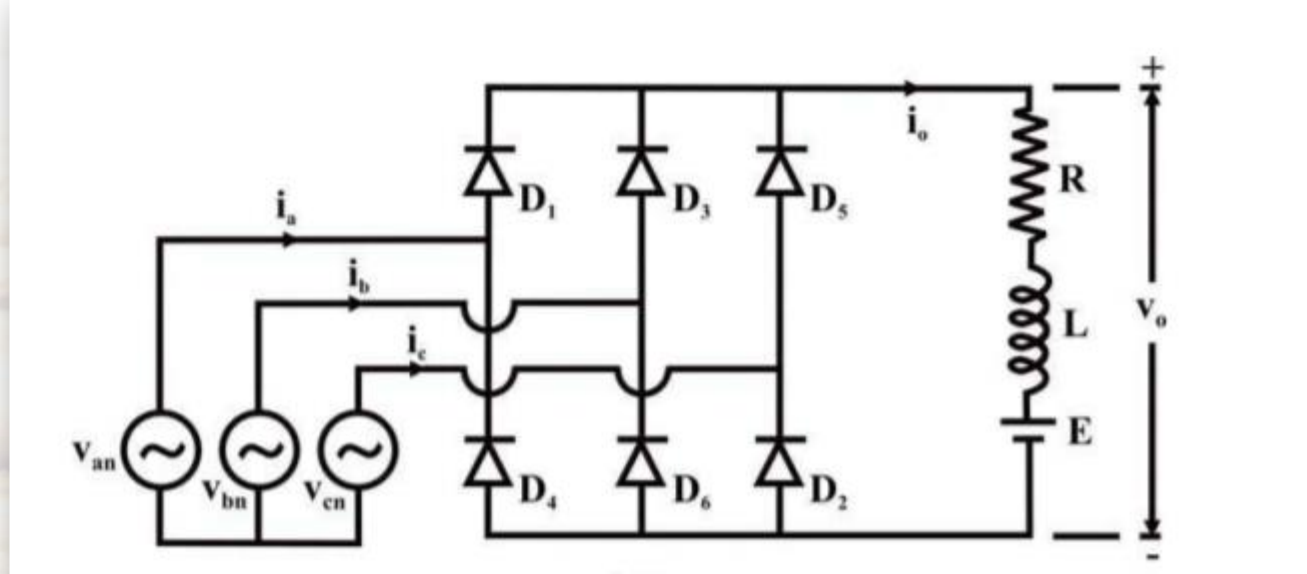
Power Quality Issues
in
High Power Applications

OUTLINE

1. Problem definition
2. Standards with requirements for harmonic current content
   a. RTCA DO-160
   b. MIL-STD-704
   c. MIL-STD-461
   d. MIL-STD-1399
   e. IEEE 519
3. Non -isolated methods
4. Isolated methods

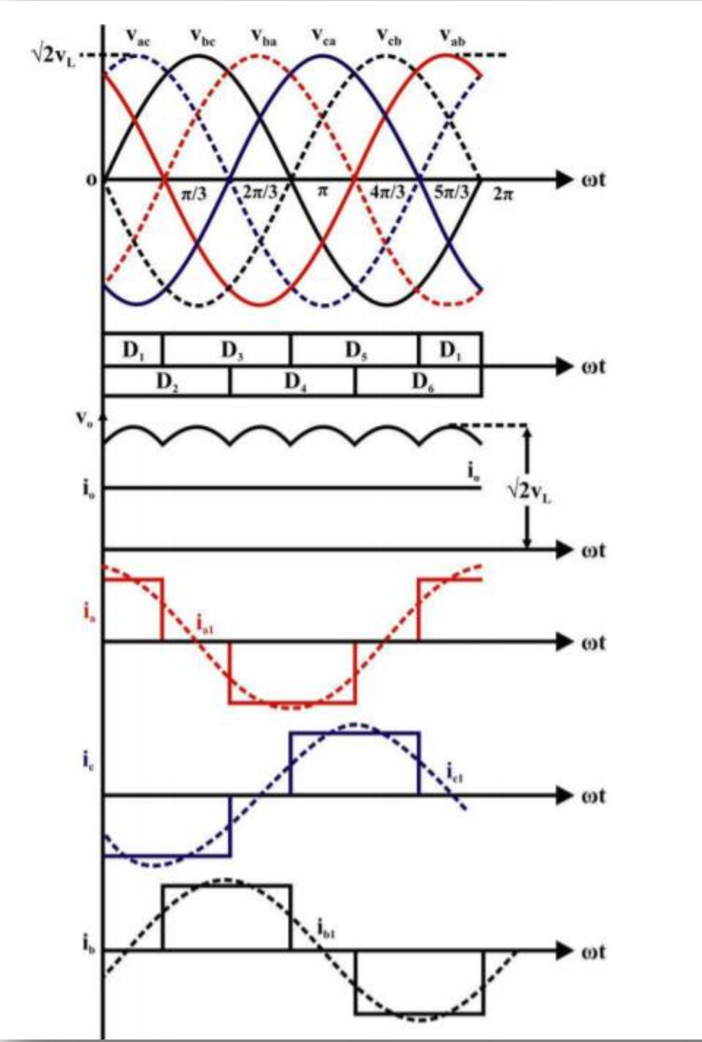
PROBLEM DEFINITION

- Typical high power rectifier circuit utilizes three-phase full wave bridge rectification or a variation thereof
- At any point in time there are only two diodes commutated on
- Line current is theoretically a square wave with a highly inductive load

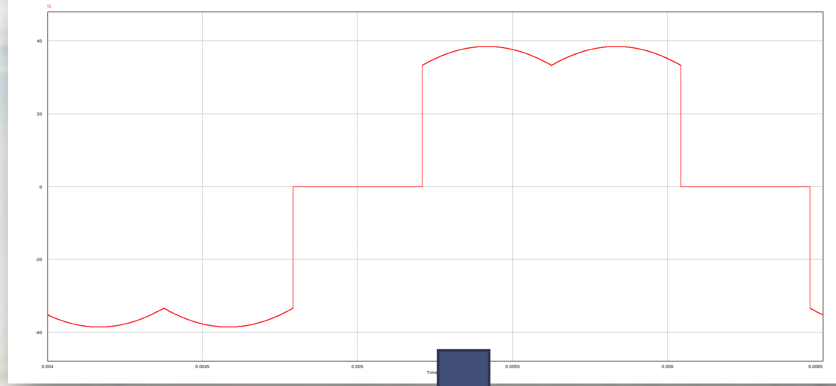


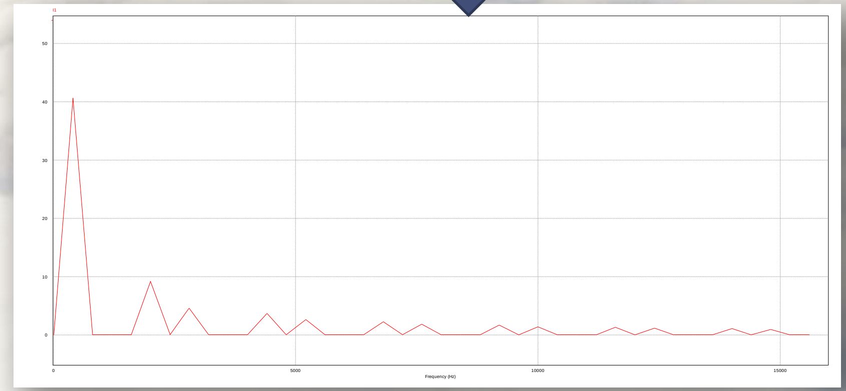
Device / Mode	V_{D1}	V_{D2}	V_{D3}	V_{D4}	V_{D5}	V_{D6}	V_o
$D_1.D_2$	0	0	V_{ba}	V_{ca}	V_{ca}	V_{cb}	V_{ac}
$D_2.D_3$	V_{ab}	0	0	V_{ca}	V_{cb}	V_{cb}	V_{bc}
$D_3.D_4$	V_{ab}	V_{ac}	0	0	V_{cb}	V_{ab}	V_{ba}
$D_4.D_5$	V_{ac}	V_{ac}	V_{bc}	0	0	V_{ab}	V_{ca}
$D_5.D_6$	V_{ac}	V_{bc}	V_{bc}	V_{ba}	0	0	V_{cb}
$D_6.D_1$	0	V_{bc}	V_{ba}	V_{ba}	V_{ca}	0	V_{ab}

PROBLEM DEFINITION



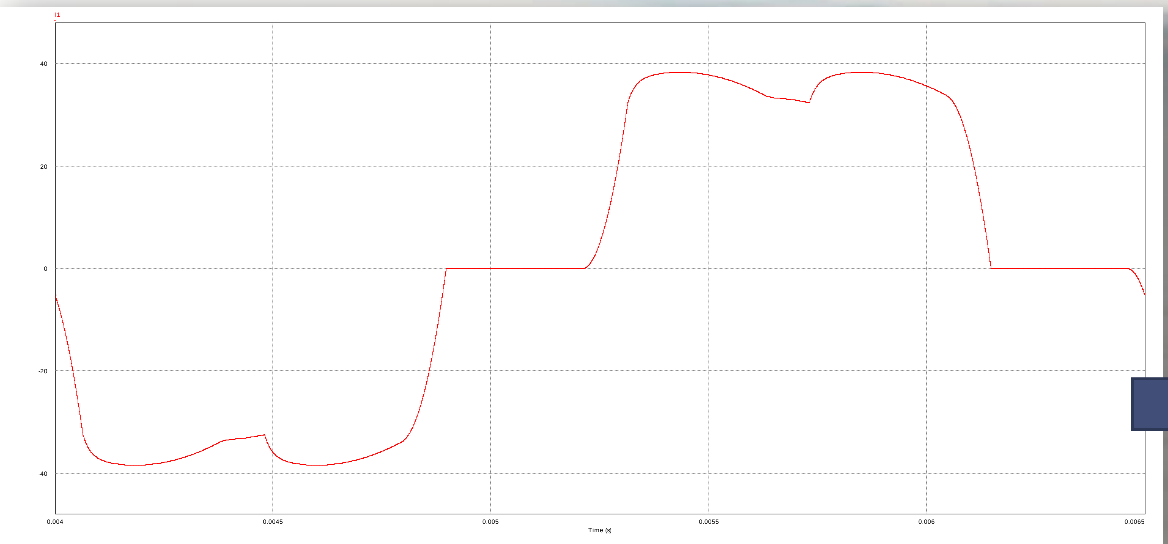
In practice, without energy storage on the DC side (resistive loading), the line current waveform becomes a bit more complex, but still discontinuous. THD is about 30%

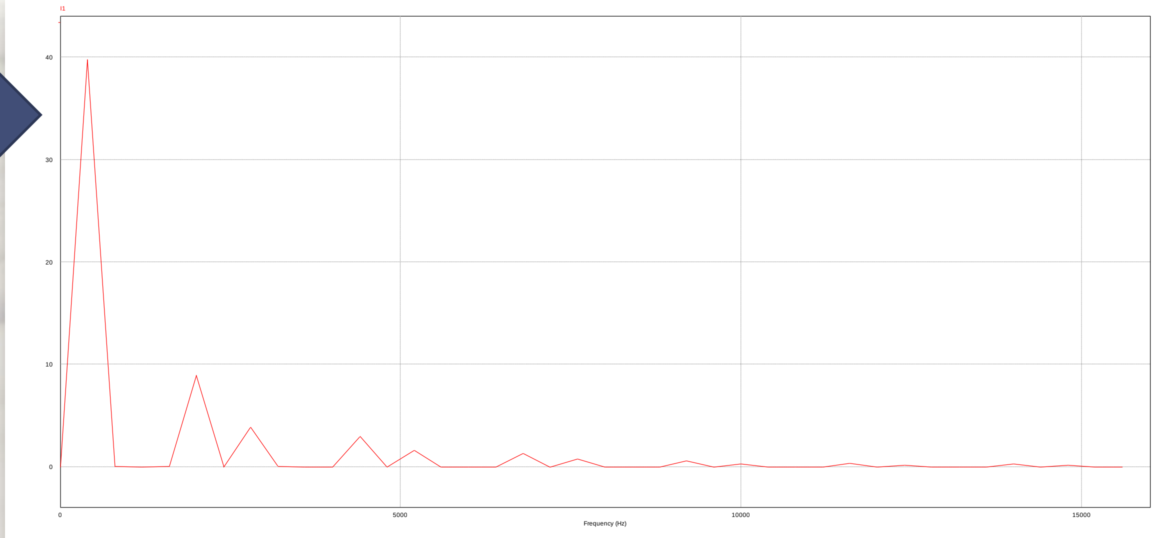




PROBLEM DEFINITION

With normal levels of source impedance the high frequency components are attenuated some, but changes in the commutation angle can further complicate the waveform



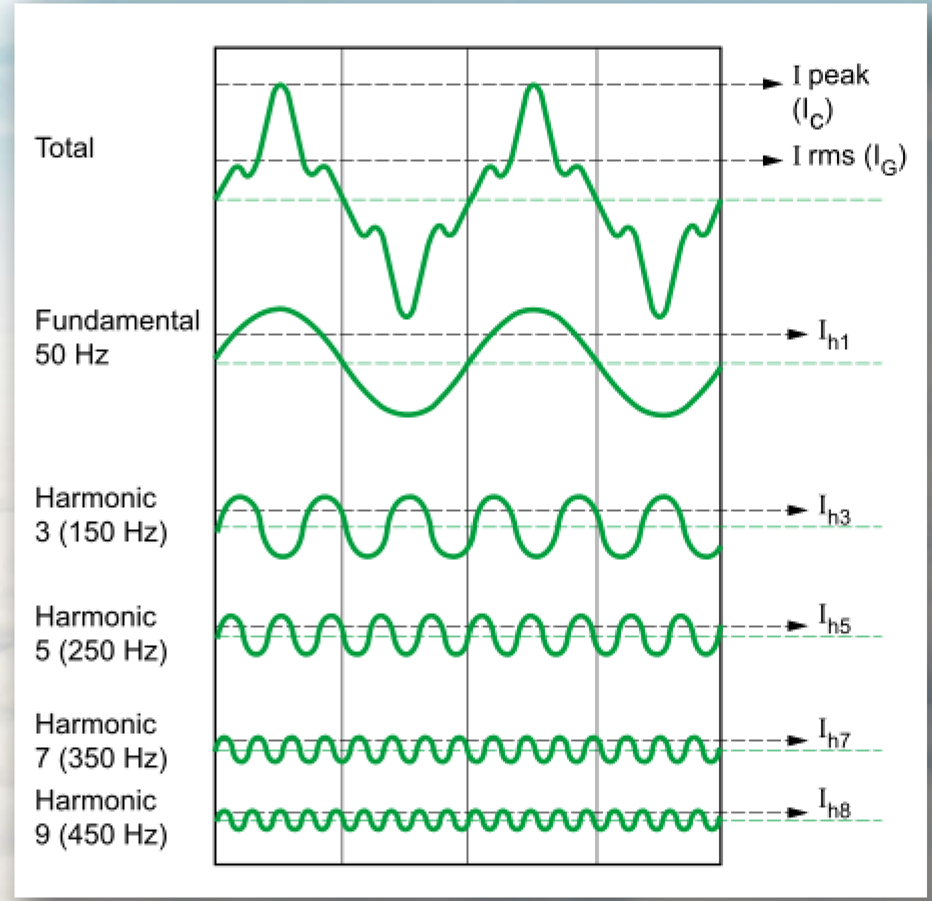


PROBLEM DEFINITION

The proceeding analysis was for linear type loads. When switching elements are present on the DC side – motor drives are common – the harmonic content gets significantly worse.

Harmonic components in the source currents are disadvantageous for numerous reasons

- Additional heating of large conductors
- EMI issues
- Low power factor
- Voltage distortion in high impedance sources



STANDARDS GOVERNING POWER QUALITY

Aircraft standards

Commercial aircraft – RTCA DO-160

DO-160 is often the guiding document for power quality in commercial aircraft. Both Boeing and Airbus have standards that are variations of the DO-160 – power quality requirements vary some (specific harmonics are less at some frequencies) but the DO-160 is a good overall requirement.

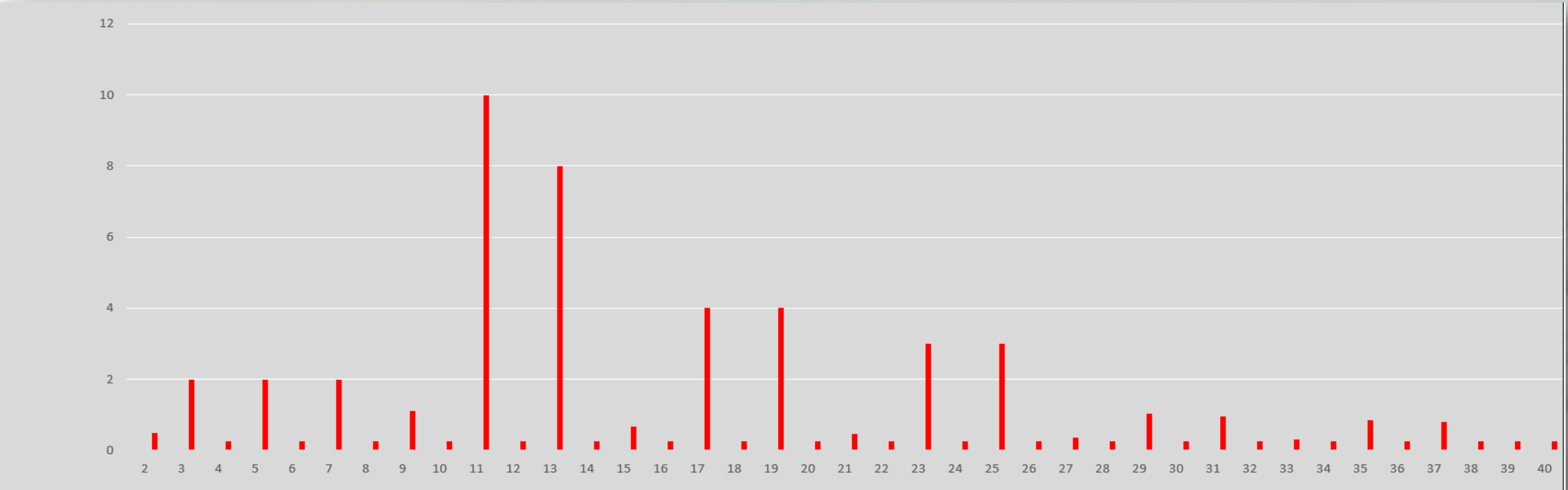
Harmonic order	Limits
3, 5, 7	$I_3 = I_5 = I_7 = 0.02I_1$
Odd triplen-9,15,21,27,33,39	$I_h = 0.1\,I_1/h$
11	$I_{11} = 0.1I_1$
13	$I_{13} = 0.08I_1$
Odd non triplen-17 and 19	$I_{17} = I_{19} = 0.04I_1$
Odd non triplen-23 and 25	$I_{23} = I_{25} = 0.03I_1$
Odd non triplen-29,31,35,37	$I_h = 0.3\,I_1/h$
Even-2 and 4	$I_h = 0.01\,I_1/h$
Even > 4 (6,8,10,12,…,40)	$I_h = 0.0025I_1$

STANDARDS GOVERNING POWER QUALITY

Aircraft standards

Commercial aircraft – RTCA DO-160

Maximum allowable harmonic current as
a percentage of the fundamental



2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
0.5	*2*	*0.25*	*2*	*0.25*	*2*	*0.25*	*1.111*	*0.25*	*10*	*0.25*	*8*	*0.25*	*0.667*	*0.25*	*4*	*0.25*	*4*	*0.25*	*0.476*	*0.25*	*3*	*0.25*	*3*	*0.25*	*0.37*	*0.25*	*1.034*	*0.25*	*0.968*	*0.25*	*0.303*	*0.25*	*0.857*	*0.25*	*0.811*	*0.25*	*0.256*	*0.25*

STANDARDS GOVERNING POWER QUALITY

Aircraft standards

Military aircraft – MIL-STD-704

MIL-STD-704 does not address current harmonics directly but has limits on voltage distortion. High current harmonics can cause voltage distortion in high impedance sources

Current harmonics are addressed at a system level where source impedance is known

TABLE I. AC normal operation characteristics - 400 Hertz (see 5.2.3).

Steady state characteristics	Limits
Steady state voltage	108.0 to 118.0 Volts, RMS
Voltage unbalance	3.0 Volts, RMS maximum
Voltage modulation	2.5 Volts, RMS maximum
Voltage phase difference	116° to 124°
Distortion factor	0.05 maximum
Distortion spectrum	Figure 7
Crest factor	1.31 to 1.51
DC component	+ 0.10 to - 0.10 Volts
Steady state frequency	393 to 407 Hz
Frequency modulation	4 Hz
Transient characteristics	Limits
Peak voltage	±271.8 Volts
Voltage transient	Figure 3
Frequency transient	Figure 5

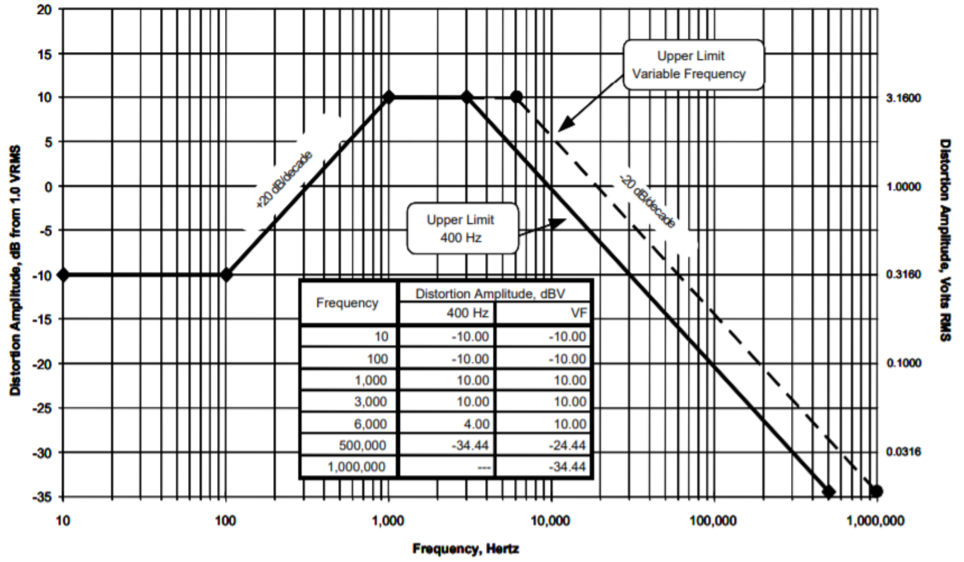


FIGURE 7. Maximum distortion spectrum of 400 Hz and variable frequency AC voltage.

STANDARDS GOVERNING POWER QUALITY

Naval and aircraft standards

Military ships, submarines and some aircraft – MIL-STD-461

MIL-STD-461 contains EMI requirements for surface ships, submarines and some military aircraft applications. 400 Hz applications must comply with the limits set forth in CE101-3, 60 Hz applications are governed by CE101-2. Aircraft applications use CE101-4

When specified for high power applications only – not always a requirement. Current harmonic emissions around 3% of the fundamental maximum at any frequency above 2nd harmonic

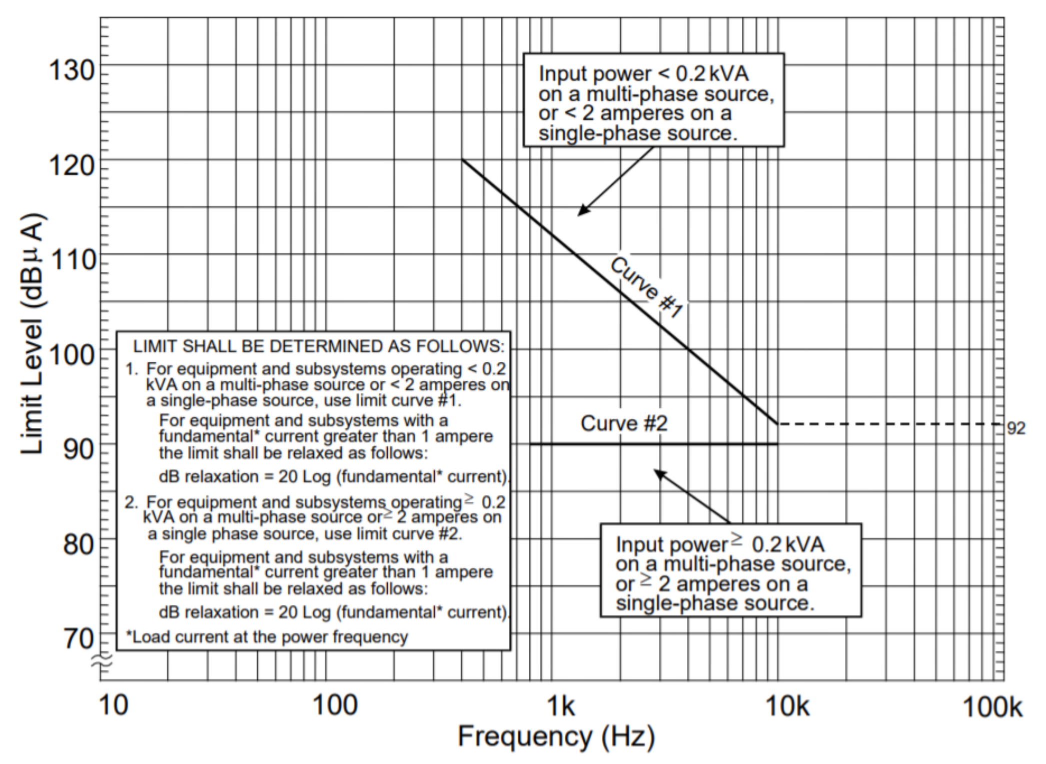


FIGURE CE101-3. CE101 limit for surface ships and submarine applications, 400 Hz.

STANDARDS GOVERNING POWER QUALITY

Naval and aircraft standards

Military ships, submarines and some aircraft –
MIL-STD-461

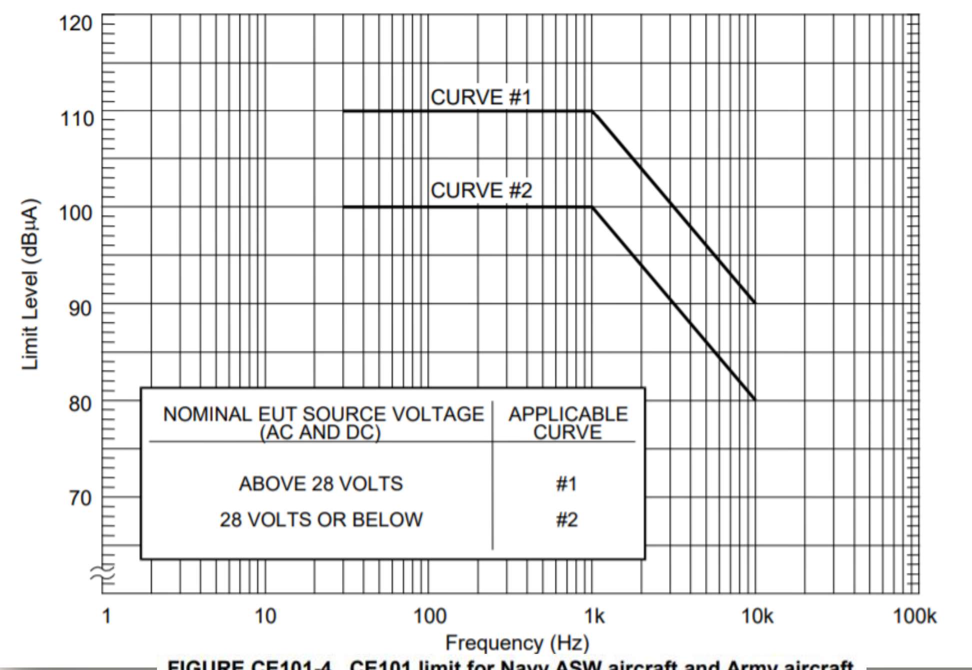


FIGURE CE101-4. CE101 limit for Navy ASW aircraft and Army aircraft (including flight line) applications.

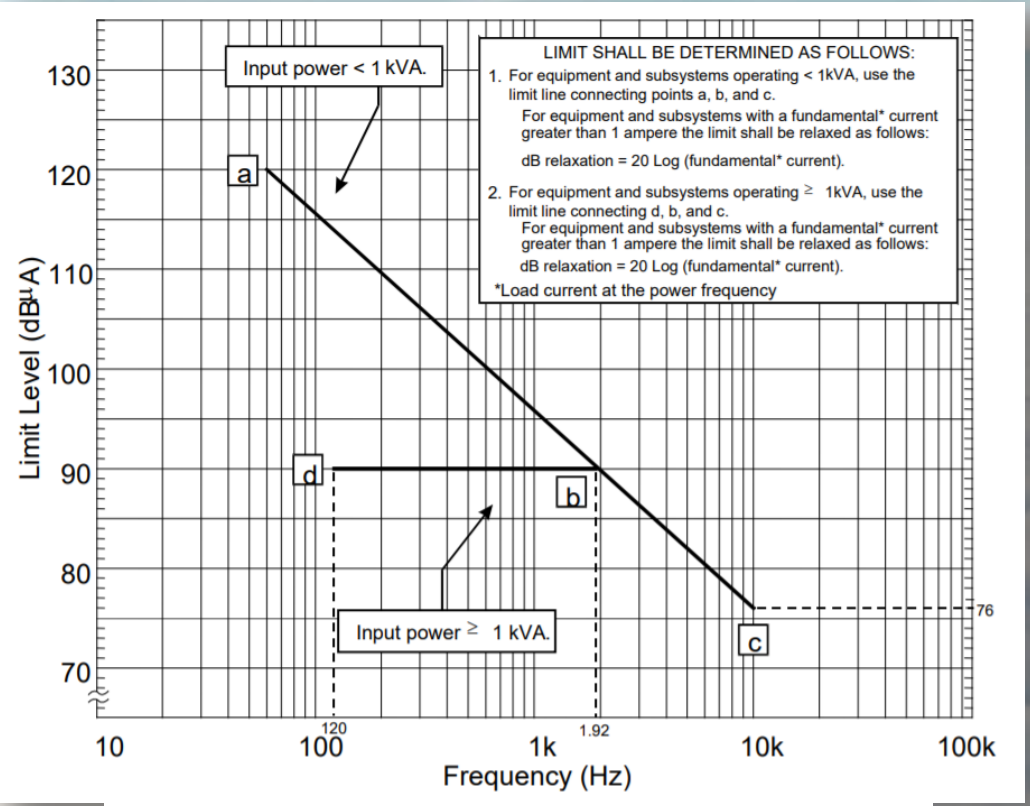


FIGURE CE101-2. CE101 limit for surface ships and submarine applications, 60 Hz.

STANDARDS GOVERNING POWER QUALITY

Naval standards

Naval ships and submarines are primarily governed by MIL-STD-1399 Section 300. This standard requires all single current harmonic emissions be limited to 3% of the fundamental maximum, and THD is limited to 5% maximum. Limits are reduced above 2 kHz (60 Hz) and 13.3 kHz (400 Hz)

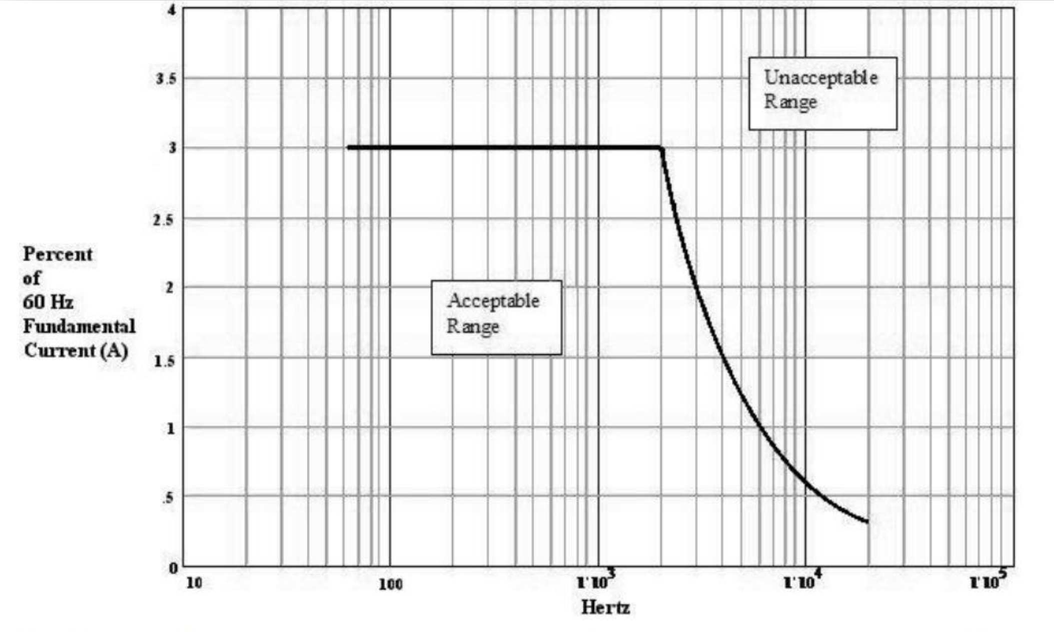


FIGURE 22. Limit line for currents at frequencies greater than 60 Hz for equipment greater than or equal to 1 kVA.

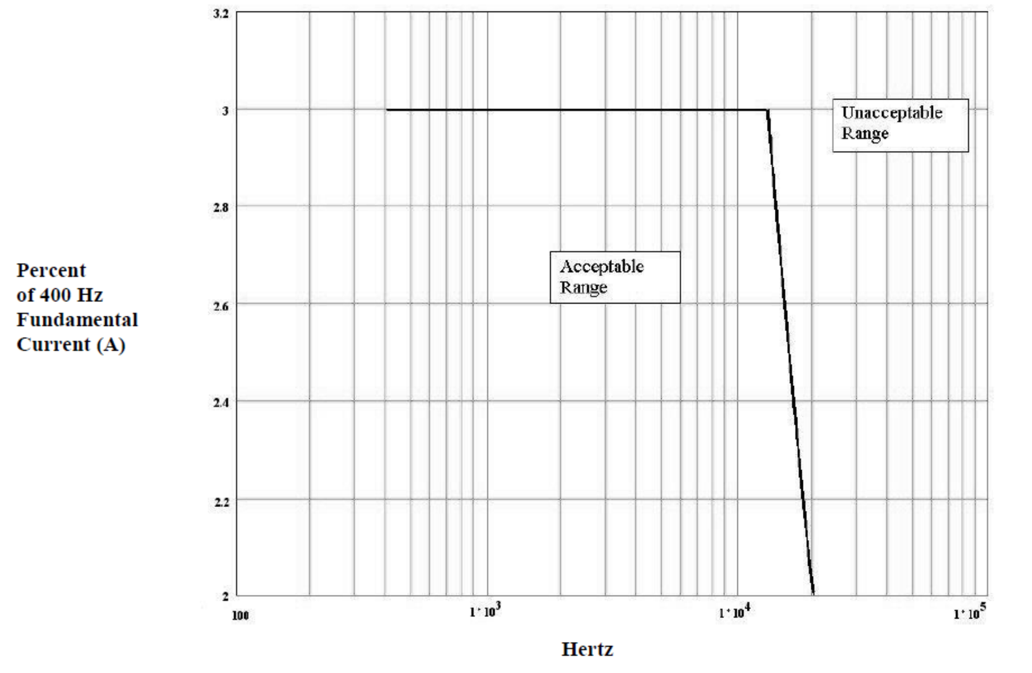


FIGURE 24. Limit line for currents at frequencies greater than 400 Hz for equipment greater than or equal to 0.2 kVA.

STANDARDS GOVERNING POWER QUALITY

Commerial standards

IEEE 519 and IEC 61000-4-7 are used for guidance in commercial applications. Harmonic current limits are determined using the ratio of available short circuit current to normal load current as a factor. There is allowance for the "characteristic harmonic" of multi-pulse rectifiers

IEEE STD 519-2014

Table 2—Current distortion limits for systems rated 120 V through 69 kV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a, b]						
I_{SC}/I_L	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h \le 50$	TDD
< 20[c]	4.0	2.0	1.5	0.6	0.3	5.0
$20 < 50$	7.0	3.5	2.5	1.0	0.5	8.0
$50 < 100$	10.0	4.5	4.0	1.5	0.7	12.0
$100 < 1000$	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

[a]Even harmonics are limited to 25% of the odd harmonic limits above.

[b]Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

[c]All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L

where

I_{sc} = maximum short-circuit current at PCC

I_L = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions

IEEE STD 519-2014

- However, the recommended multipliers in Table 5 apply regardless of the method used to reduce the harmonics that would be considered "non-characteristic harmonics" for a *p-pulse* converter as long as all "non-characteristic harmonics," including even-order harmonics, are kept below 25% of the limit values given in Table 2, Table 3, or Table 4 as appropriate.

$$\text{Multiplier} = \sqrt{\frac{p}{6}}$$

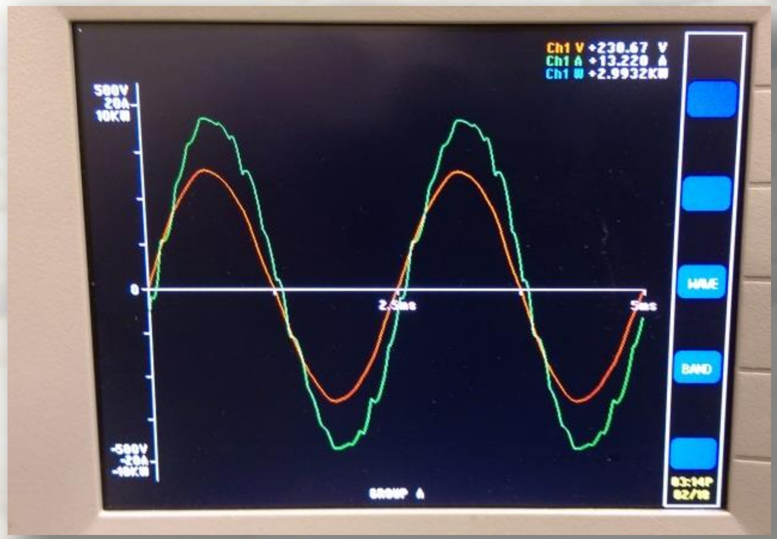
Table 5—Recommended multipliers for increases in harmonic current limits

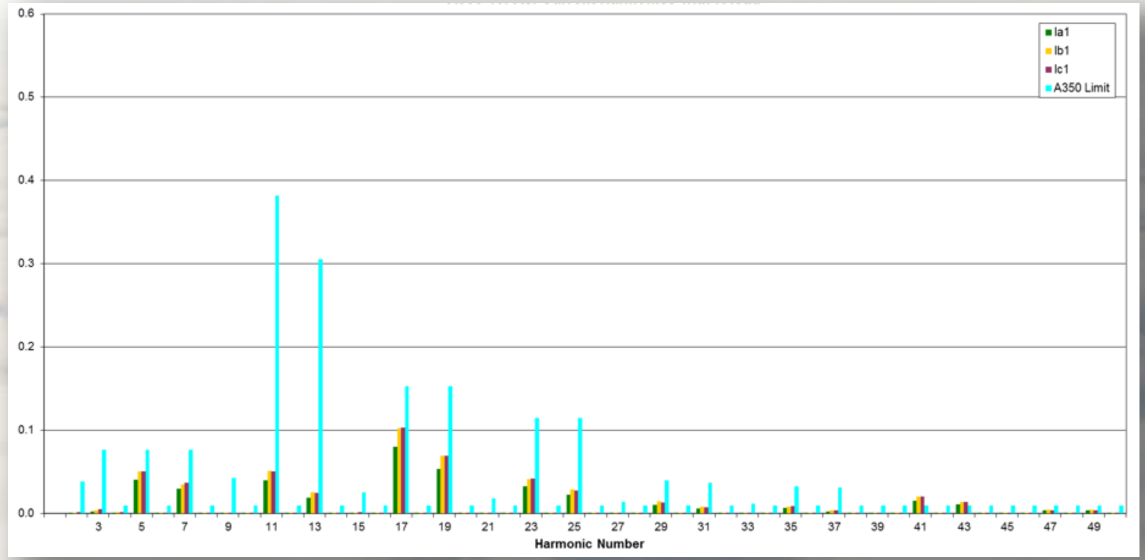
Harmonics orders limited to 25% of values given in Table 2, Table 3, and Table 4	Multiplier
5, 7	1.4 p=12
5,7,11,13	1.7 p=18
5,7,11,13,17,19	2.0 p=24
5,7,11,13,17,19,23,25	2.2 p=30
↓	↓

Non-isolated methods

For airborne applications the use of an Auto-Transformer Rectifier Unit (ATRU) is the most common for high power converters. Advantages are :

1. Very high power density
2. Rugged – very few components are required
3. Low harmonic current content when properly designed
4. Low ripple voltage without filtering
5. Good power factor (> 0.98 typically)





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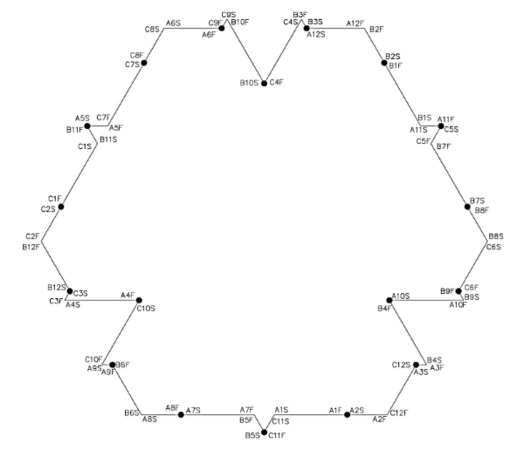
Non-isolated methods

Why not high frequency switch-mode converter?

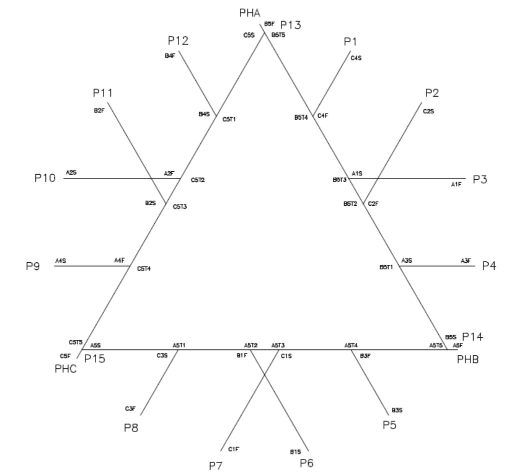
Parameter	HF Switch Mode Converter	Multiphase Converter
Design Approach	3-phase input stage (power factor correction) followed by DC-DC converter.	3-phase to multiphase transformer followed by rectifier.
Size and Weight	• Overload conditions drive size and weight. • Energy storage components (inductors and capacitors) must be oversized to support overload requirements.	• Transformer is a very robust component and has ability of supporting temporary overloads without increasing its size. • For 400 Hz applications the size/weight of multiphase converter (with overload capabilities) is up to 40% lower than HF switch mode converter.
Efficiency	90% to 95%	96% to 98%
Output Voltage Regulation	Excellent (within a few volts) – due to active voltage regulation provided by DC-DC converter.	• Normally passive regulation. • Output voltage follows input voltage variations (stays within DO-160 or MIL-STD-704 limits). • Tighter regulation possible with implementation of additional voltage regulator – about 1% on efficiency impact.
Reliability	Low – due to high amount of components.	High – due to simplicity and low total components count.
Cost	High	Generally lower than HF switch mode converter due to lower total components cost and simpler construction.

Non-isolated methods

Even though DO-160 allows fairly high levels at the 11th and 13th harmonic (the characteristic harmonics for a 12-pulse rectifier) it can be difficult to comply with the requirements at the 5th and 7th harmonic using a 12-pulse system without adding additional filtering. For this reason 18-pulse systems are most common. Two basic circuits are used – one using -20/0/+20 deg. phasing in the autotransformer and Interphase Transformers (IPTs) and the other using -40/0/+40 deg. phasing and no IPT. In the first the auto-transformer is smaller physically (smaller phase shift equates to smaller relative kVA size) but has the additional magnetic components. In the second, the transformer is larger (higher equivalent kVA) but the IPTs are eliminated. Both of these are very efficient in the conversion of 115 Vrms L-N power to 270 VDC and 230 Vrms L-N power to 540 VDC

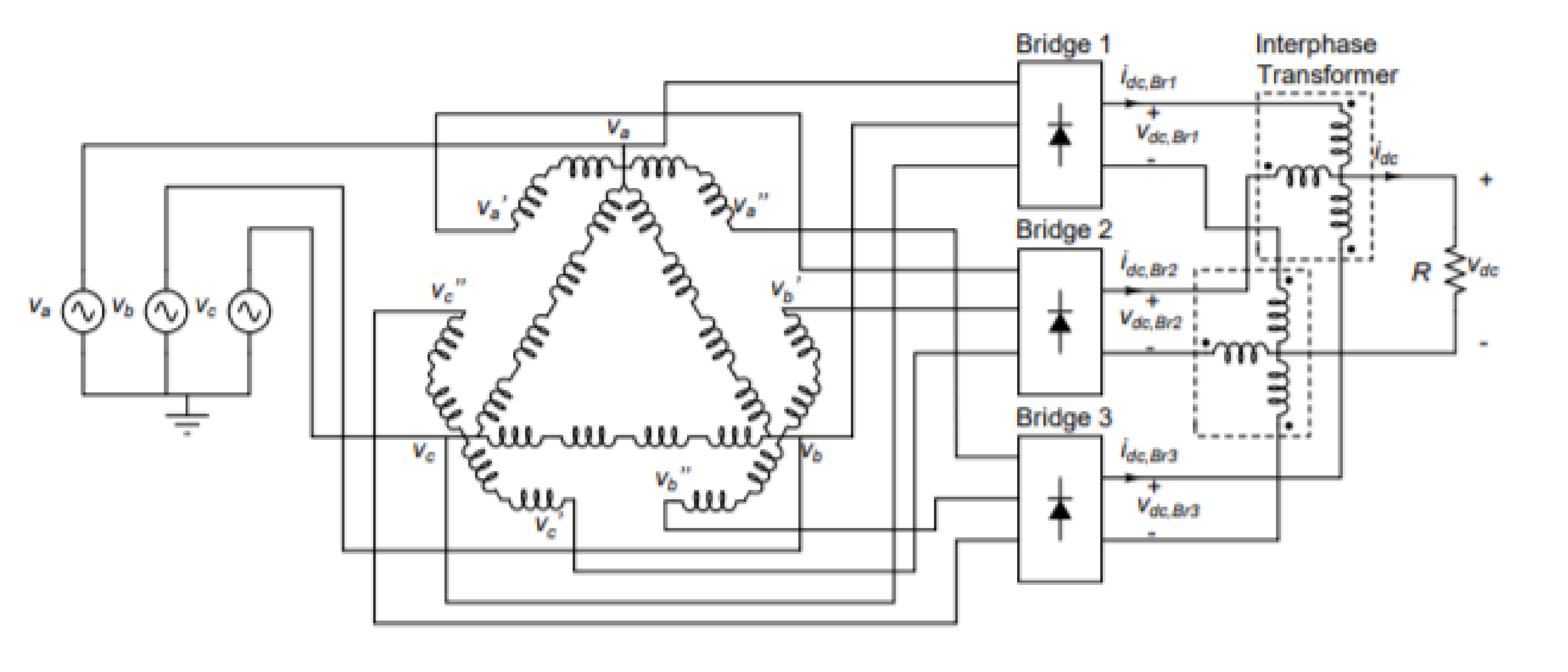


For applications requiring greater harmonic attenuation or where step-up or step-down is required a 30-pulse transformer configured such as that shown can be used.



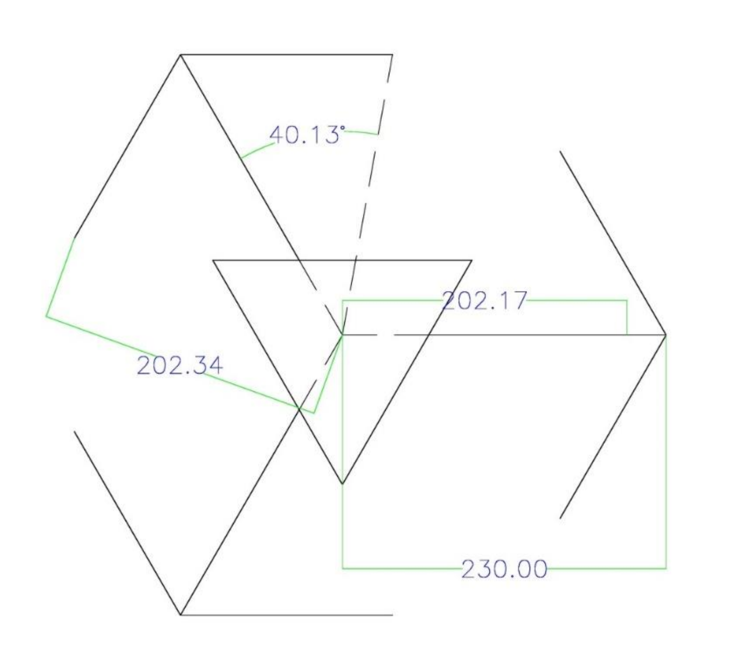
Non-isolated methods

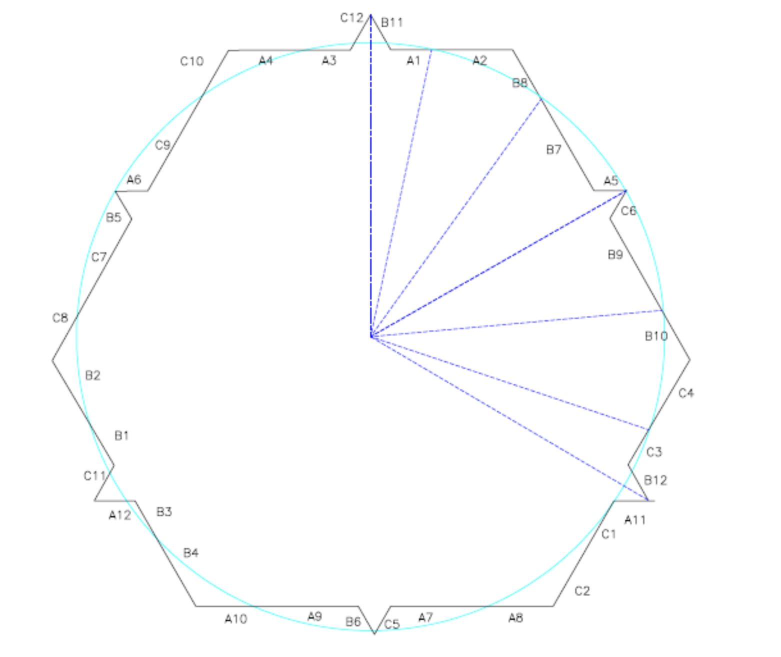
The interphase transformers allow the 3 three-phase full wave bridge rectifiers to operate independent of the others – commutation in one bridge is isolated so that each bridge works separate from the others. Many different transformer configurations are available to use – inclusion of a delta connection in the transformer is helpful in eliminating odd-triplen (3rd, 9th, 15th etc.) harmonics



Non-isolated methods

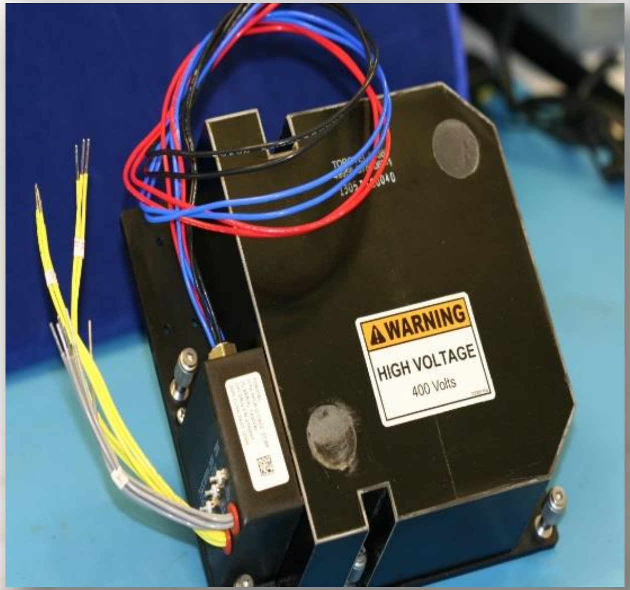
With the +/- 40 deg. 18-pulse and the 24 deg. 30-pulse auto-transformers the diode commutation is unlike that of a three-phase full wave bridge. Due to this the DC output voltage is higher and means must be taken to step-down the voltage to the rectifiers if 115 Vrms to 270 VDC or 230 Vrms to 540 VDC is required. For 400 Hz operation harmonic performance is compliant with a well-designed transformer. At wild frequency input (360-800 Hz) additional filtering is typically required for compliance



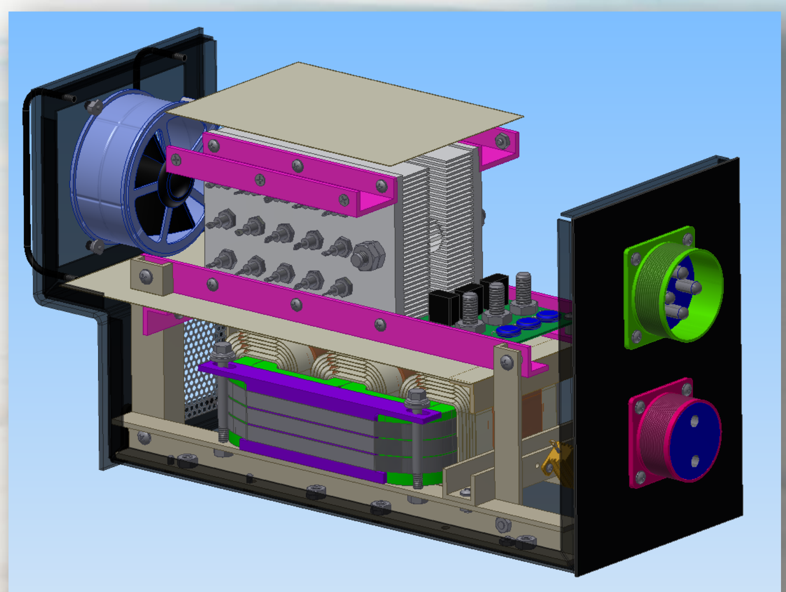


Non-isolated methods

ATRU examples



12 kW, 400 VDC output

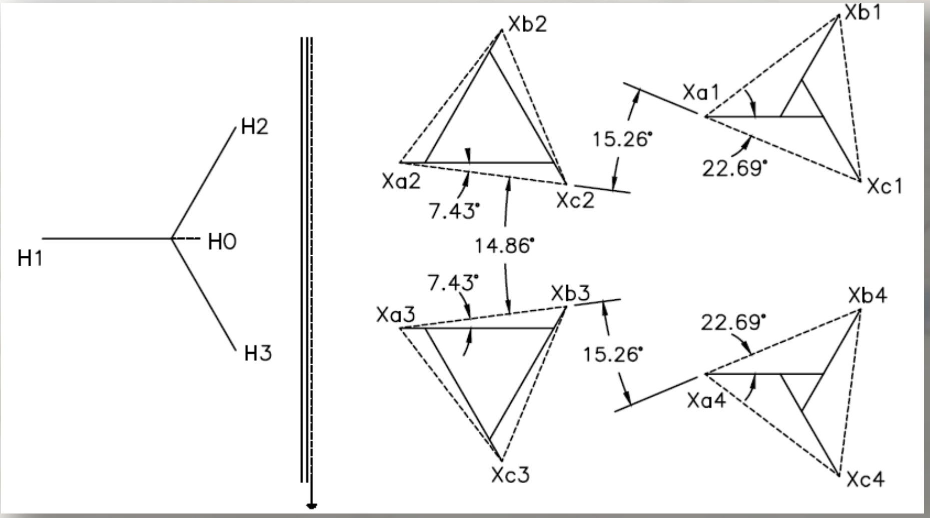


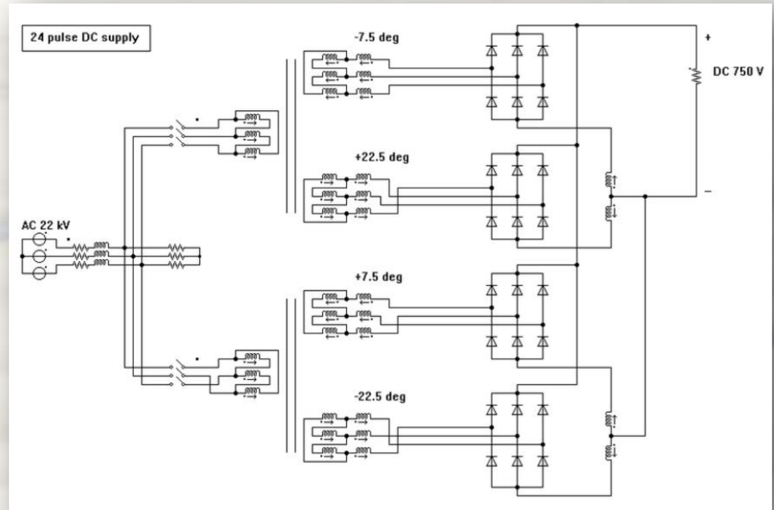
30 kW, 30 pulse

20 deg. assembly with IPTs and line reactor

Isolated methods

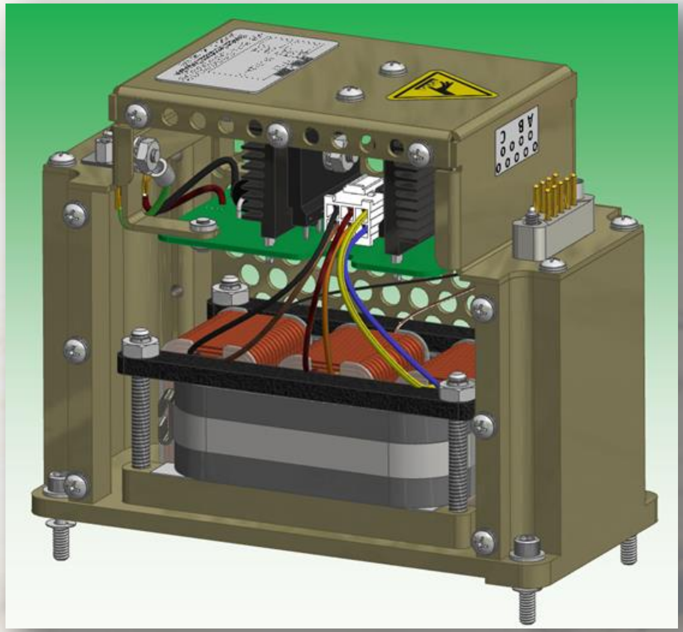
Where galvanic isolation between the source and load is required the ATRU is not available. In this case an isolated 12-pulse or 24-pulse system is used. 18-pulse can be designed, but for many applications (particularly for MIL-STD-1399 or MIL-STD-461 compliance, where 3% at any harmonic is required)24-pulse rectifier is needed. There are many ways this can be accomplished using delta/wye, zig-zag or extended delta windings, depending on detailed requirements. For very high power (megawatt+) this is best implemented using 2 transformers as all windings can be identical, just connected differently .This assures optimum impedance balance, improving power quality



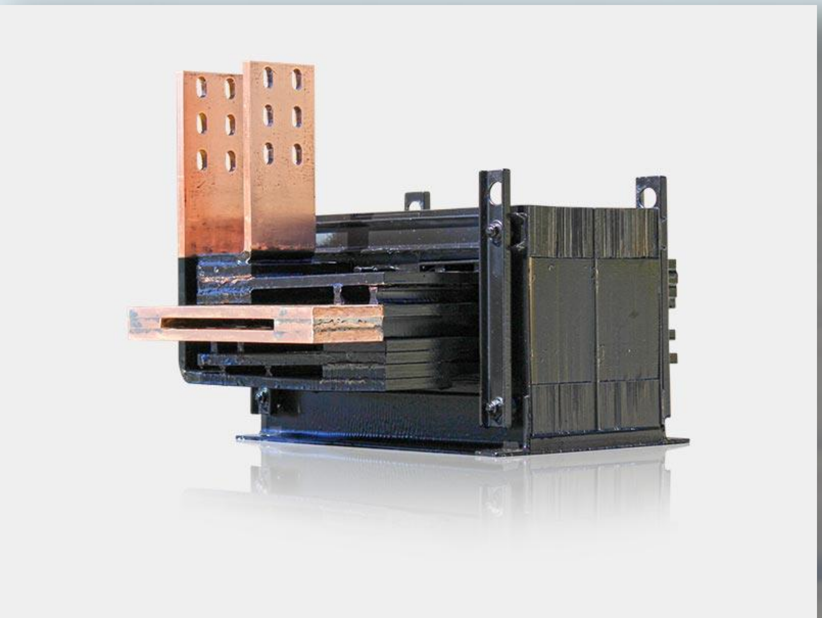


Isolated methods

Examples



Airborne 28 VDC 12-pulse



6 kA Interphase Transformer

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