

Hernan Escarria, Transformer Day – Santo Domingo, July 2011

ABB Special Transformers Variable Speed Drive Applications

ABB Special Transformers (PG SPT) Allocation Map



ABB Special Transformers (PG SPT) Factories for VSD transformers



Vaasa, Lead Center

- Marketing & Sales
- Market Intelligence
- Engineering
- R&D
- Production
- All VSD



Zhongshan

- Marketing & Sales
- Engineering
- Production
- all VSD (excl. ACS5000)



Pereira

- Marketing & Sales
- Engineering
- Production
- up 10MVA (excl. ACS5000)



South Boston

- Marketing & Sales
- Engineering
- Production
- LV VSD, ACS 1000



Shanghai

- Production
- LV VSD, ACS 1000

ABB Pereira, Colombia

Special Transformer Manufacturer in SAM Region



- SPT Focused Factory for LAM region
- Strategic geographical location
- Full current ABB Technologies implemented
- More than 40 years of experience in transformers
- Manufacturing culture based on operational excellence.
- World class test failure rate.

Railway track side transformers



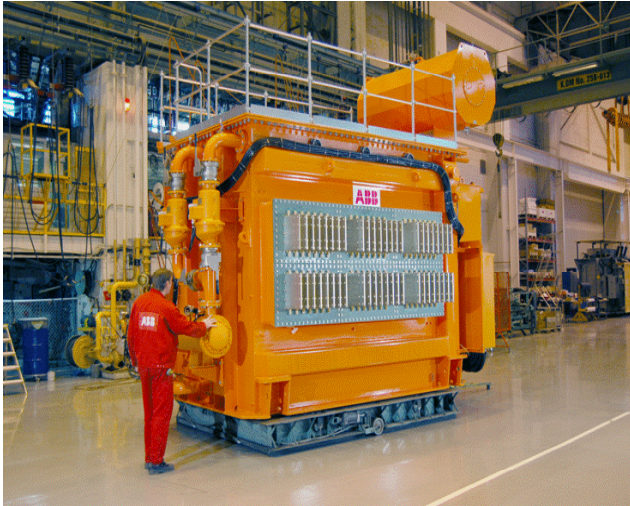
Railway transformers

- Autotransformers
- Booster Transformers
- Rectifier Transformers
- Feeder Transformer

Customers

- EPC's, Railway companies

Furnace and Rectifier transformers



Furnace and Rectifiers transformers

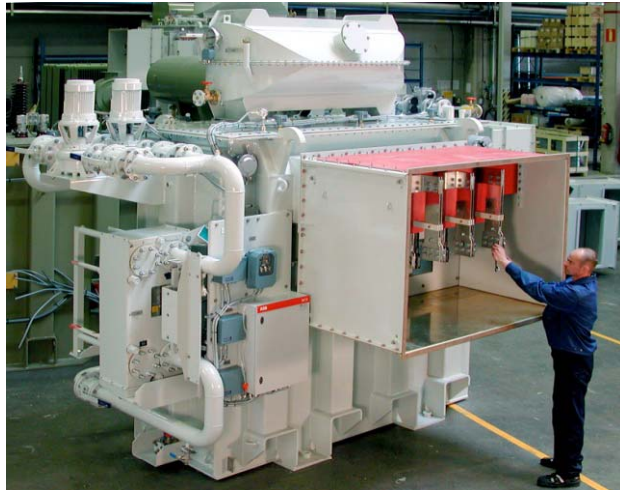
- Transformers for Arc Furnaces
- Transformers for Medium and High Current Rectifiers
- New installations or replacements

Customers

- Chemical and Metal Industry



Marine transformers



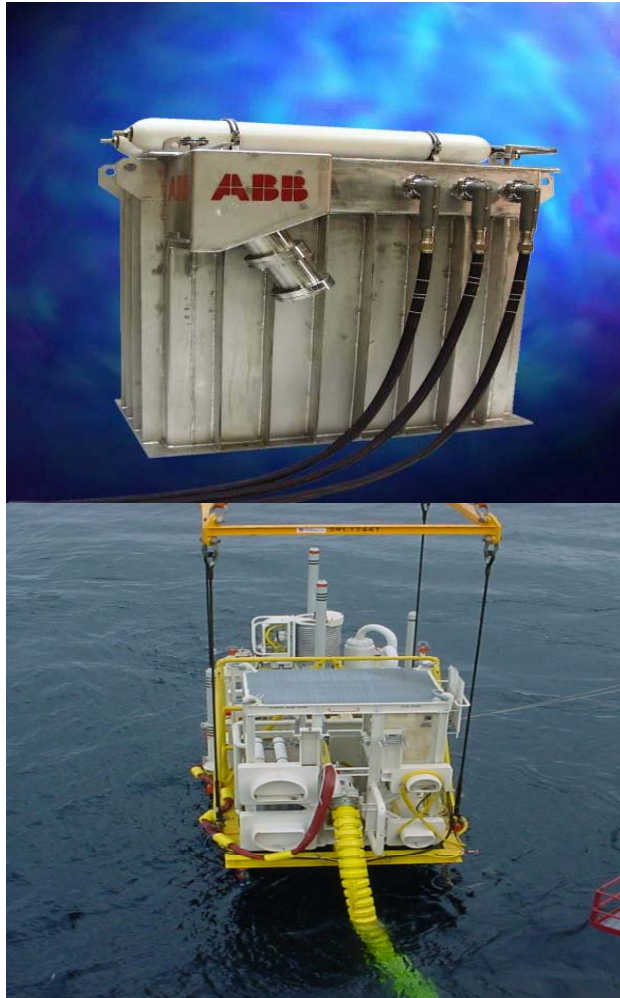
Oil type transformers for Marine

- Propulsion Transformers
- Hotel Transformers
- Magnetising Transformers
- Environmental friendly applications, Midel

Customers

- Marine Industry

Offshore transformers



Offshore transformers

- Subsea Transformers
- Converter Transformers
- OLTC Feeder Transformers
- Converter Step Up Transformers

Customers

- Oil & Gas producers on offshore platforms, gas fields, FPSO vessels and movable units

VSD transformers



VSD transformers

- Supply Transformers for frequency converters
- Step-up Transformers

Customers

- Metals, Minerals and Mining Industry
- Pulp and Paper, Water & Waste Water



Reactors



Reactors

- Current limiting reactors
- Neutral earthing reactors
- Shunt reactors
- Starting reactors
- Earthing transformers

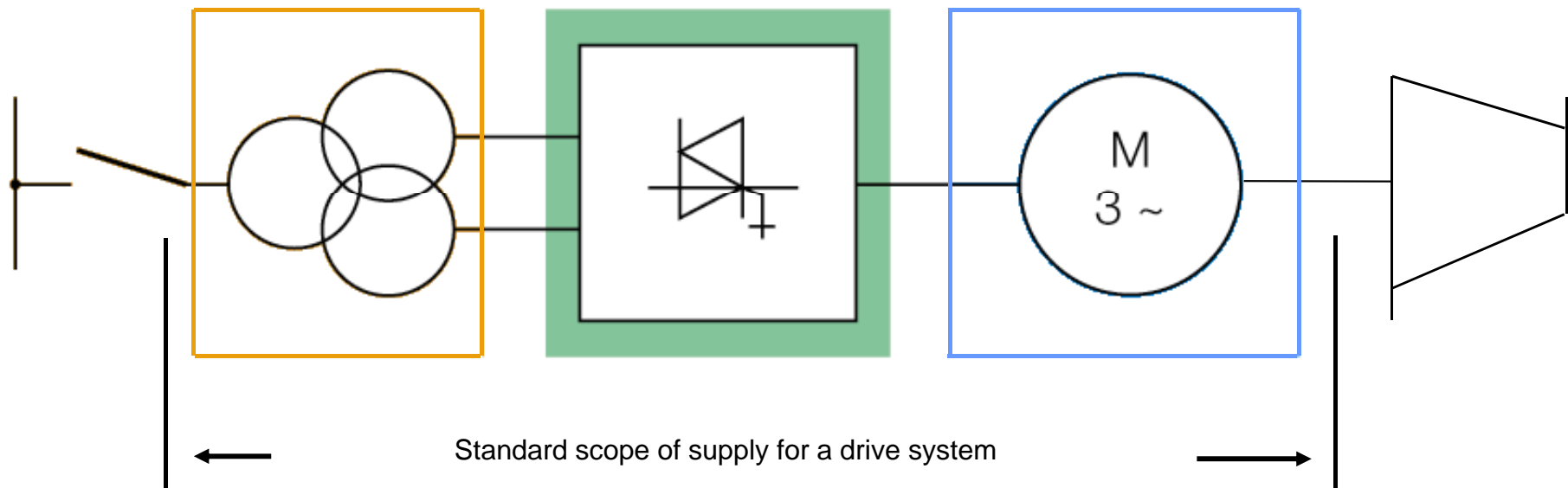
Customers

- Utilities
- Metal industry

Transformers for Variable Speed Drive Applications

What is a drive system?

- A drive system is used to control speed, torque and power of an electric motor in the most efficient way in an application
 - It consists of **transformer**, variable speed drive and motor
- **The main components need to be with matching characteristics**



Transformers for Variable Speed Drives (AC) for ...



Cement, Mining & Minerals



Chemical, Oil & Gas



Marine



Metals



Power



Pulp & Paper



Water



**Special applications,
e.g. wind tunnels**

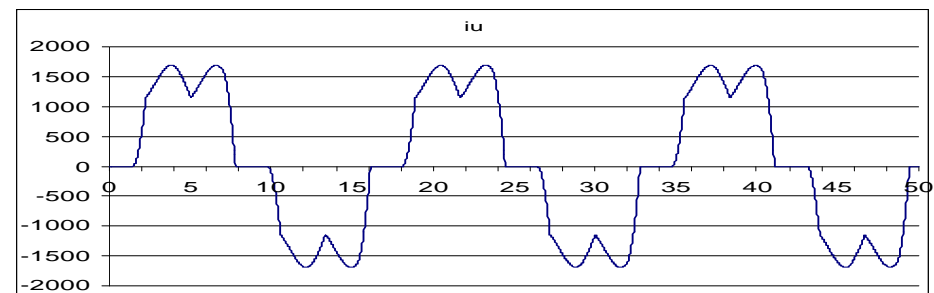
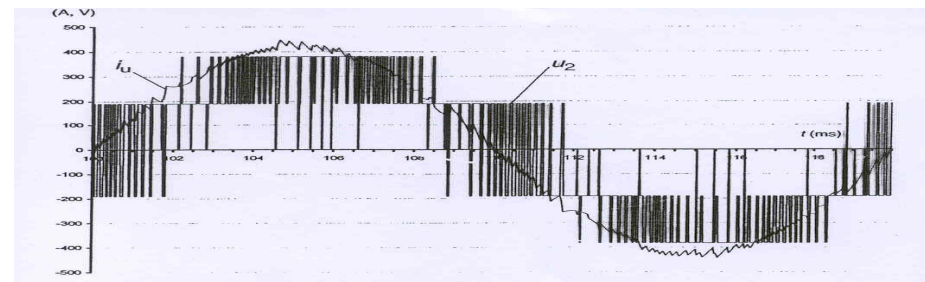
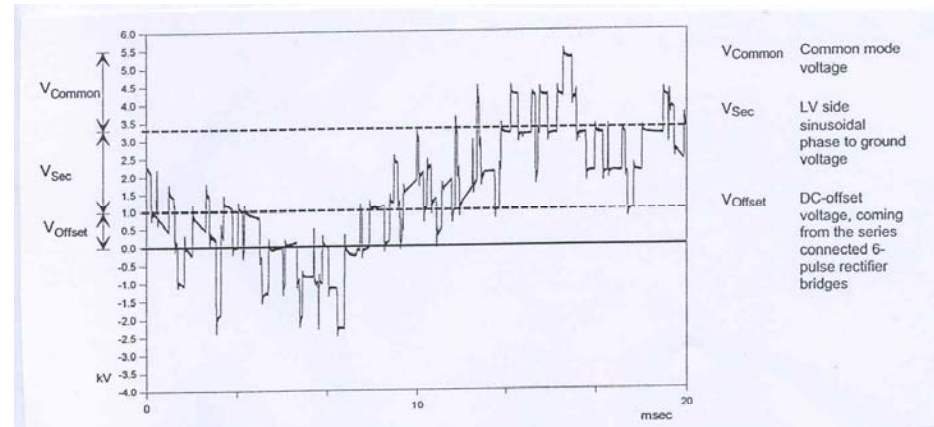
Typical Applications



- Blowers & fans
- Conveyors
- Compressors
- Crushers, rolling mills
- Extruders, mixers
- Marine propulsion
- Mine hoists
- Pumps
- Refiners
- Gas & hydro turbine starters
- Soft starters for large machines
- Test stands, wind tunnels

Standards

- IEC 61378-1 Converter transformers, Part 1 Transformers for Industrial Applications
- IEEE C57.18.10 IEEE standard Practices for Semiconductor Power Rectifier Transformers”
- IEC makes no requirements for BIL levels unlike IEEE
- We design always to cover
 - Increased electrical stress drive side
 - Common mode voltages
 - High DU/dt
 - Harmonic currents
 - EMC reduction
 - EU requirement, applied also in MEA and ASIA markets, CE labelled



Transformer ratings in IEC 61378-1

- Rated power = Fundamental kVA
 - kVA calculated with rated voltage and fundamental current component of the load current
- RMS kVA
 - kVA calculated with rated voltage and total RMS load current
- Equivalent kVA
 - kVA calculated with rated voltage and defined equivalent sinusoidal current which will give the same losses in the transformer than the actual load current when all its harmonic components are considered in relation they cause losses in the transformer
- IEEE C57.18.10 is technically close to IEC 61378-1, differences mainly in terminology
 - IEEE gives defined requirements for insulation levels (BIL-levels)

Transformer ratings in IEC 60076

- Fundamental kVA = RMS kVA = Equivalent kVA
 - = kVA calculated from rated voltage and rated sinusoidal current
 - No allowance for harmonic currents or harmonic distortion in voltage
- IEC 60076 series is standard for power (network) transformers with clean sinusoidal currents and voltages
- Rules of performing routine tests at factory are valid generally also to converter transformers, test currents and voltages are sinusoidal, with fundamental frequency only, tests with real harmonic / common mode content cannot be done at factory

Converter duty for transformers

Fundamentals

- Harmonic currents arise extra stray losses in windings, bars, core clamps and tank / enclosure
- Degree of severity depends on drive type, load type and transformer design

Dimensioning

- Calculation of equivalent current or derating factor is enough in standard VSD applications (limited power & current)
- More detailed study is necessary as power / current / harmonic content gets higher.

Converter duty for transformers

- Simplified dimensioning based on motor power:

$$S_n \geq \frac{U}{U_n} \times \frac{P_{motor_shaftpower}}{\eta_{motor} \times \eta_{output_trafo} \times \eta_{converter} \times \cos \varphi}$$

$$S_t = S_n \times K$$

- S_n = Rated power, harmonics not included, S_t = Type power (Sinusoidal equivalent power), effects of harmonics included, U/U_n = voltage tolerance, K = sinusoidal equivalent factor

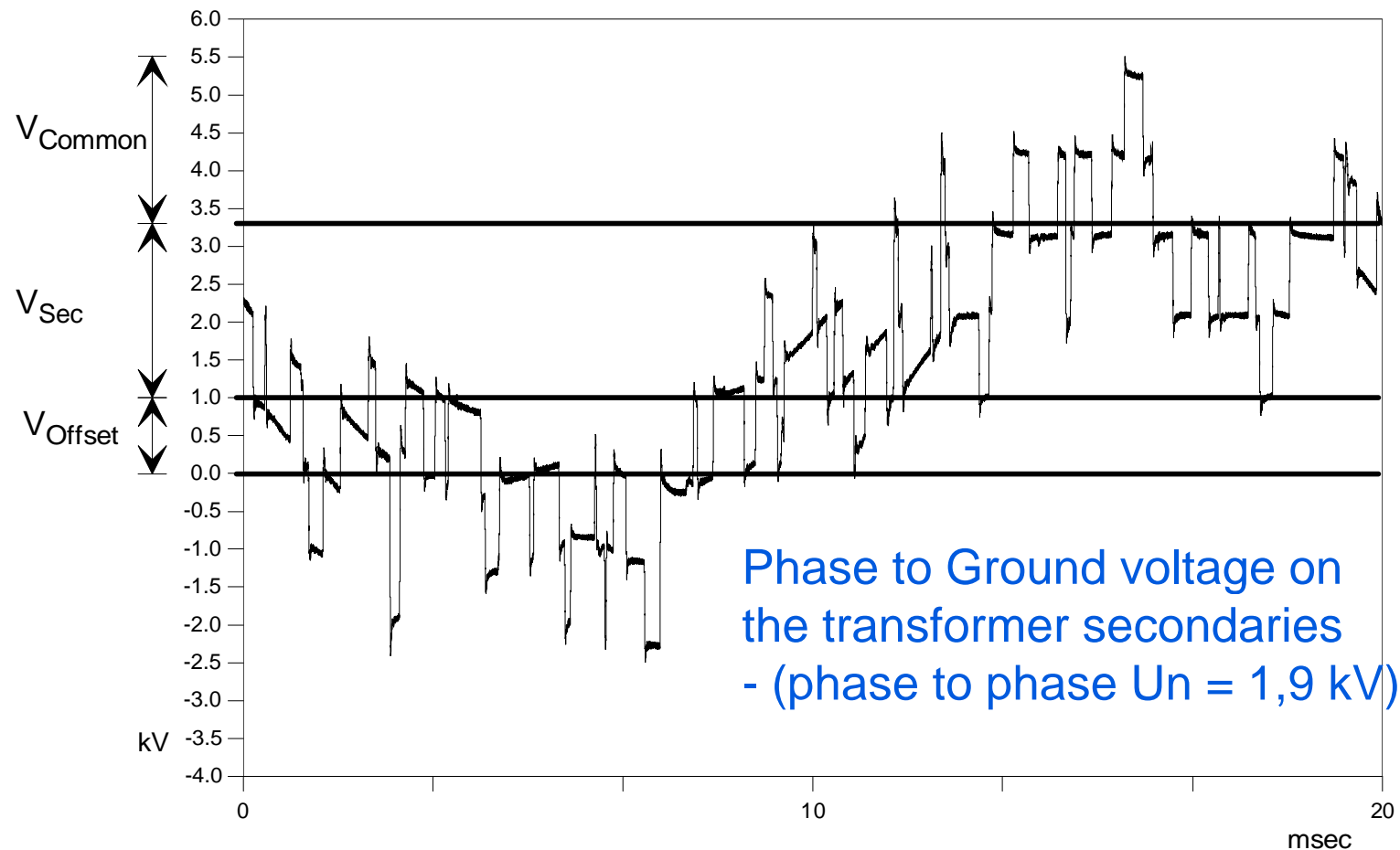
Converter duty for transformers

Temperature rise

- The temperature rise with actual load current, including harmonic loss components must be within rise limits specified
- Margin exists in temperature rise with sinusoidal current
- Winding design must be able to withstand mechanical/thermal stresses due to more uneven temperature distribution than with sinusoidal current only ("end effect")
- Temperature rise test can be done with equivalent power or with more detailed calculation based on IEC 61378

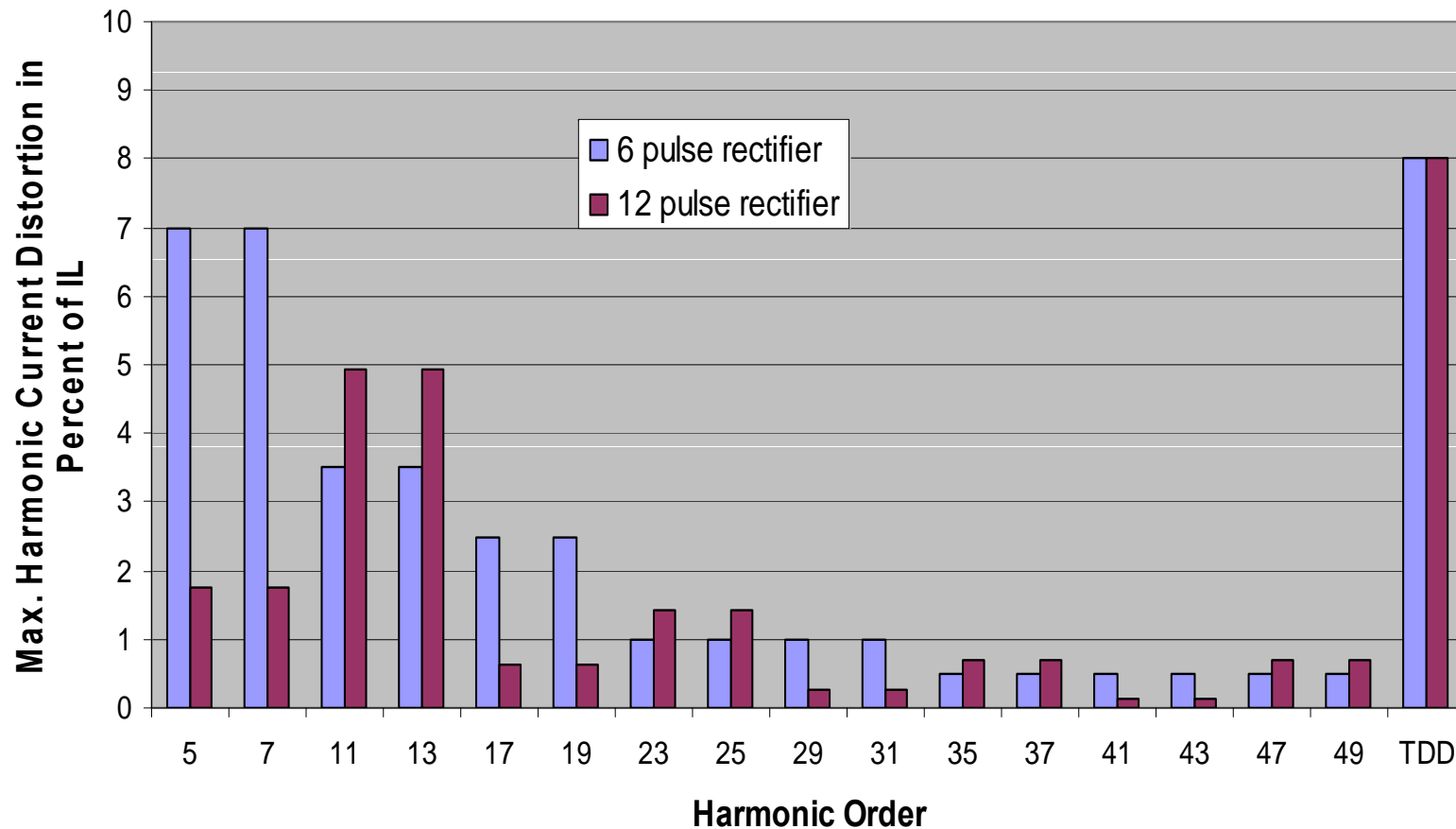
Common mode voltage /Input transformer specification

- Common mode voltages result from inverter switching operation and appear through capacitive coupling at the transformer LV windings against ground (also called zero sequence component).
- These common mode voltages increase the voltage stress of the transformer insulation and must be considered in the transformer design (insulation level to be increased compared to IEC 60076 requirements)



How to apply IEEE519 - harmonic distortion limits

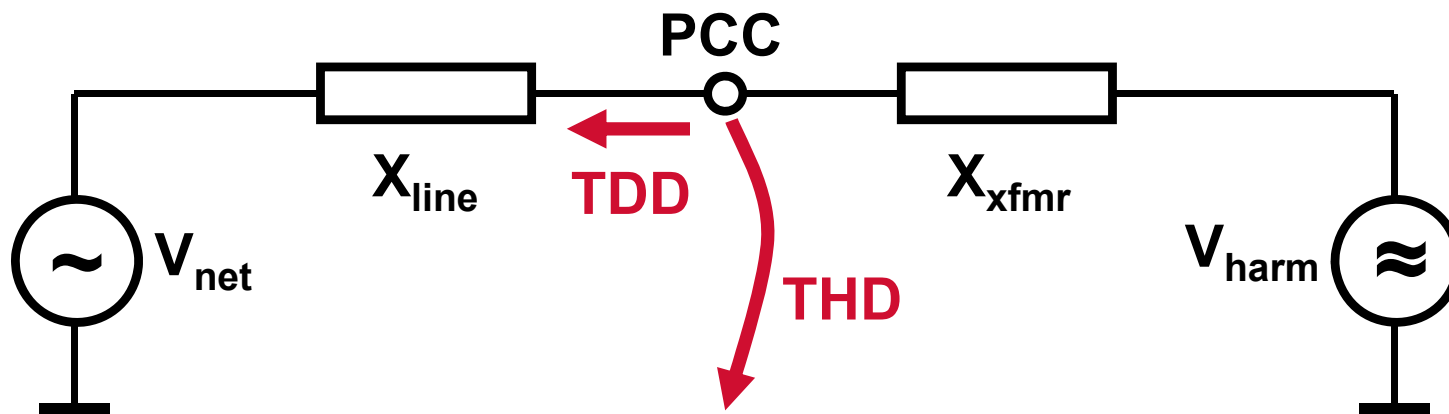
- Comparison: Current Distortion Limits 6-p versus 12p
Example for I_{sc}/I_L : $20 < 50$



Effects of system parameters on harmonics

Simplified Equivalent Circuit Diagram for Line Harmonics

- V_{net} Mains supply voltage source (infinitely strong)
- V_{harm} Harmonic voltage source (generated by the drive)
- X_{line} Line impedance (representing the fault level of the network - mainly inductive)
- X_{xfmr} Transformer impedance (value with only one secondary winding shorted)



Converter Transformers / Definition & Why

- **Why converter transformers are needed (main issues)**
- Adapts the network supply voltage to the converter input voltage
- Isolates the converter from feeding network and restricts short-circuit currents to the converter
- Relieves the motor and/or network from common mode voltages
- Reduces radio interference (EMC) from drive to the network (special screen)
- Protects the drive from voltage transients from the feeding network
- Reduces harmonics (transformer impedance and special connections for multipulse operation)



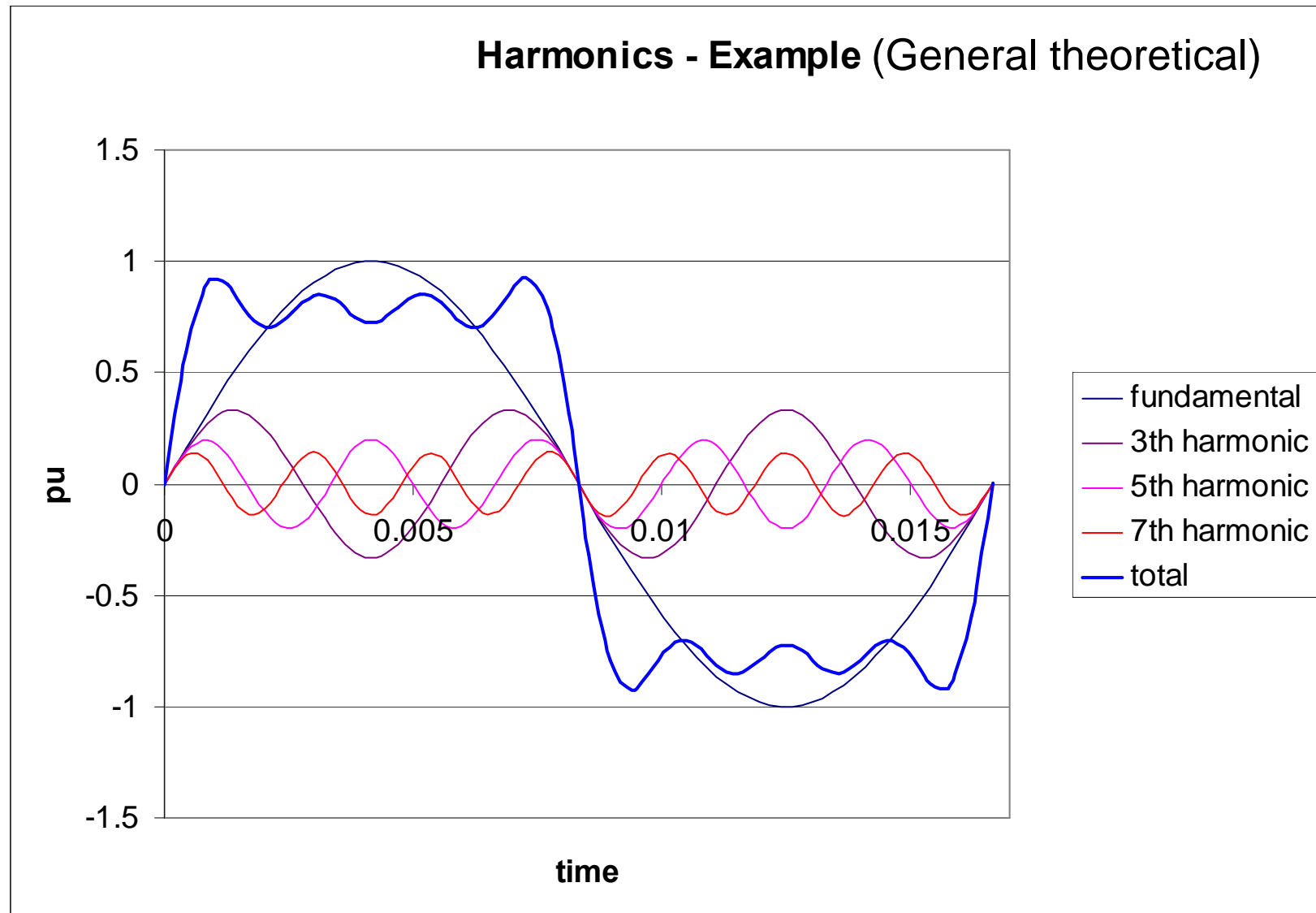
Converter duty for transformers / Harmonics

- Reducing line harmonics with transformer connections
- As the power increases the network harmonics come more critical
- Harmonics on the line side: $n \times p \pm 1$ ($n=1,2,3\dots$), p =pulse number
- The order of characteristic harmonics (h) in relation to the rectifier pulse number (n):
 $h = k \times n \pm 1$
 - k is any integer,
 - a 6 pulse rectifier produces $6-1=5$ th, $6+1=7$ th, $12-1=11$ th and $12+1=13$ th harmonic currents (in ideal case)
 - a 12 pulse rectifier produces $12-1=11$ th, $12+1=13$ th, $24-1=23$ rd and $24+1=25$ th harmonic currents (in ideal case)
- Pulse number can be increased by applying multiple 6 pulse groups with phase shifted supply voltages
- 30 degrees phase shift can be obtained by using basic connection groups on the transformer (Y and D)
- Phase shifts other than 0° , 30° (or multiple) require a special phase shift winding. Most common are Z and “extended delta” connection

Converter duty for transformers / Connections

Pulse number	No of 6 pulse groups	Phase shift between groups	Transformer connection
6	1	-	Yy0
12	2	30° (60 minutes)	Dy11d0
18	3	20° (40 minutes)	IIIz11:20 IIIz0:40 Yy0
24	4	15° (30 minutes)	Dy10:45d11:45 Dd0:15y11:15
30	5	12° (24 minutes)	Special
36	6	10° (20 minutes)	Yd11d11:20d11:40 y0d0:20d0:40
42	7	8.57° (17 minutes)	Special
48	8	7.5° (15 minutes)	Zy11:45d10:45 Zy0:15d11:15 Zy11:30d10:30 Zy0d11

Harmonics - Visualisation



Effect of Harmonics / Fundamentals

- Harmonic currents arise extra stray losses in windings, bars, core clamps and tank / enclosure which may lead to thermal problems including premature aging
- Degree of severity depends on drive type, load and transformer design
- In oil transformers the oil equalizes the temperature difference winding to oil rise (gradient) is ca 20% of the total rise
- Winding design must be able to withstand mechanical/thermal stresses due to more uneven temperature distribution than with sinusoidal current only ("end effect")
- Local hot spots must be avoided and each physical winding may need to have separately analysed but otherwise it is not very much different where the additional losses arise, windings, bars or tank, all increase the oil rise
- The temperature rise with harmonic loss components must be within rise limits specified for the actual load current
- Margin in the design temperature rise with sinusoidal current
- Temperature rise test to is be done with the **equivalent kVA** power

Effect of Harmonics / Fundamentals

Table 11—Theoretical harmonic currents present in input current to a typical static power rectifier in PU of the fundamental current

It is the specifying engineer's responsibility to specify the harmonic content of the load current for which the transformer should be designed. However, if the actual harmonic spectrum is not known, Table 11 may be used with the full knowledge and consent of the user.

Harmonic order	Converter pulses for individual windings				
	3	6	12	18	24
2	0.500				
4	0.250				
5	0.200	0.200			
7	0.143	0.143			
8	0.125				
10	0.100				
11	0.091	0.091	0.091		
13	0.077	0.077	0.077		
14	0.072				
16	0.063				
17	0.059	0.059		0.059	
19	0.053	0.053		0.053	
20	0.050				
22	0.046				
23	0.043	0.043	0.043		0.043
25	0.040	0.040	0.040		0.040

Effect of Harmonics / Fundamentals

Secondary winding		q = 6							
h	fh(pu)	lh(pu)rms	fh ²	fh ² *h ²	lh(pu) ²	lh ² *h ²	lh*h ²		
1	1.000	0.960	1.000	1.000	0.922	0.922	0.922		
2	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
4	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
5	0.200	0.192	0.040	1.000	0.037	0.922	0.184		
7	0.143	0.137	0.020	1.000	0.019	0.922	0.132		
8	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
10	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
11	0.091	0.087	0.008	1.000	0.008	0.922	0.084		
13	0.077	0.074	0.006	1.000	0.005	0.922	0.071		
14	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
16	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
17	0.059	0.056	0.003	1.000	0.003	0.922	0.054		
19	0.053	0.051	0.003	1.000	0.003	0.922	0.049		
20	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
22	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
23	0.043	0.042	0.002	1.000	0.002	0.922	0.040		
25	0.040	0.038	0.002	1.000	0.001	0.922	0.037		
29	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
31	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
35	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
37	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
41	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
43	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
47	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
49	0.000	0.000	0.000	0.000	0.000	0.000	0.000		
			1.041	9.000	1.000	8.300	1.573		
					0.078				

Effect of Harmonics / Fundamentals

HV (Primary)		LV (Secondary)	
Eddy Loss multiplier	8.300	Eddy Loss multiplier	8.300
Stray loss multiplier	1.573	Stray loss multiplier	1.573
		0.077754887	
		TDD	27.9%

	LV Losses				HV Losses			Total Loss
	I2R	Eddy	Stray		I2R	Eddy	Stray	
Power TX designed	22605	3.5		30898	3.3	4780	60094	
Rectifier	22605	<u>791.175</u> 6567	0	30898	<u>1019.634</u> 8463	7519	76052	
New Power	60093.81	/	76052	=	0.790166976			
Power TX designed		12650kVA		Power Required		10000		
Max Power appl		9996kVA		Power new design		12656		

DISEÑO BASE OK

Effect of Harmonics / Thermal Modeling

KTRP 36 NC 32600 1 - 23, new ; 3: 1 - 2 & 3 - / 6: 2- 3 via 1 -

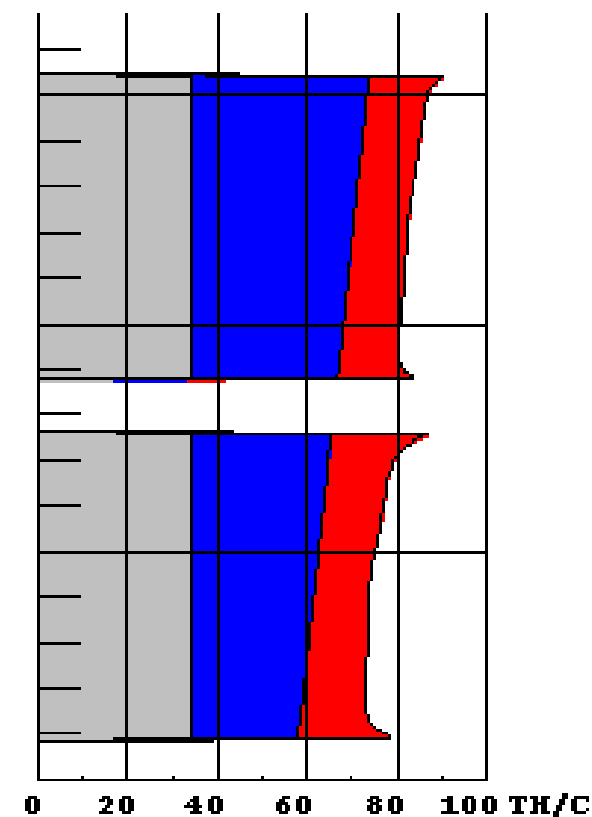
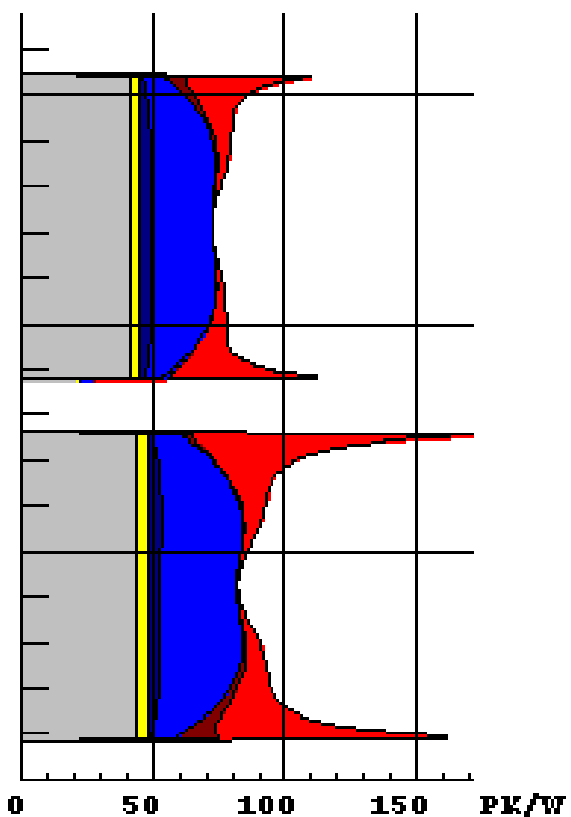
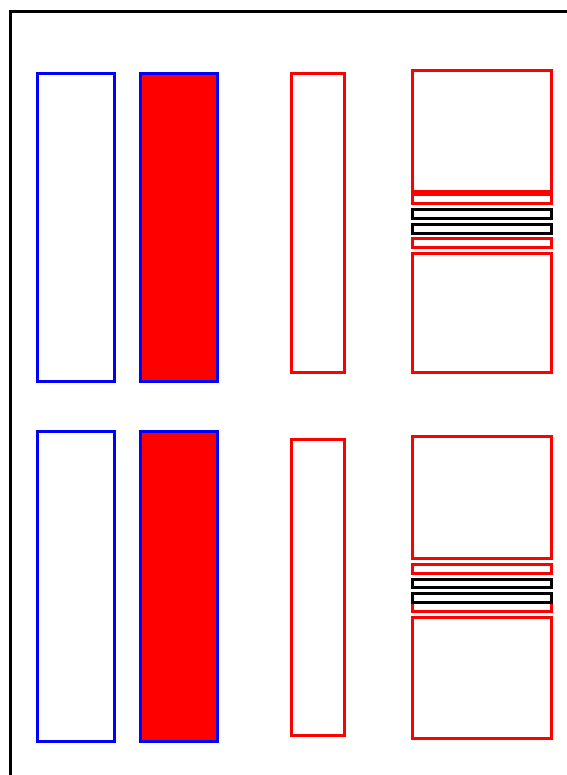
LOSS / DISC, TRN

TEMPERATURES

PK-RR-fun
 PK-RX-fun
 PK-DC-fun

PK-RR-har
 PK-RX-har
 PK-DC-har

TH-winding / C
 TH-oil / C
 TH-ambient / C



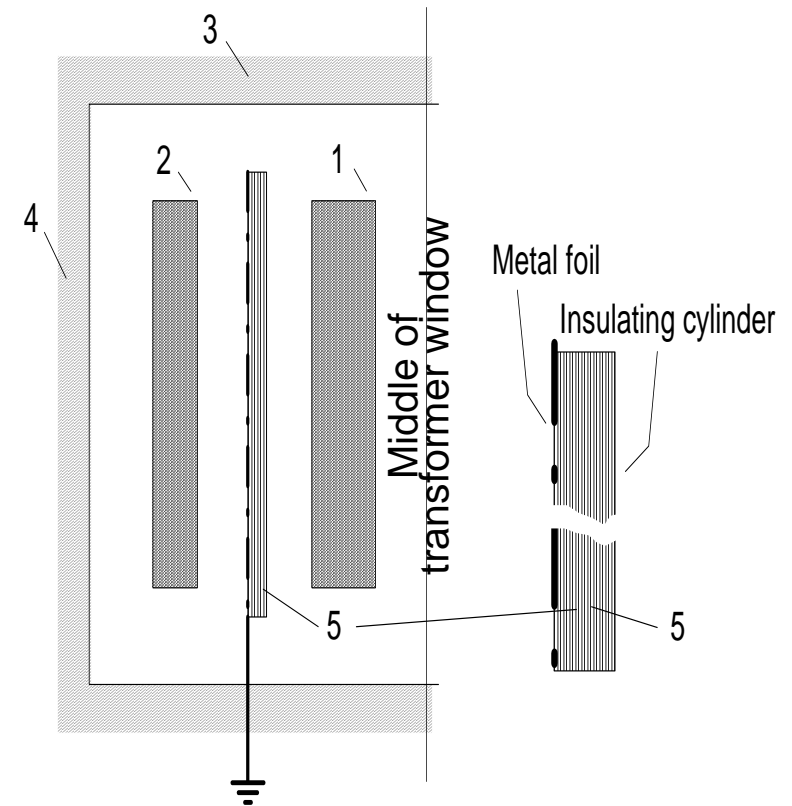
Increased mechanical stress

- High di/dt due to the diode bridge current waveshape is causing mechanical forces that are not present with normal smooth sinusoidal load (ie. so called "hammering effect")
- Typically the drives are protected with fire-through-function ie. making full short circuit purposely to the transformer in order to make HV breaker to trip fast. The VSD transformers are facing considerably more short-circuits during their life time than normal utility duty transformers
- Some variable speed drive applications are having very cyclic loads with continuous rapid changes from few % to 100% loads (ie. for an instance typically rolling mills)



EMC screen

- EU has set limits for radio frequency (RF) pollution of power supply system at point of power drive system connection (including transformer) EN 61800
- Same regulation is applied increasingly also outside Europe
- Drive systems generally do not fulfill requirement without filtering or screening
- Industry requires system to be EMC compliant (CE labelling) anywhere although EU requirement is valid only at point of connection to public network or at 10 m distance from the border fence
- Correctly designed electrostatic screen is a cost efficient way of fulfilling the requirement for drive-transformer package
- Electrostatic screen is also protecting the drive against common mode voltage stress from supply system (lightning and switching)



Hint: This is the general description of screen in transformer specification, but making functional screen is not so simple

Static screen issues

- At ratings above some MVA with typical harmonic currents, losses at screen are important, design must be correct to allow for cooling
- With transformers feeding VSD having high switching frequency on input side (active front end), losses at screen can be dramatic
- Wrong type of earthing leads from screen can make the screen not functional



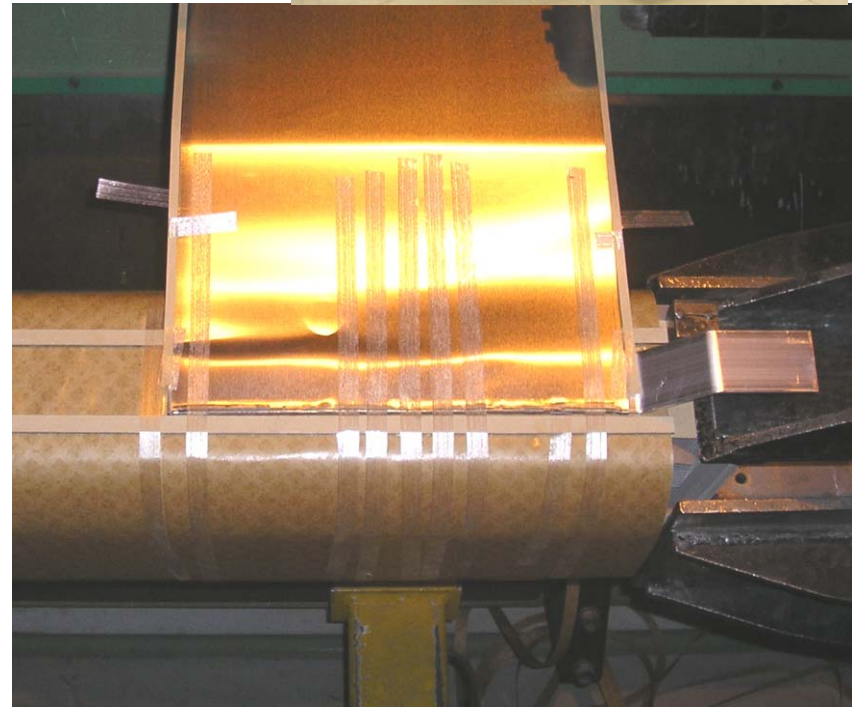
Hint: This is view of locally made low cost VSD transformers screen in Far East after few successful weeks of operation with 25 % load with active front end , switching frequency 2-3 kHz

Liquid insulated transformers IEC 60076

- Insulation liquids O,K, L
 - Mineral oil O is standard for industrial installations, but out of question (low fire point and high combustion energy) on ships and offshore
 - Less flammable liquids class K, fire point >300 C, are applied when low fire risk is required
 - synthetic esters (bio-degradeable non-toxic) IEC 61099, (Midel 7131)
 - silicone oils (non-toxic, stable) IEC 60836, (DC 561, TR50)
 - Non flammable liquids class L not existing today
- Liquid transformers are quite new application area for ships and FPSO
 - Increasing power of propulsion drives created need for compact solutions-liquid transformers up to 20 -30 MVA feasible as one unit
 - Water cooling easy to apply
 - Low height , can be fitted on one deck height
 - Cost benefits
- Liquid transformers dominant for drive applications on off-shore platforms and rigs with harsh environmental conditions, so not new technology
- Installation of liquid transformers possible at explosion hazard Zone 1 and Zone 2 with simple measures.

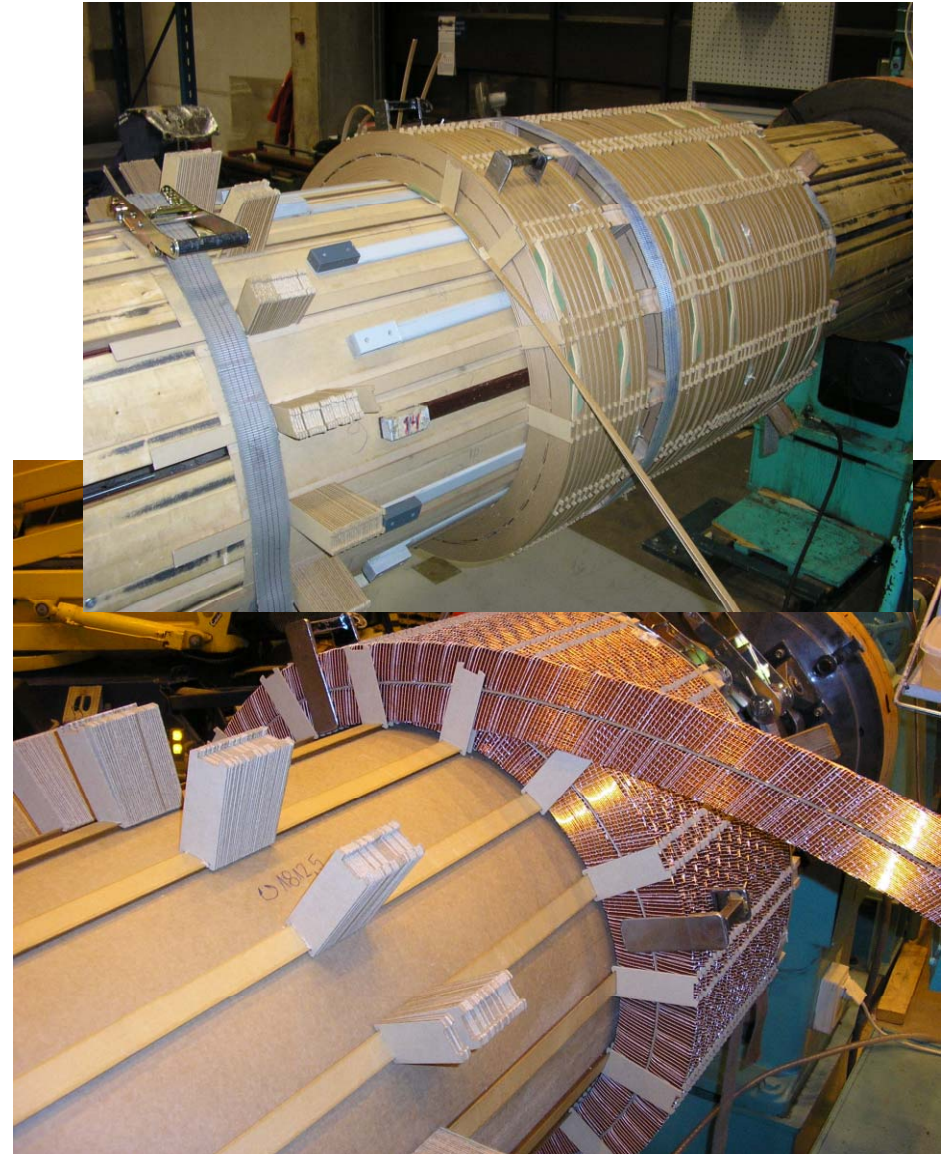
Winding types- foil-layer

- Small transformers
 - Layer HV windings
 - Foil LV windings
- Foil winding is easy to make and economic
 - Can applied to 6 pulse transformers
 - **cannot** be applied to all 12- pulse converter transformers, only at lower power ratings
 - Copper or aluminium
- Vaasa makes selection based on reliability, not only based on lowest cost
- Some customers have bad field experience in the past and do not accept foil



Winding types- helical-disc-CTC

- At higher ratings most common winding types are
 - HV continuous disc
 - With paper insulated strands or CTC depending on current
 - LV winding helical
 - With paper insulated strands or CTC depending on current
- CTC consist of enamel insulated strands continuously transposed between each other
- Use of CTC minimizes harmonic losses in windings, (but has nothing to do with losses eg in tank wall or busbars)



Cores

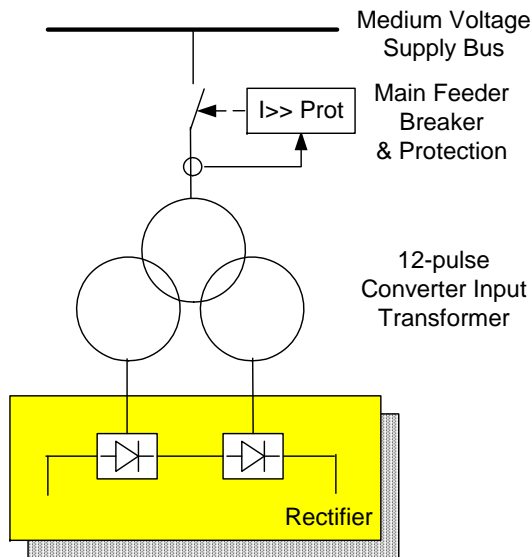
- Small transformers cores have 2 steps
- Large transformers round cores with many steps
- Hi-B material from Japan
- Special core joints made for converter transformers to avoid DC saturation
 - Distributed gaps
 - Air gaps
- Heavy duty mechanical clamping
- Semi automated manufacturing



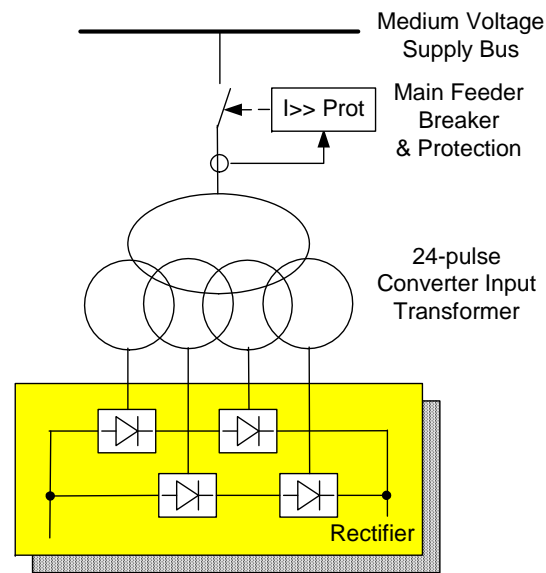
Summary & Conclusions

- **Modern AC converter drives need transformers of special design – normal distribution transformers are not feasible**
- The above fact has been a reason why separate standards have been published by IEC and IEEE
- Without appropriate design and manufacturing the performance, reliability of the system and adequate lifetime of the transformer can not be ensured
- The special design needs to consider especially;
 - increased dielectric stress
 - thermal issues (related to harmonics etc.)
 - increased mechanical stresses
 - many cases complex internal connections with phase shifts & multiwinding designs for ensuring
- The special considerations need to be done especially for medium voltage drives and in general for drives above 1 MW
- The drive transformer manufacturer should have some general and specific knowledge about drives
- ABB has a unique position since it can offer the full scope of a drive system with its products. ABB Transformers is having a unique position since it has global common product design platforms that are making broadening of the manufacturing footprint possible (technical support and technical transfers)

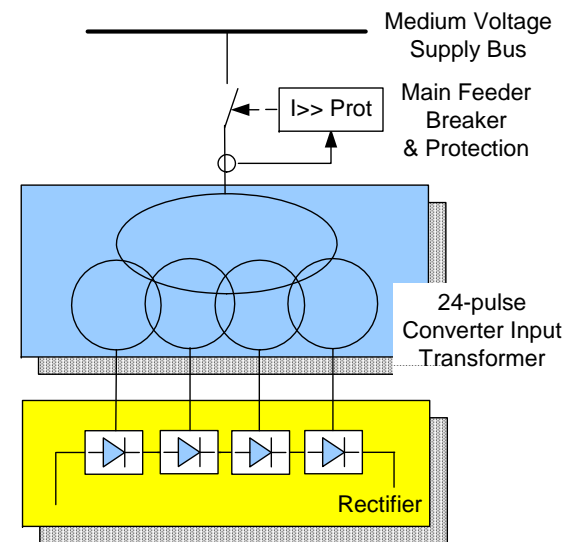
ACS 1000 – Input Transformer



12-pulse



24-pulse



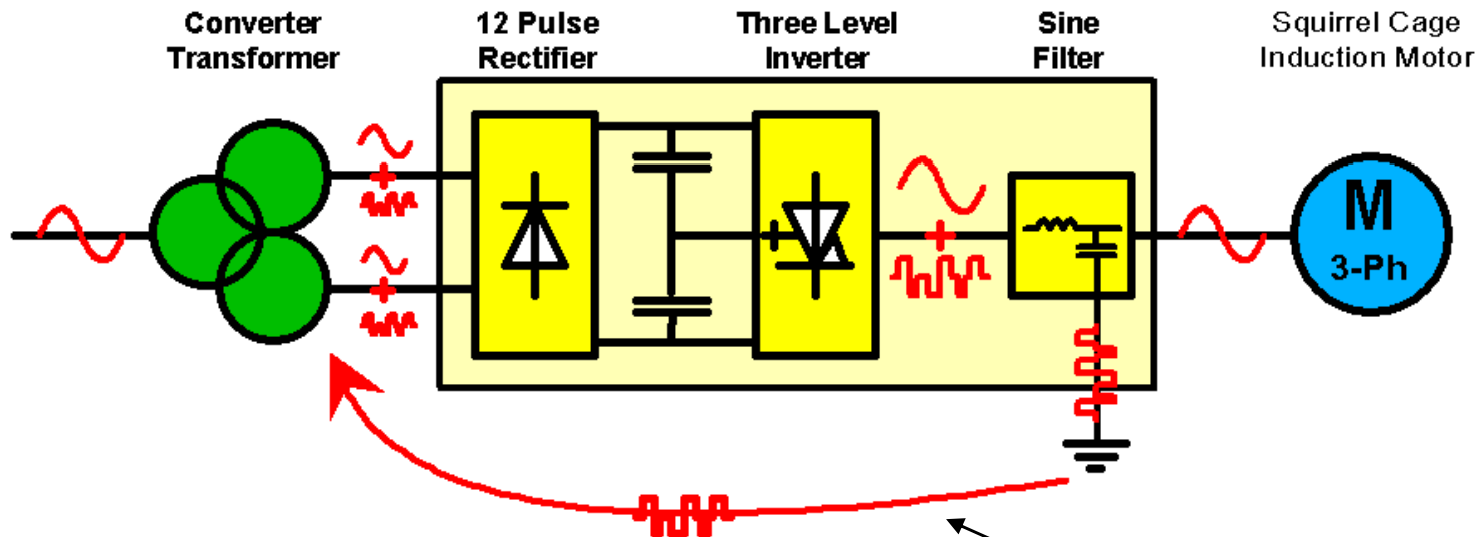
24-pulse ACS 1000i

- 12-pulse or 24-pulse topology
- Oil or dry type transformer

- ↑ Conformity to IEC 61000-2-4 and IEEE 519/1992
- ↑ Total power factor: 0.95 constant over speed range
- ↑ Transformer can be placed inside the building or outdoor

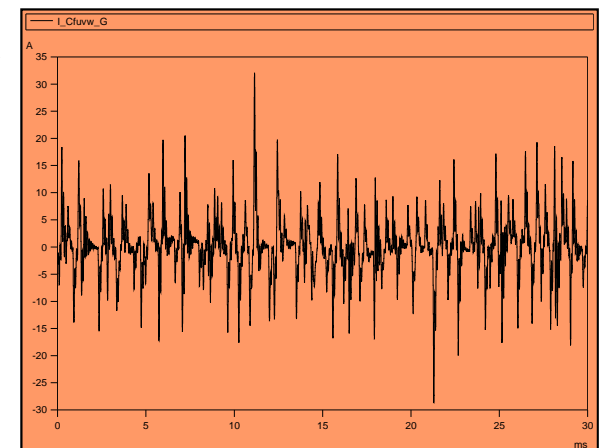
ACS 1000 – common mode voltage

- Common Modes inside the Drive System



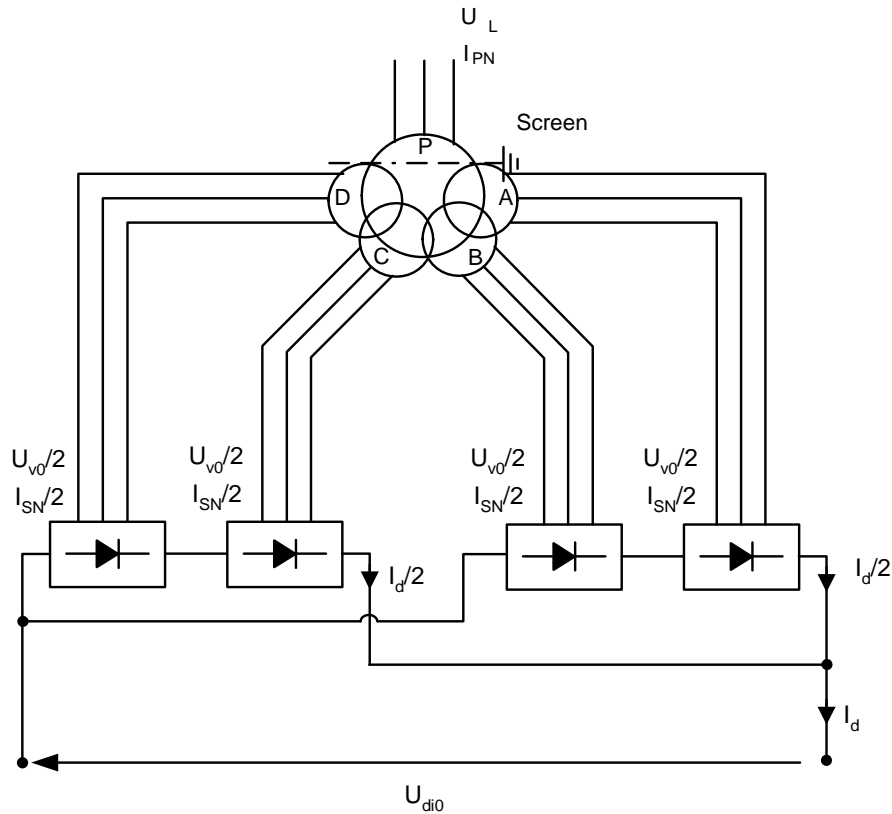
Common Modes are produced from every inverter, independent which topology is used and which manufacturer is considered.

In ACS 1000 they are directed back to the transformer, but kept completely away from the motor.



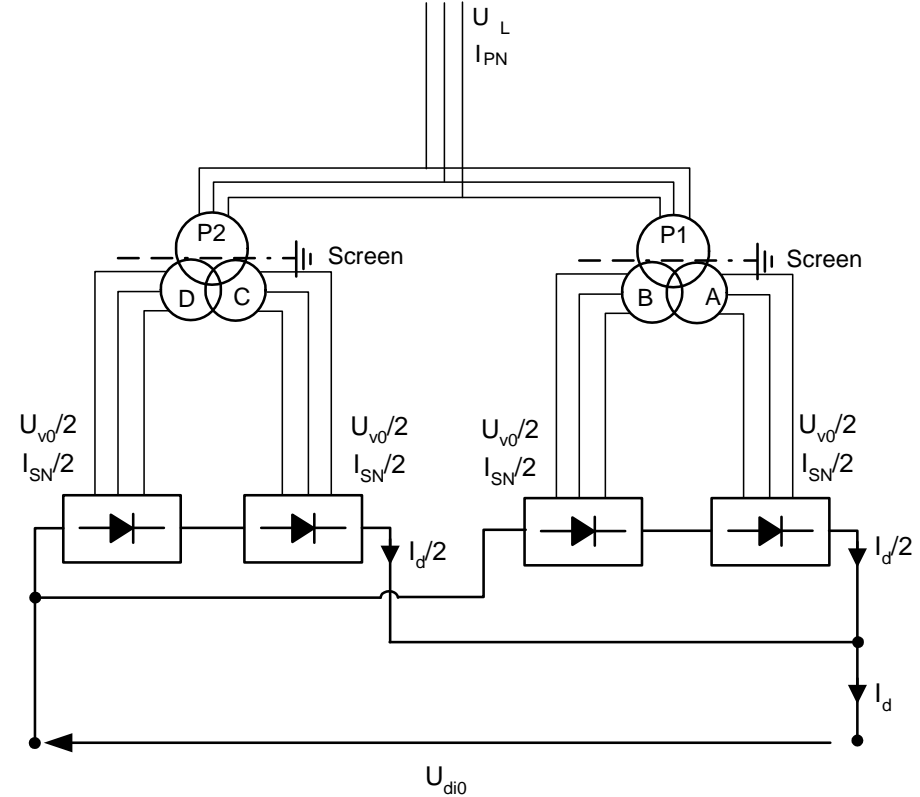
ACS 1000 – 24-pulse input transformer

One 5-winding transformer



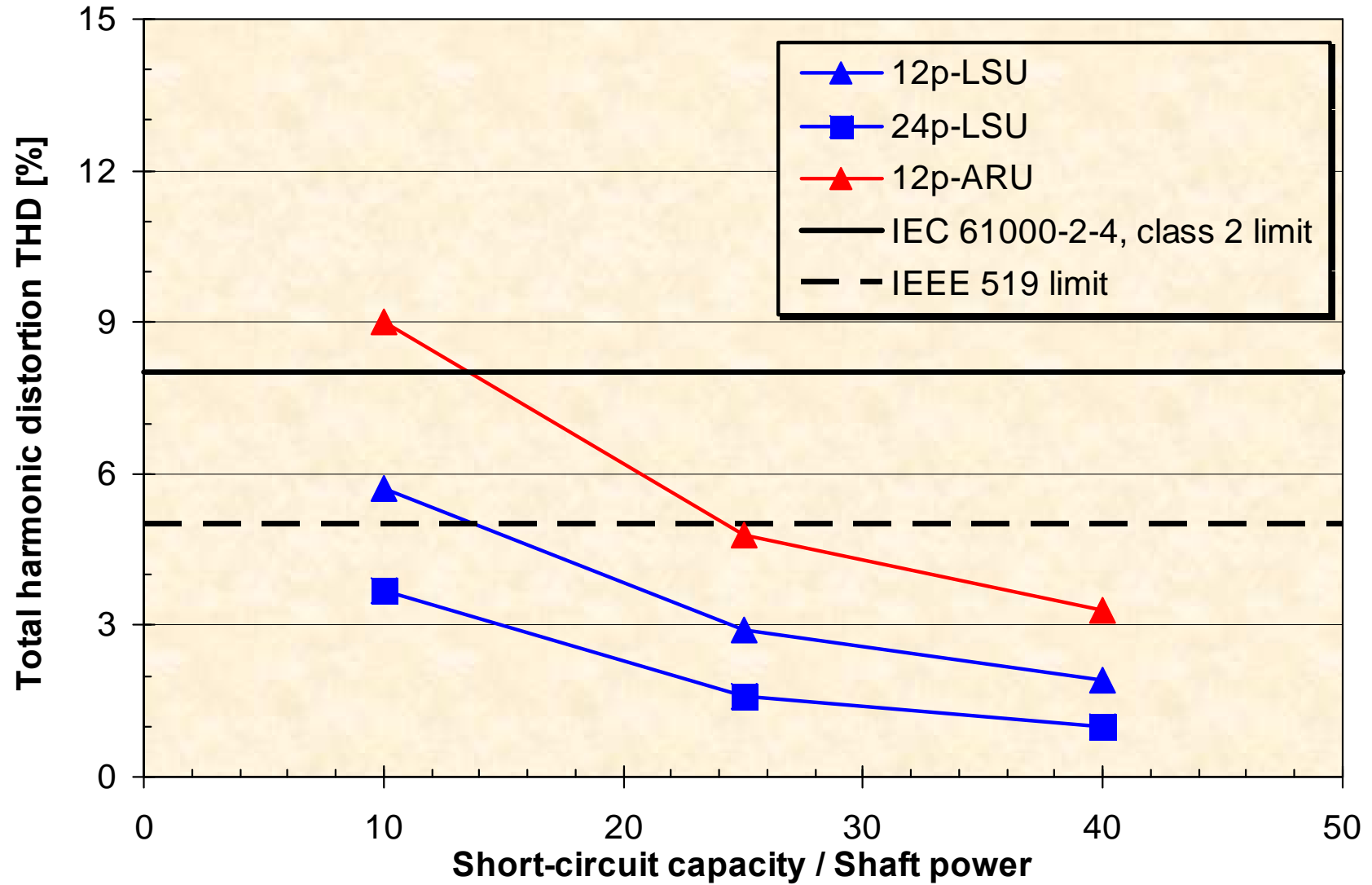
- Technically a compromise (non-characteristic harmonics)
- More compact and lower costs

Two separate 3-winding transformer



- Technically ideal and “save” solution
- Large in size and expensive

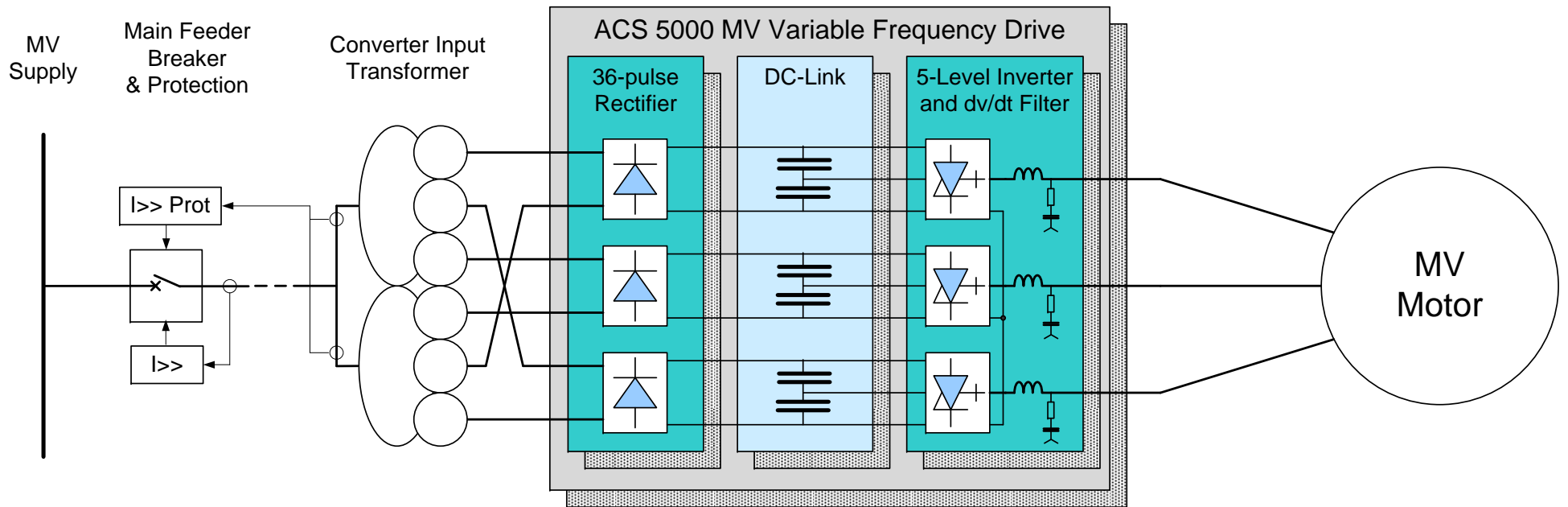
Example 10 MW - Voltage THD



Large 12 pulse rectifier transformer active part

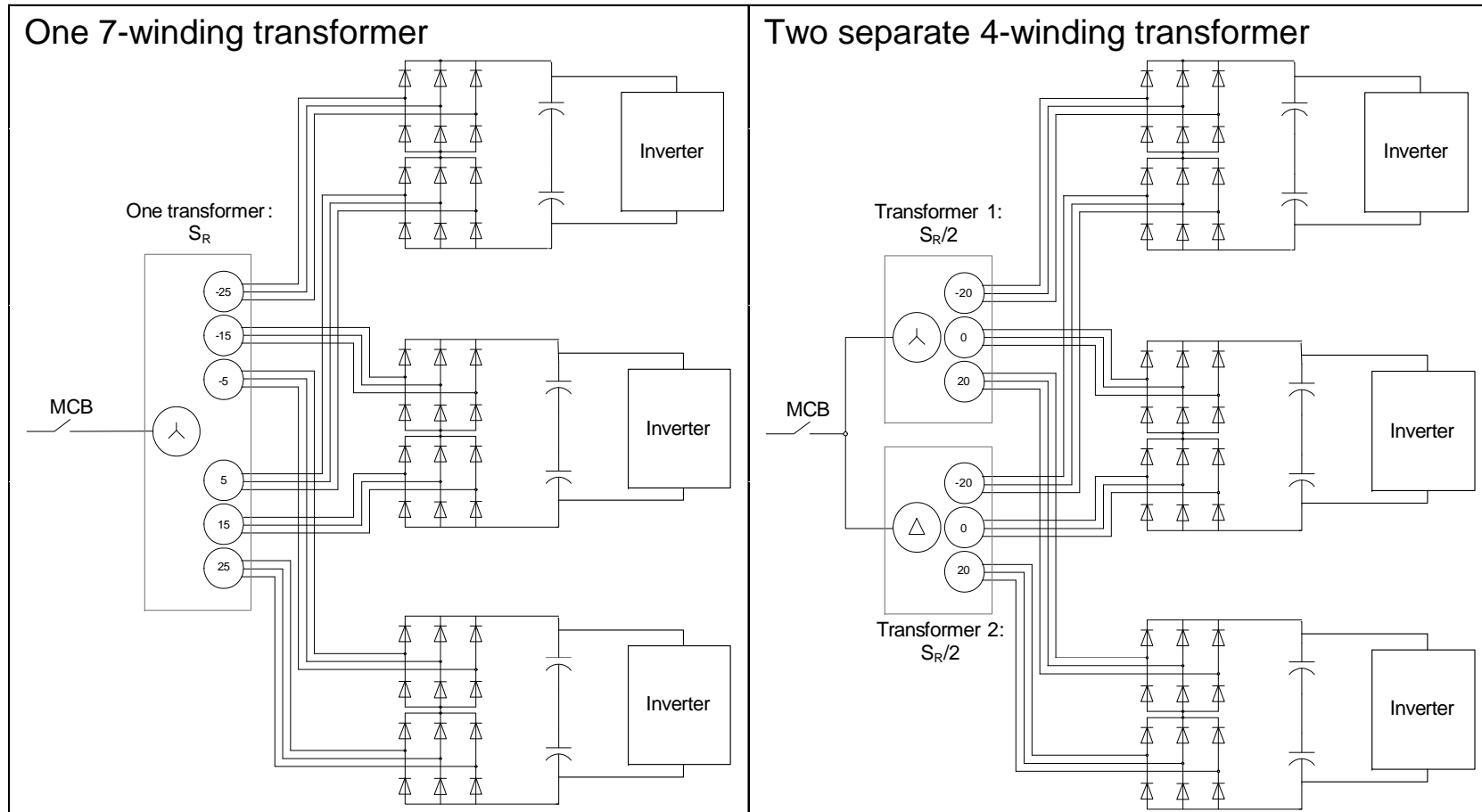


ACS 5000 Converter topology



- Transformer
 - 2 x 4-winding or 1 x 7-winding
 - Optional integrated dry type solution
- 36-pulse diode rectifier
 - 3 x 12-pulse bridges
 - Input voltage: 1920 V / $\pm 10\%$
- DC link (in triplicate)
- Three 5-level inverter unit
 - H-bridge configuration
- Output voltage up to 6.9 kV
- EMC-filter (dv/dt limitation at output) as standard
- Motor type
 - Asynchronous
 - Synchronous
 - Permanent magnet

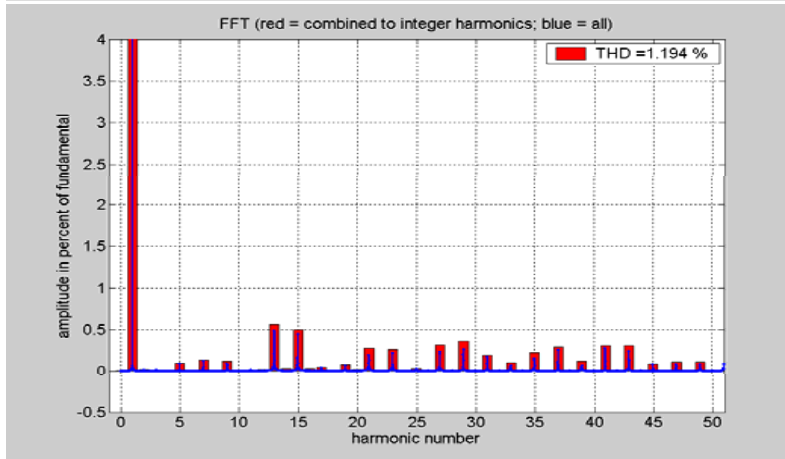
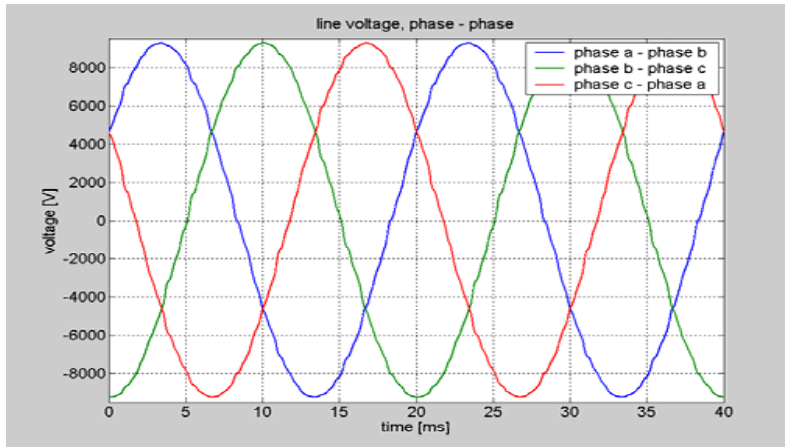
ACS5000 - 36-pulse transformers



- Technically a compromise, only for small powers (non-characteristic harmonics)
- More compact but not always lowest costs
- Primary currents must be measured separately

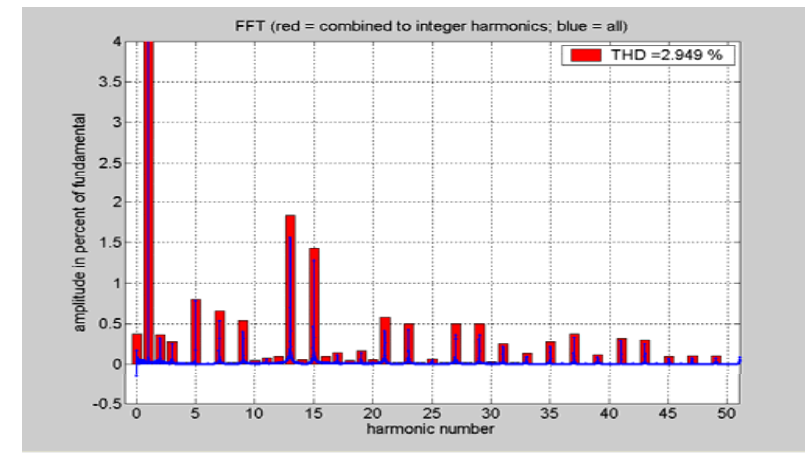
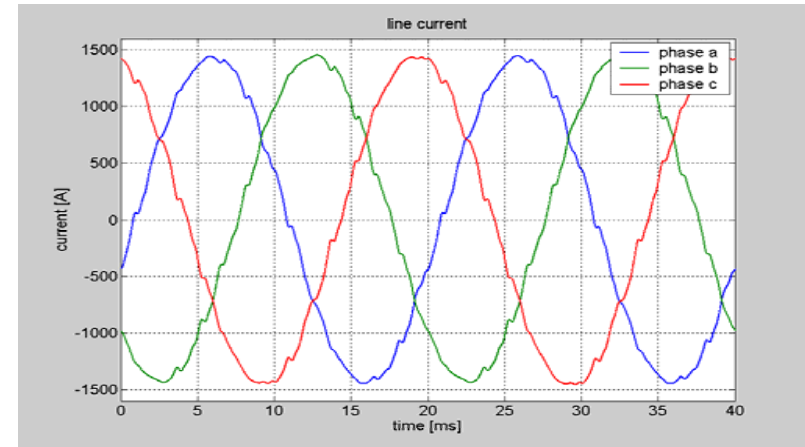
- Technically ideal and “save” solution
- Larger in size; compromise is to have two active parts in one oil tank
- Oil transformers, two separate transformers are lowest costs
- 2 sets of CTs on primary side is required for overcurrent detection (each primary side measured separately)

ACS 5000 Network friendliness



Line to line voltage THD = 1.19%

Sc = 500MVA, Xsc = 10%



Phase current THD = 2.95%

Power and productivity
for a better world™

