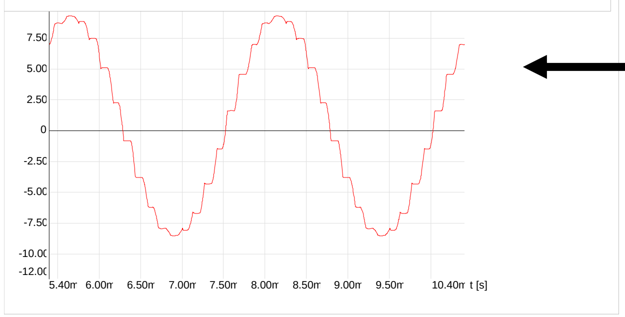
- Simulate converter performance and verify power quality

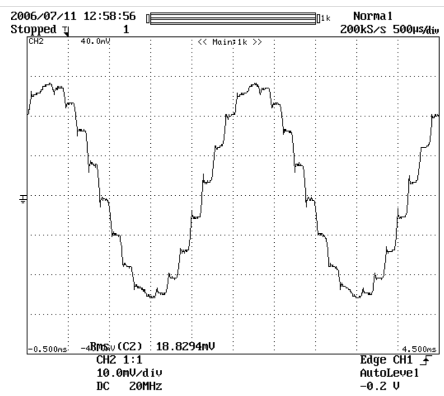
Autotransformer Configuration



Input Current Waveforms







Design

First Completed Design

Power Quality not met; several current harmonics exceed limits

Interactive Optimization

Optimized Design

All current harmonics within specification plus margin

Fabrication

Completed Hardware

Performance correlates very closely with optimized design

Performance Summary of Existing Hardware

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

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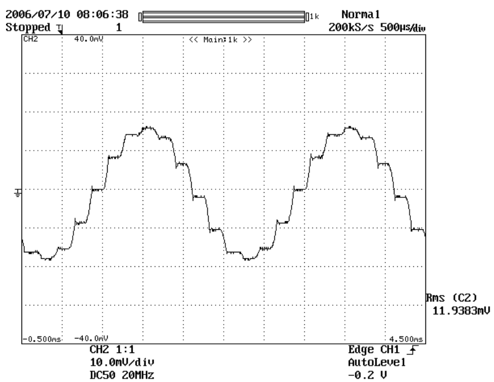
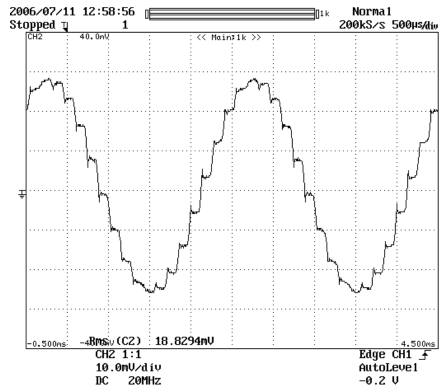
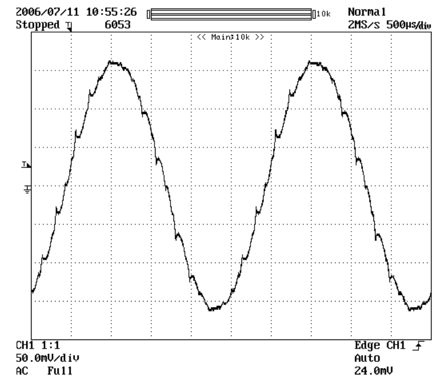
Input Current Waveforms of AC/DC Converters



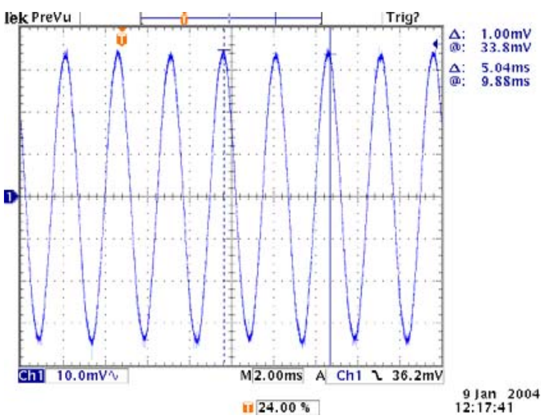
A) Passive, 12-pulse



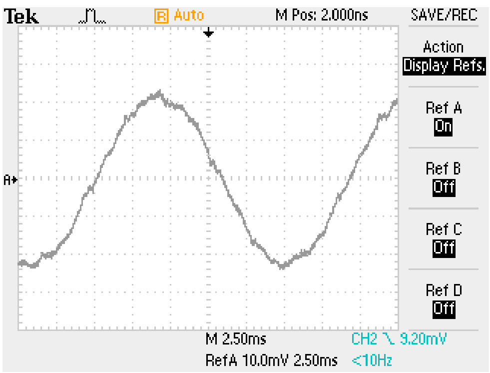
B) Passive, 18-pulse



C) Passive, 30-pulse



D) Active, Boost



E) Active, Buck

Comparison between Active and Passive Approaches

	Active Harmonic Reduction (Switch Mode)	Passive Harmonic Reduction (Multi-Phase)
Input Voltages	115 or 230 Vac	115 or 230 Vac
Output Voltages	150 - 230, 320 – 600 Vdc (without use of additional DC/DC converter) Is regulated over variations in line and load	150 – 600 Vdc (set by adjusting transformer turns ratio) Varies with line voltage and load
Harmonics	THD 3 – 7%	THD 3 – 12% (dependent on topology)
Power Factor	0.980- 0.998	0.980 – 0.998
Output Ripple	Dependent on output filter	Dependent on output filter
Efficiency	95 – 97%	96 – 98%
Soft Start	Available with existing design	Needs to be added on
Over-current Protection	Available with existing design	Needs to be added on
Cooling Method	Conduction, liquid or air	Conduction, liquid or air
Advantages	Precise output voltage regulation Output voltage can be adjusted Built in soft-start Built in over-current protection/current limiting The same unit can operate at 400Hz or 60Hz Significantly lower weight at 60 Hz	Simplicity No need for energy storage devices or control High reliability Typical MTBF - 250,000 hours Robust – accepts high overloads Lower weight at 400 Hz applications Lower cost
Disadvantages	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	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

Existing Hardware Examples

1 kW Converter - 115Vac/270Vdc

5 kW Converter - 230Vac/540Vdc

8 kW Converter - 115Vac/300Vdc
(Fan cooled)

15 kW Converter -115Vac/270Vdc

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

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 becoming the motor of choice on new airplanes – it requires DC power to operate
- New power conversion technologies are needed to fully meet recent power quality requirements – creating new challenges
- Effective simulation and optimization tools are critical in successful development of new generation aerospace power converters
- Two groups of technologies, capable of meeting 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, Power Solutions, designs, manufactures and supports products and capabilities via our brands: ELDEC, Interpoint and Keltec. We provide both Standard Power Products and Custom Power Products.
  - Standard Power Products consist primarily of our DC-DC converter and filter modules sold under the Interpoint brand.
  - Custom Power Products consists of our custom and semi-custom low voltage and high voltage power products and subsystems.
  - Our Power solutions meet the current and future needs of our customer's applications:
    - **Power for Electronic Systems** – Our full range of standard and custom products delivers compliant product performance, low cost of ownership and ease of integration thereby providing the lowest risk comprehensive solutions (Ex. Embedded low voltage power supplies)
    - **Power Distribution** – Low weight, high power quality and high efficiency platform power conversion, management and distribution. We can provide significant weight and volume savings through integrated power conversion, bus control and power control. (Ex. TRUs, ATRUs, etc.)
    - **Electronic Warfare & Radar** – Solid-State or traveling wave tube (TWT) based low/high voltage, high power products and subsystems for mission critical defense platform and payload applications (Ex. TWT amplifiers, high power / high voltage power supplies, etc)
    - **Energy Storage** – Delivering safe integration of energy storage devices into electrical systems while providing the longest maintenance interval and service life at the lowest weight. (Ex. Battery systems, battery charger/controller, batteries, etc.)
    - **Motor Power Conversion and Control** – High power quality ac-dc converters as standalone solutions or as part of an integrated electric drive motor package (Ex. ATRUs, active PFC converters, etc.)
- Information: www.craneae.com
- Technical assistance: Kaz Furmanczyk, Principal Engineer
  - Tel. 425-743-8106; e-mail: Kaz.Furmanczyk@crane-eg.com

Crane Power Solutions

Questions?

- Conversion, protection, monitoring
  - Milliwatts to megawatts
    - Custom and off-the-shelf
      - Module, SRU, LRU, integrated sub-system