Description, selection and feedbacks of use of MV VSD technologies in Oil&Gas

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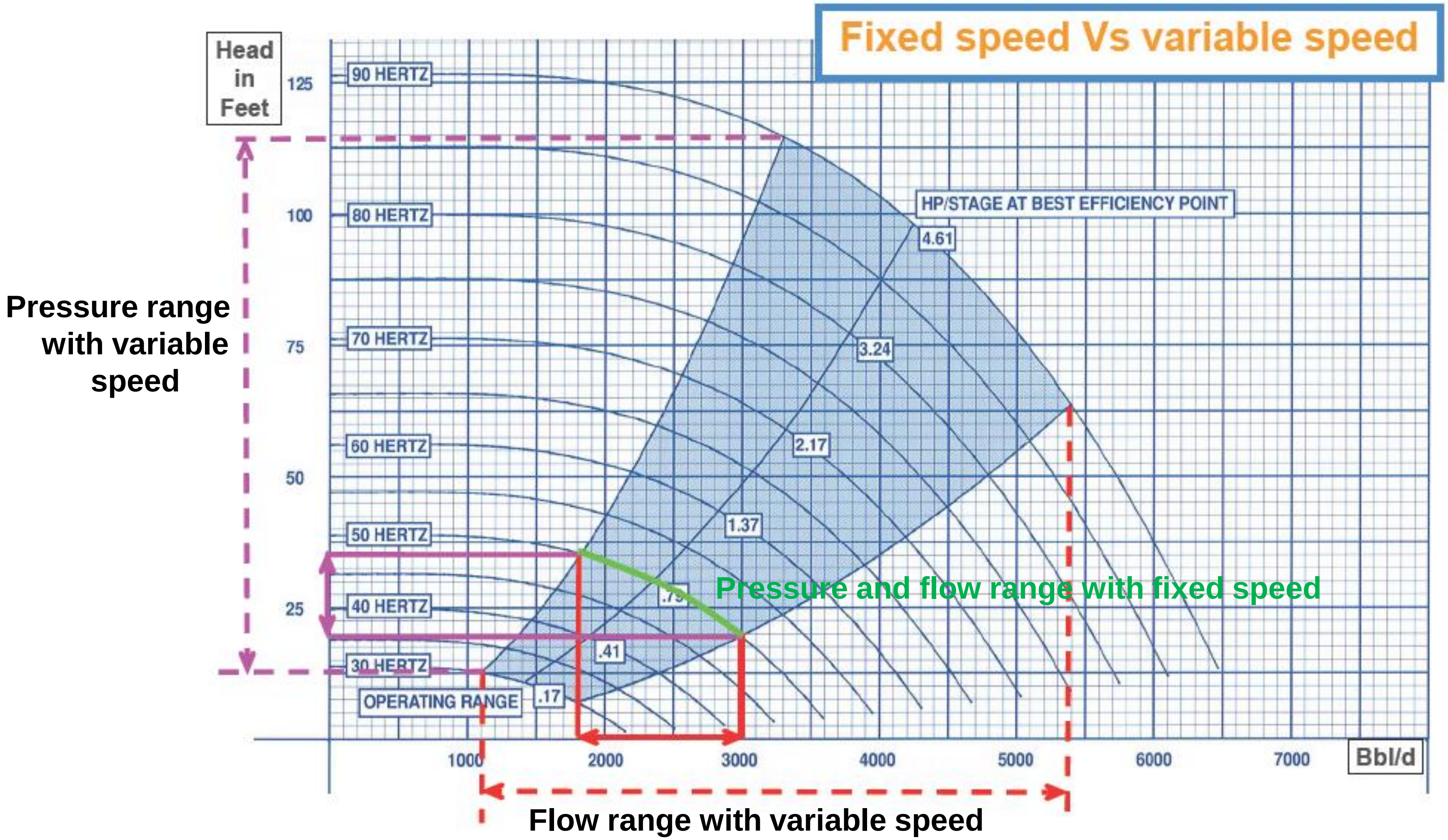
Summary

- Why using variable speed ?
- Mains Medium Voltage VSD's used in O&G
- Power semi-conductors used
- Load Commutated Inverter LCI
- Voltage Source Inverter VSI
- VSD cooling
- Return of EXperiences REX

Why using variable speed ?

Maximize use of pump/compressor operating envelope

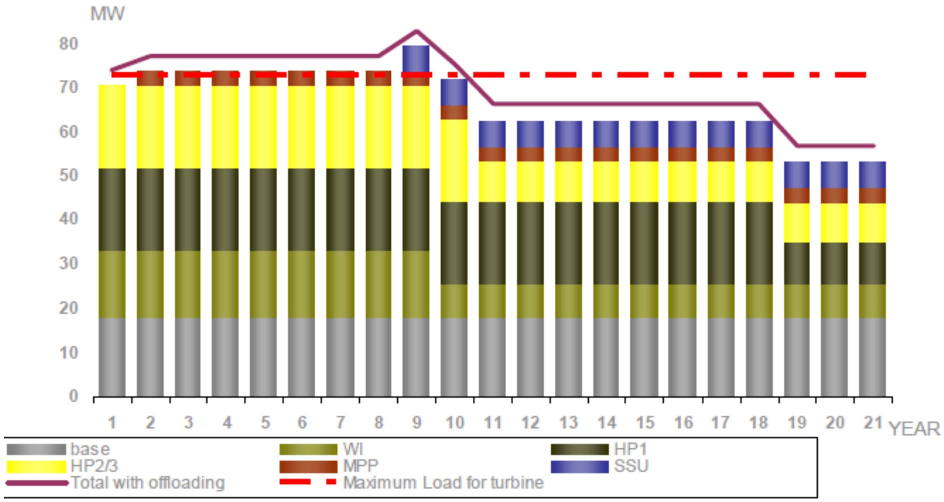


Well adapted with upstream production where process operating points change with reservoir depletion

Why using variable speed?

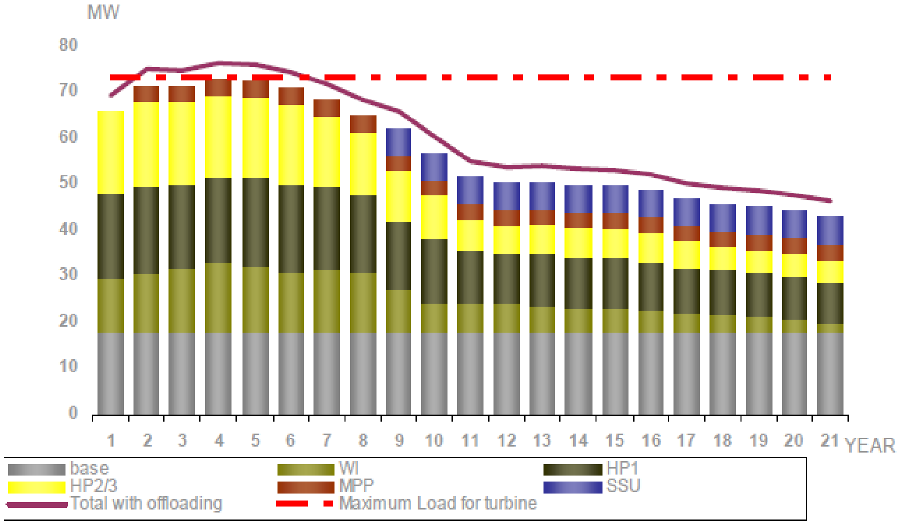
Efficiency allows to consume only what is needed

FPSO case example



FPSO with fixed motor

- Needs 5 Gas turbine to handle power consumption



Same FPSO with Variable Speed Drive

- Needs 4 Gas turbine to handle power consumption
- After year 8, large power available to tie-in production from new wells/reservoirs

Why using variable speed?

Improved stability for electrical network

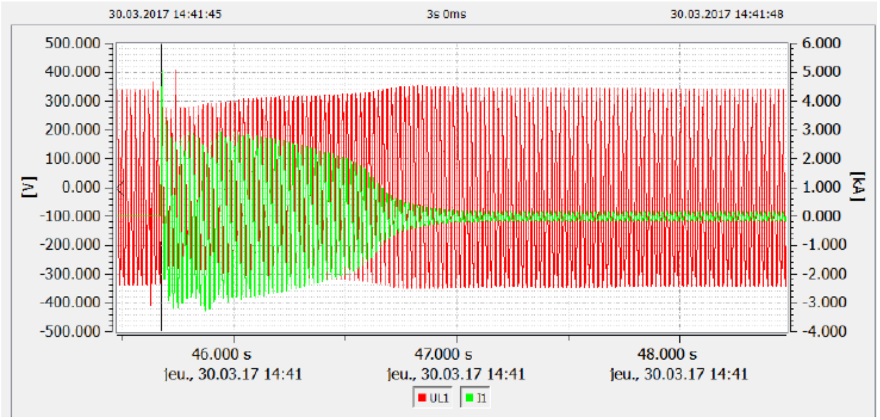
•No inrush current during motor start

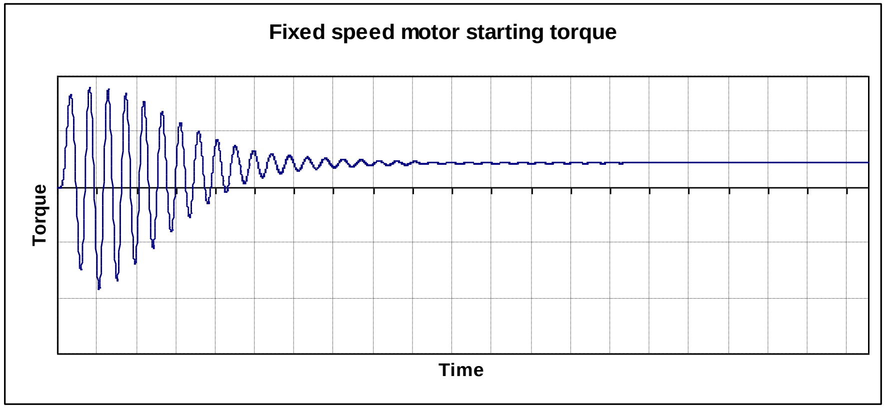
Motor mechanical lifetime

•Less mechanical constraints on the motor and its driven load (soft start)

Availability

•No limitation of number of start compared to DOL start



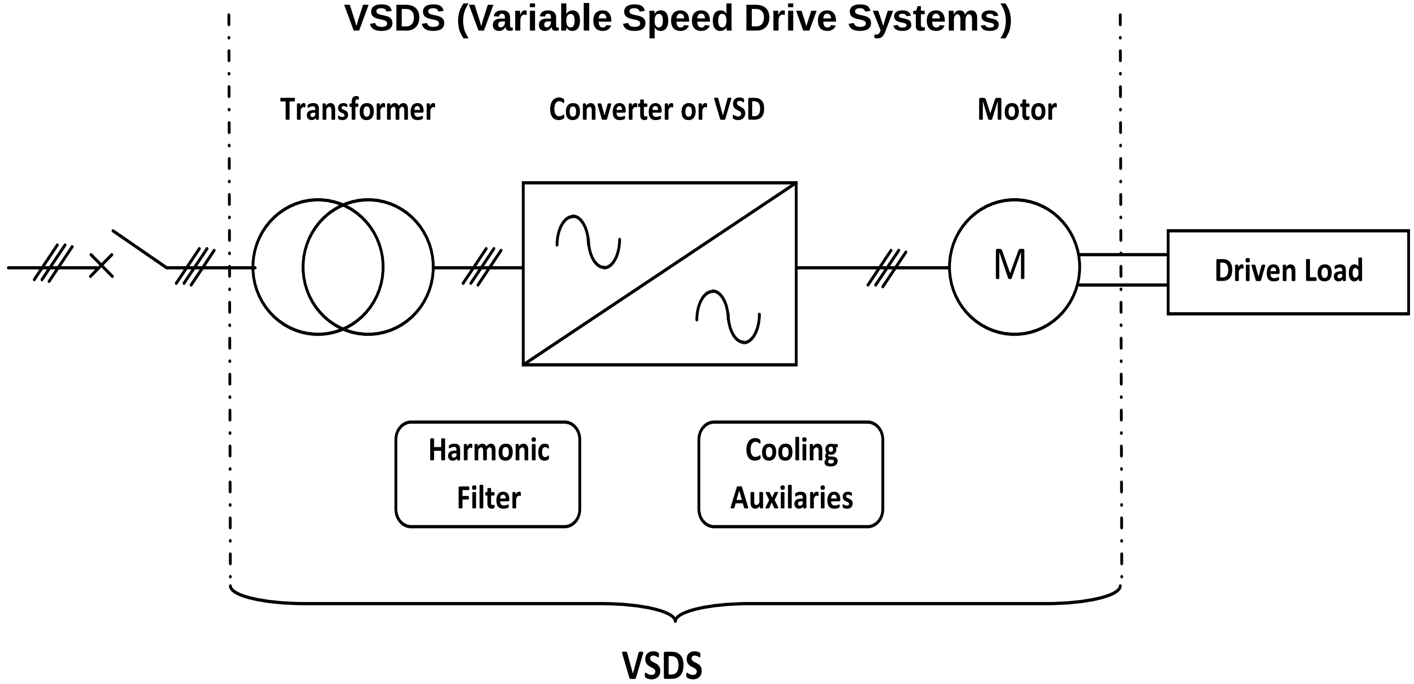


VSD, VSDS, SFC,….

VSD can also be called:

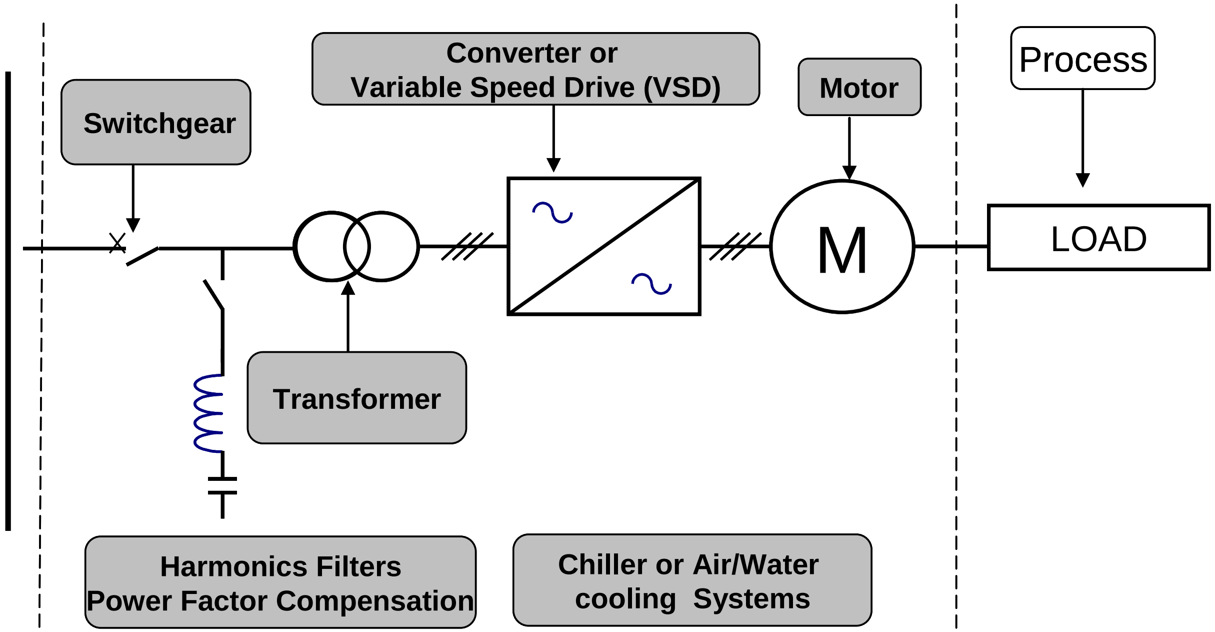
- ASD (Adjustable Speed Drive)
- VFD (Variable Frequency Drive)
- PDS (Power Drive Systems)
- SFC (Static Frequency Converter)

VSDS (Variable Speed Drive Systems)



IEC 61800 series	Adjustable speed electrical power drive systems
IEC 60146 series	Semiconductor converters

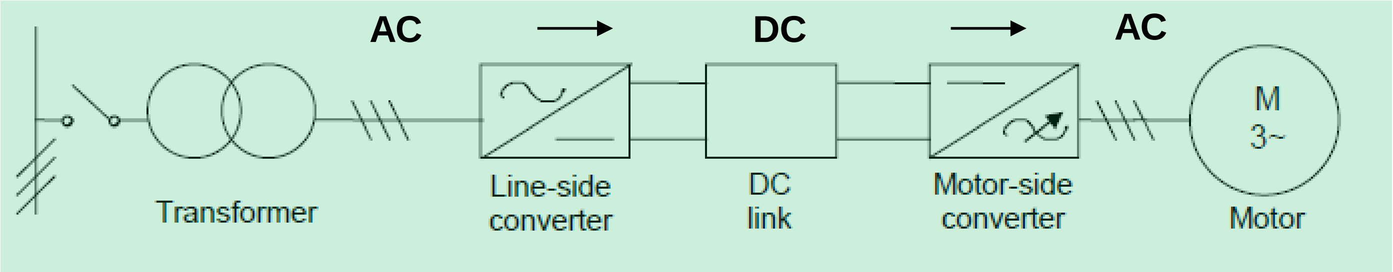
VSDS Main Components



Switchgear	Isolate, protect, connect and disconnect VSD Power Section
Harmonic filter	Redirect harmonics generated by the VSD and to keep the power factor close to 1
Transformer	Adjust the grid voltage to the VSD voltage and limit short circuit current of the VSD section.
VSD:	Generate variable voltage and frequency to drive the motor
Motor	Convert electrical power into mechanical power

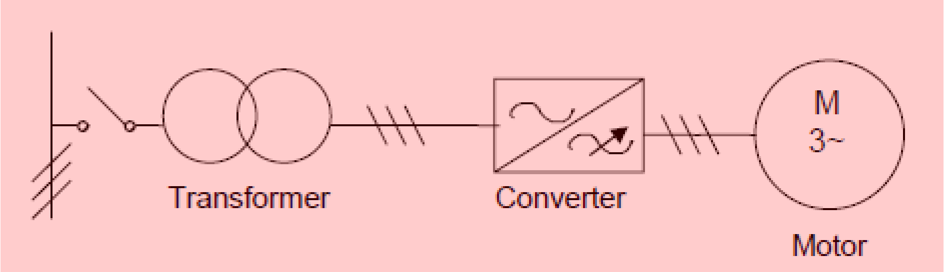
Mains Medium Voltage VSD's used in O&G

Oil & Gas uses mainly indirect converter



- Inductive d.c. link -> converter is named current source inverter (**CSI**)
- Capacitive d.c. link -> converter is named voltage source inverter (**VSI**)

Oil and Gas main converters are VSI and LCI (Load Commutated Inverter) which is a **CSI**



The power conversion is performed without intermediate d.c. link

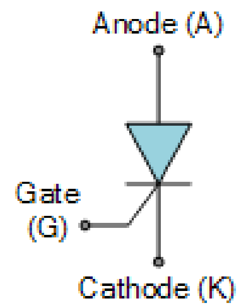
Direct converter not presented in this tutorial

Power semi-conductors used in LCI and VSI

Power semiconductors mainly used in converters

Thyristor type

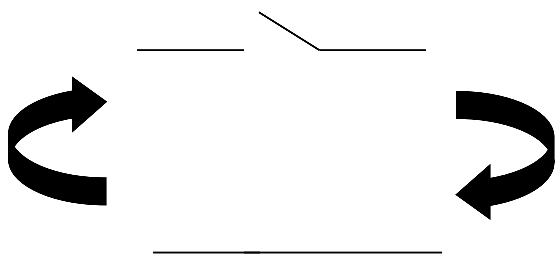
Thyristor 1956



Current direction

Thyristor Symbol

I=0

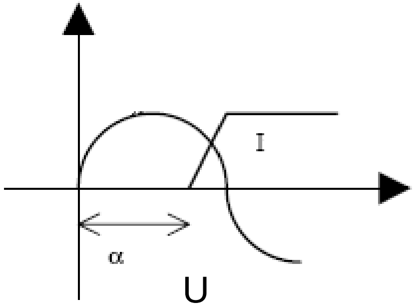


$V_{AK}>0$ & I_G

Thyristor is used in **LCI** (Load Commutated Inverter)

Power semiconductors mainly used in converters

Thyristor type



- Reactive power consumption

Press pack

- Cooled on both side which gives large current capability (several thousands of Amps)
- Explosion contained within the ceramic press pack

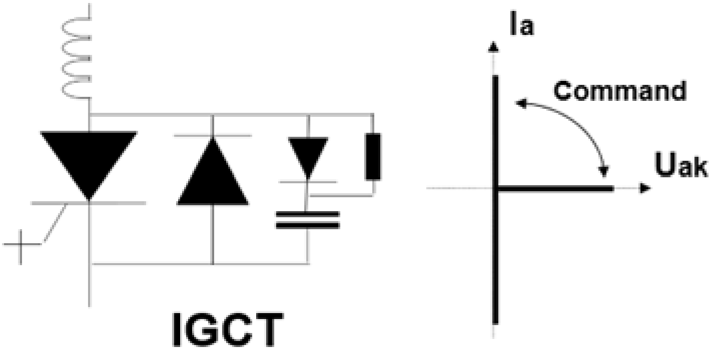
Fail short

- Possibilty of N+1 redundancy

Power semiconductors mainly used in converters

Thyristor types

Thyristor 1956	GTO 1986	IGCT 1995



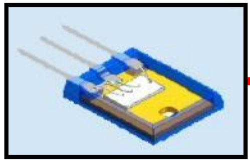
GTO   Gate Turn-off thyristor

IGCT Integrated Gate-Commutated Thyristor

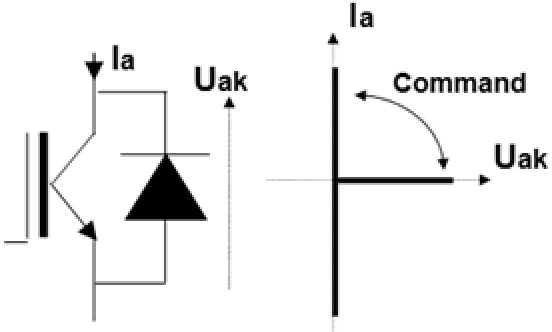
- GTO and IGCT have been developed to enable these devices to be turned on and off
- IGCT is an improved GTO with less losses, faster to switch and it is easier to implement than GTO
- In O&G, GTO and IGCT are mainly used in **VSI** (Voltage Source Inverter)

Power semiconductors mainly used in converters

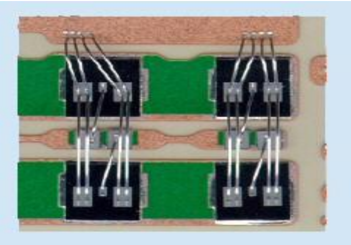
Transistor types

Transistor 1947	IGBT 1985
	

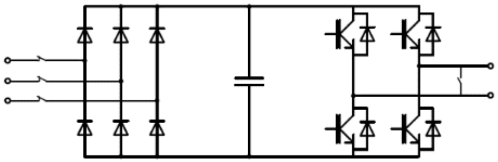
IGBT Insulated Gate Bipolar Transistor

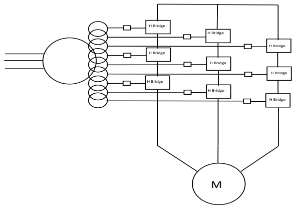


IGBT



- Transistor type can be turned on and off easily
- IGBT combines many transistors in parallel in one housing to handle large current
- IGBT has a high switching frequency
- IGBT flat pack is only cooled on one side there is current limitation compared to press pack design
- IGBT fails open -> for N+1 redundancy (multi level VSD) there is need to configure it inside a power cell and to install bypass switch to continue operation of the VSD

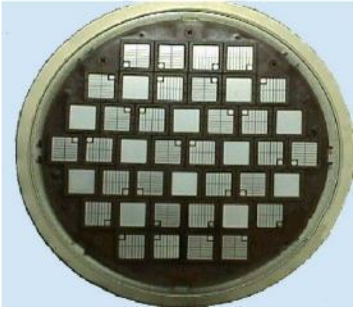




Power semiconductors mainly used in converters

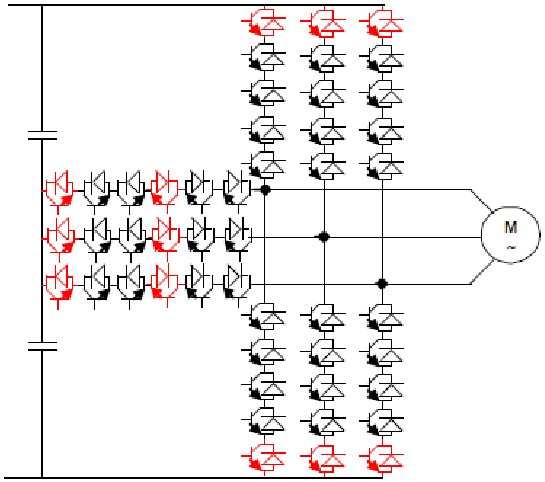
Transistor types

Transistor 1947	IGBT 1985	IEGT 1998

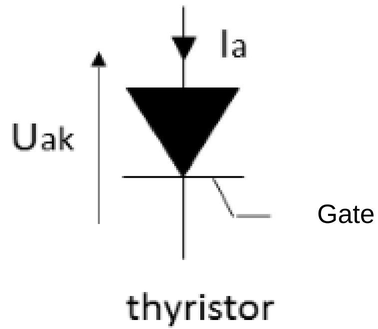


IGBT Insulated Gate Bipolar Transistor
IEGT Injection Enhanced Gate Transistor.

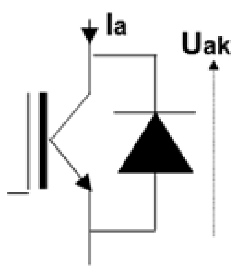
- IEGT combines as well many transistors in parallel in one housing
- IEGT has lower switching frequency than IGBT
- Fails short -> possibility of N+1 redundancy
- Press Pack IEGT provides larger current capability than IGBT with less conduction losses
- IGBT and IEGT in O&G are used in **VSI** (Voltage Source Inverter)



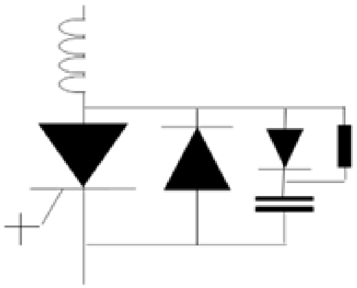
Power semiconductors mainly used in MV converters



LCI



IGBT



IGCT

VSI

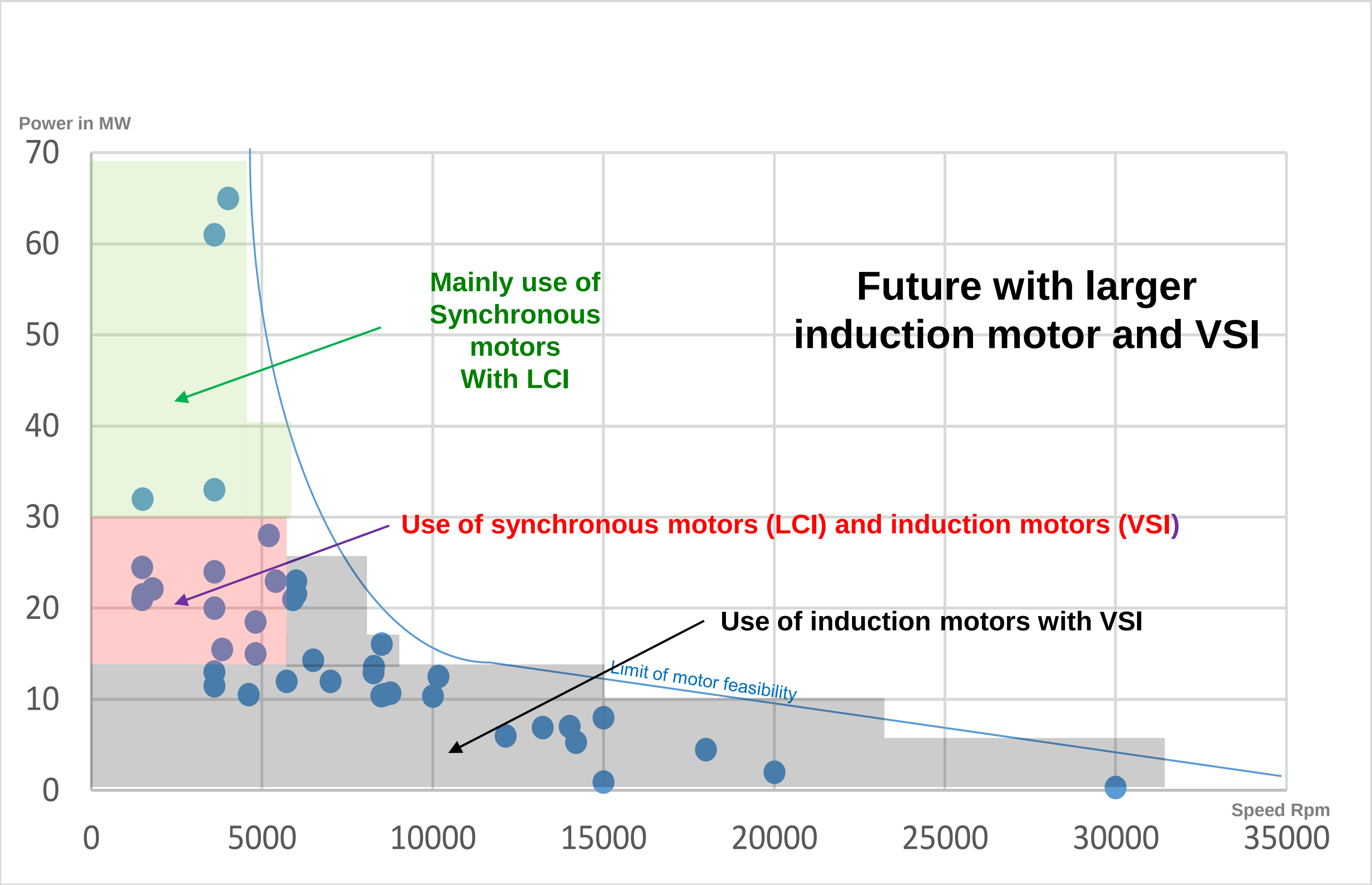
IGBT, IEGT (Transistor type)
Higher switching frequency

←→

GTO, IGCT (Thyristor type)
Larger current

Mains Medium Voltage VSDS's used in O&G

MV VSD's in Oil & Gas mainly used today

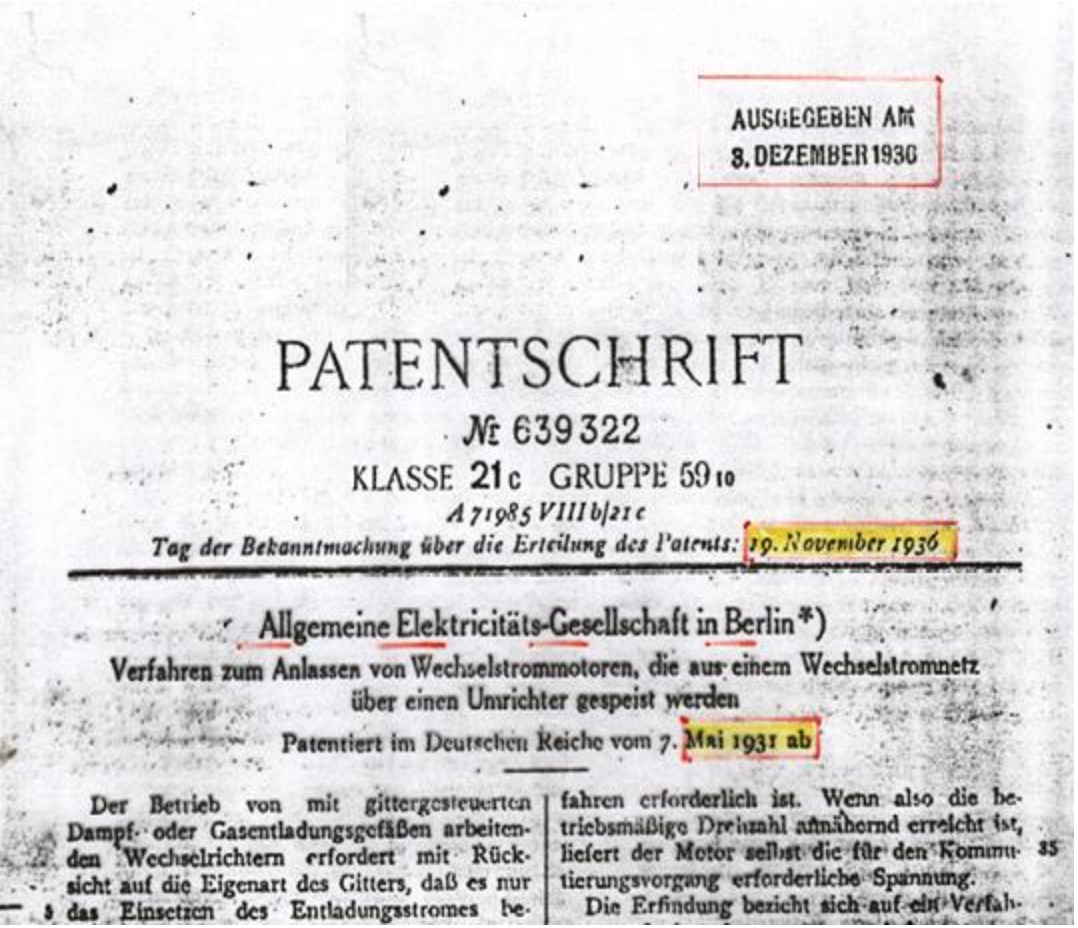


LCI Load Commutated Inverter

LCI invention

LCI patented by AEG (Germany) in 1936 for railway application using mercury vapor valve

nowadays replaced by thyristor valve


AUSGEGEBEN AM
8. DEZEMBER 1936

PATENTSCHRIFT

№ 639 322

KLASSE 21c GRUPPE 59 10

A 71985 VIII b/21c

Tag der Bekanntmachung über die Erteilung des Patents: 19. November 1936

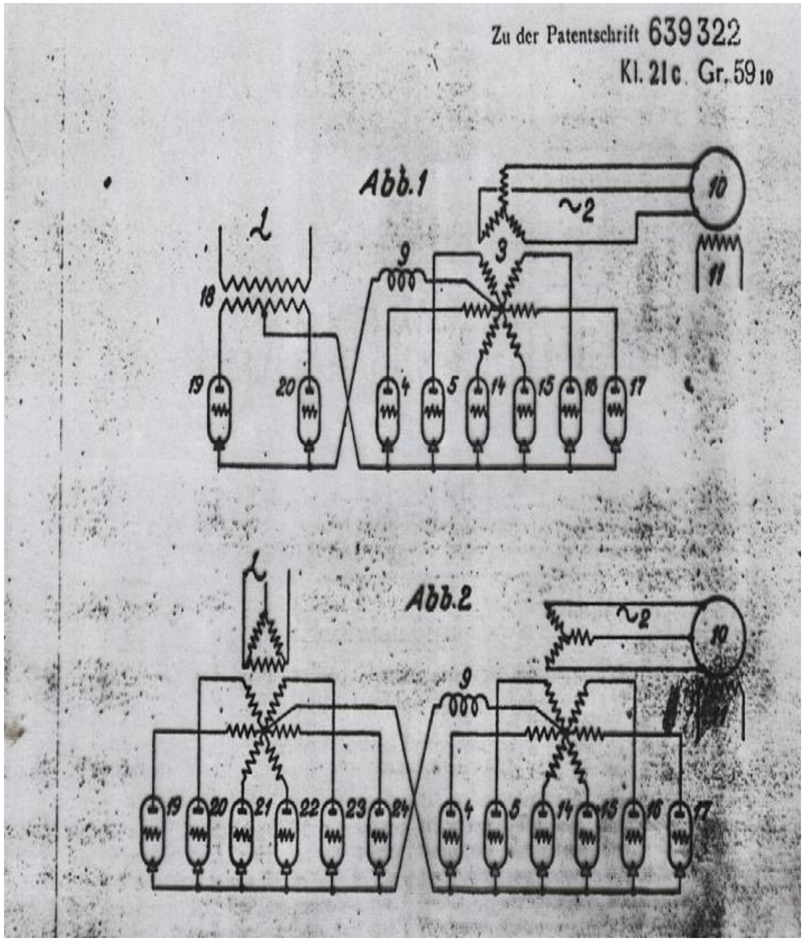
Allgemeine Elektricitäts-Gesellschaft in Berlin*)

Verfahren zum Anlassen von Wechselstrommotoren, die aus einem Wechselstromnetz über einen Umrichter gespeist werden

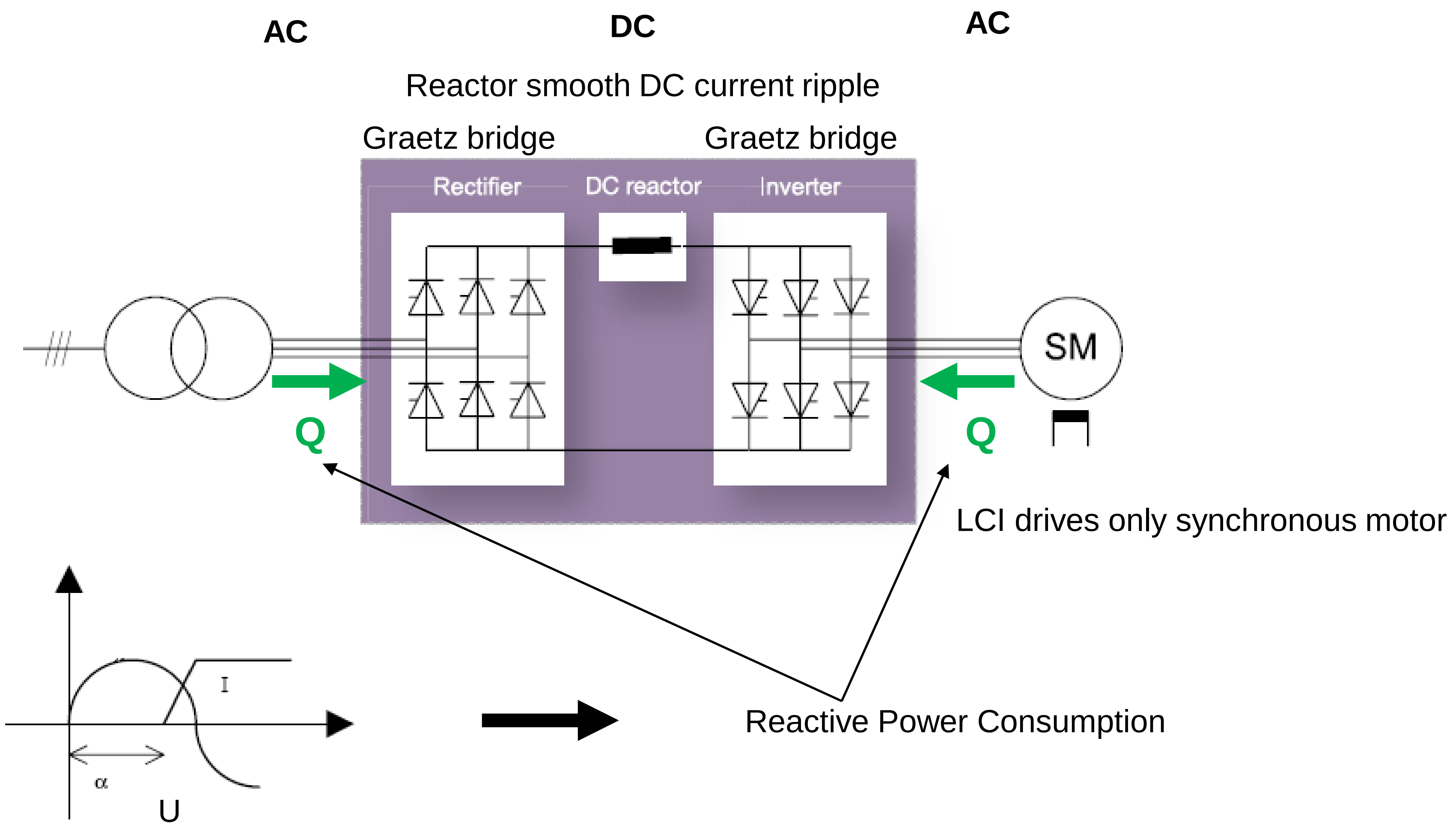
Patentiert im Deutschen Reiche vom 7. Mai 1931 ab

Der Betrieb von mit gittergesteuerten Dampf- oder Gasentladungsgefäßen arbeitenden Wechselrichtern erfordert mit Rücksicht auf die Eigenart des Gitters, daß es nur das Einsetzen des Entladungsstromes be- fahren erforderlich ist. Wenn also die betriebsmäßige Drehzahl annähernd erreicht ist, liefert der Motor selbst die für den Kommutierungsvorgang erforderliche Spannung.

Die Erfindung bezieht sich auf ein Verfah-

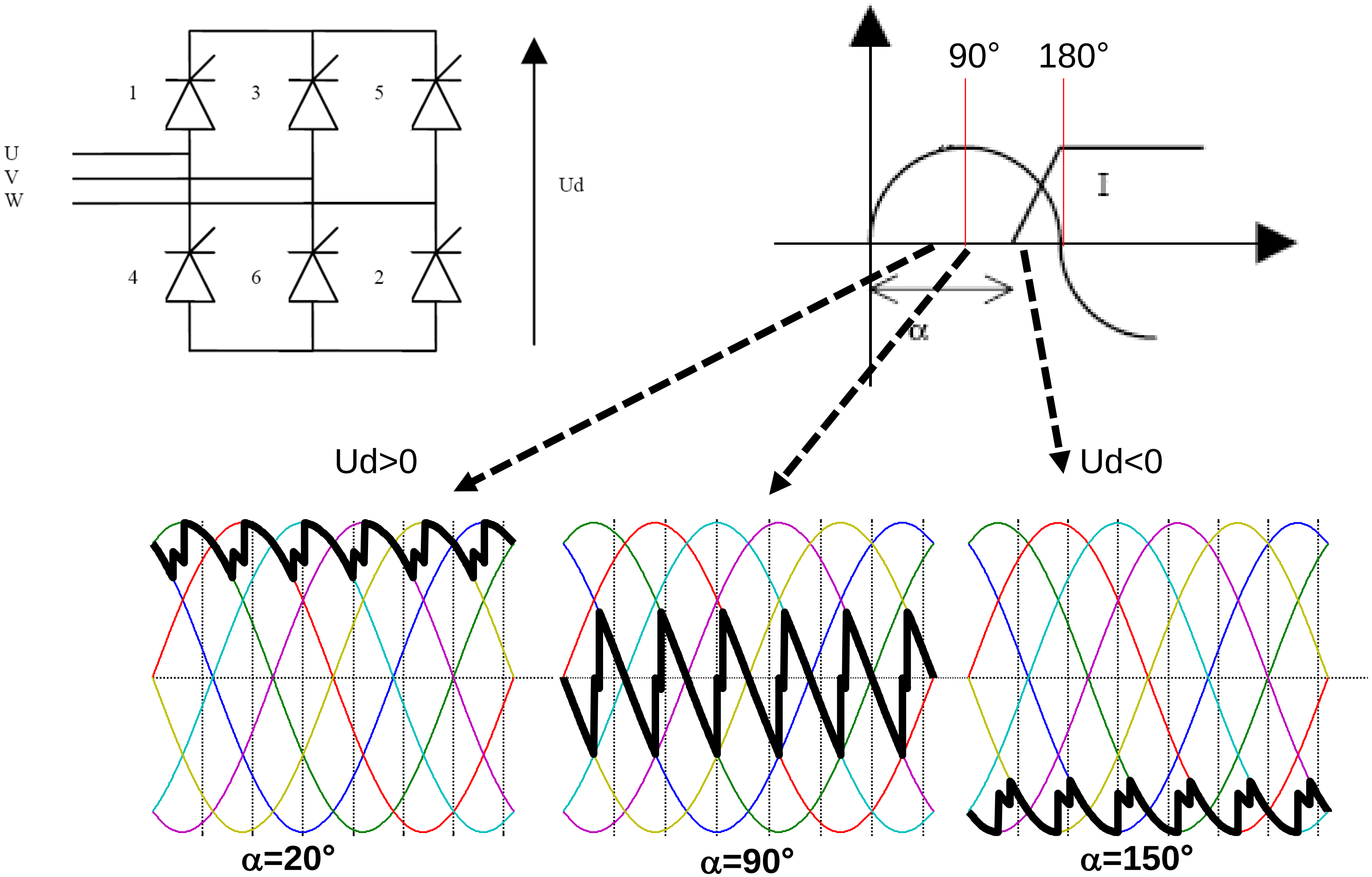


LCI (Load Commutated Inverter)



Graetz Bridge control

Graetz bridge is controlled by changing the thyristors gate firing angle
It allows to change the sign and the amplitude of the DC voltage



LCI control principle

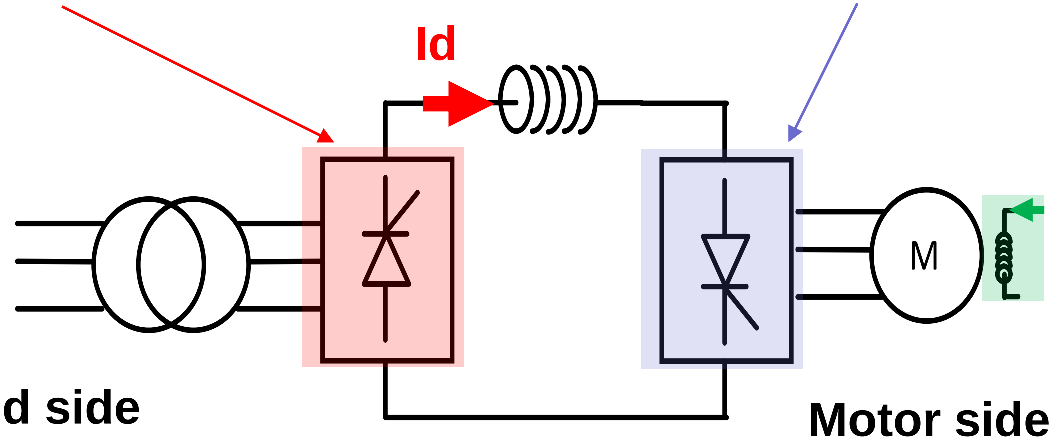
Changing Torque -> Speed variation

$$J.\frac{d\Omega}{dt} = Cm - Cr$$

LCI Motor Torque = Cm = k.Id.Cosφ.Flux

Id current (DC loop current) controlled by the rectifier bridge

Cosφ controlled by the inverter bridge



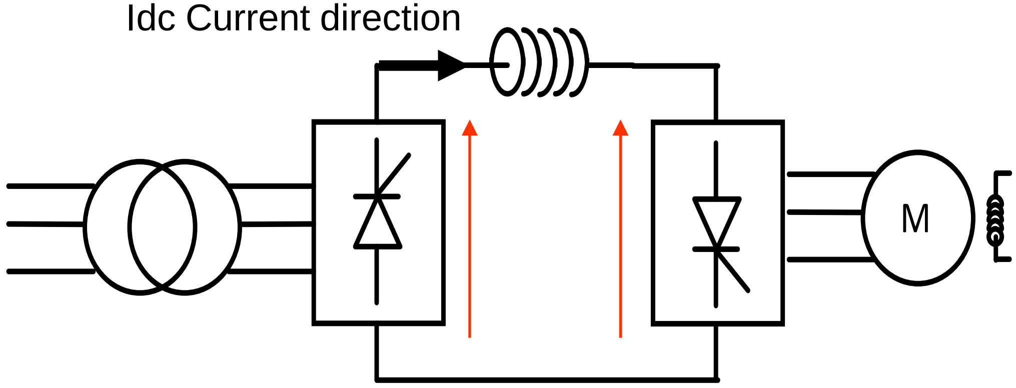
Flux controlled by the excitation current of the synchronous motor

Input grid side

Motor side

LCI active power flow

4 QUADRANTS CAPABILITY



Active Power flow

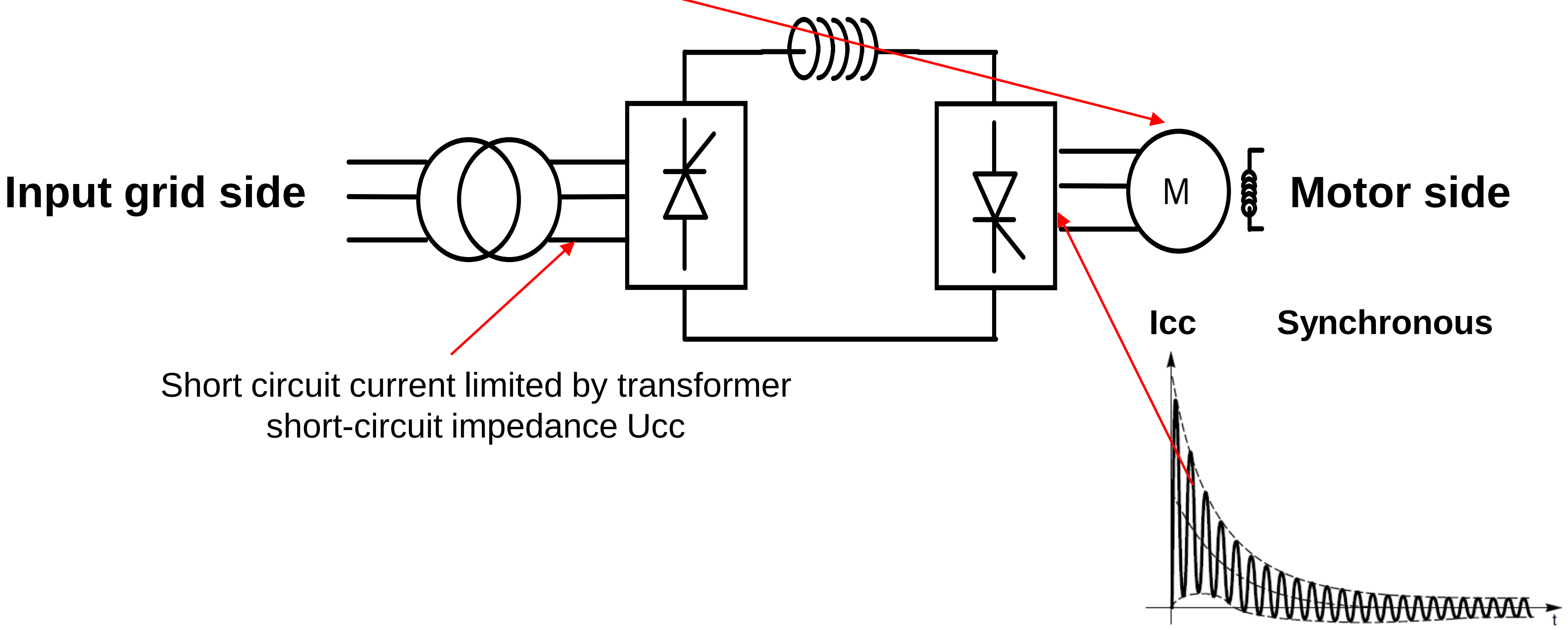
P = Udc.Idc >0 it means Udc>0 **->** 0°<Firing angle<90° (Rectifier)

Opposite for Inverter

P = Udc.Idc <0 it means Udc<0 **->** 90°<Firing angle<180° (Rectifier)

LCI short circuit power

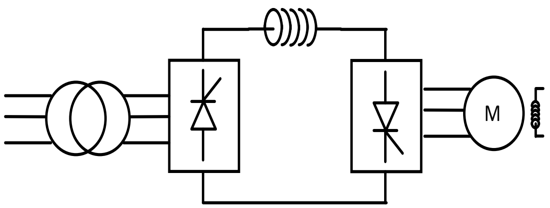
LCI has large short circuit current on inverter side
since to minimize commutation time, a small sub-transient reactance X’’ is specified -> large Icc



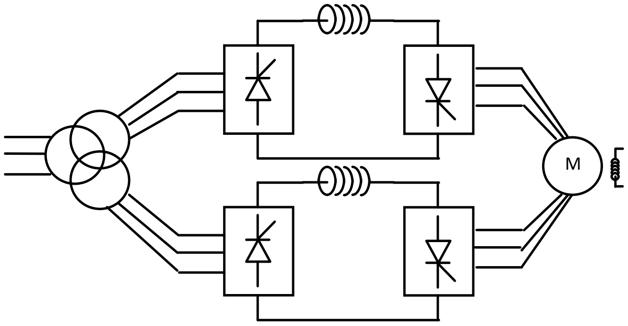
SINCE LARGE ICC, POWER SECTION CUBICLE SHALL BE ABLE TO WITHSTAND ARC FAULT

Harmonics

In large drive application, to reduce the injection of harmonics to the grid,
the rectifier is configured from 6 pulse to 12 pulse



6 pulse topology



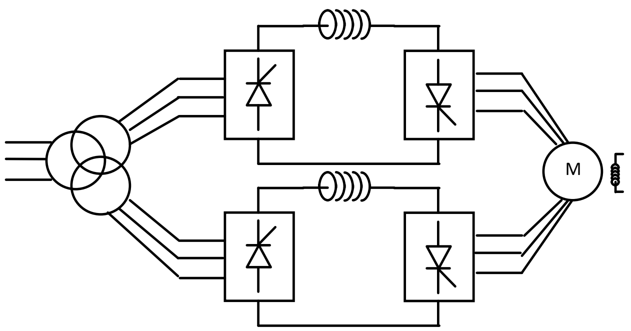
12 pulse topology

But generally even in 12 pulse configuration an harmonic filter is used with LCI:

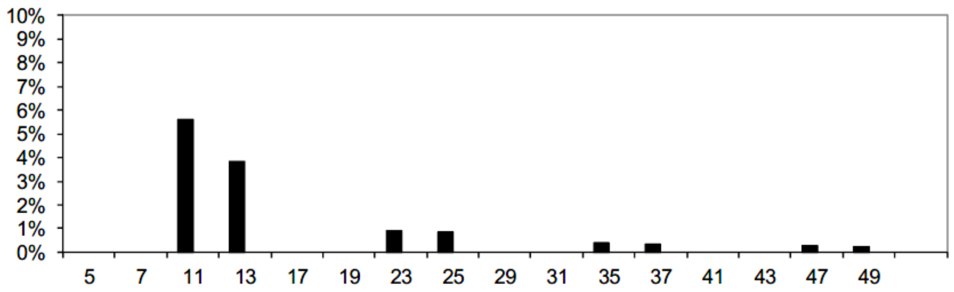
- since 12 pulse is generally not sufficient to achieve harmonics requirement limitations
- for Power Factor compensation due to the reactive power consumption of the LCI rectifier

Residual Harmonics

In theory, for a 12 pulse rectifier, harmonics 5,7,17,19,29,31,41 and 43 should be cancelled.



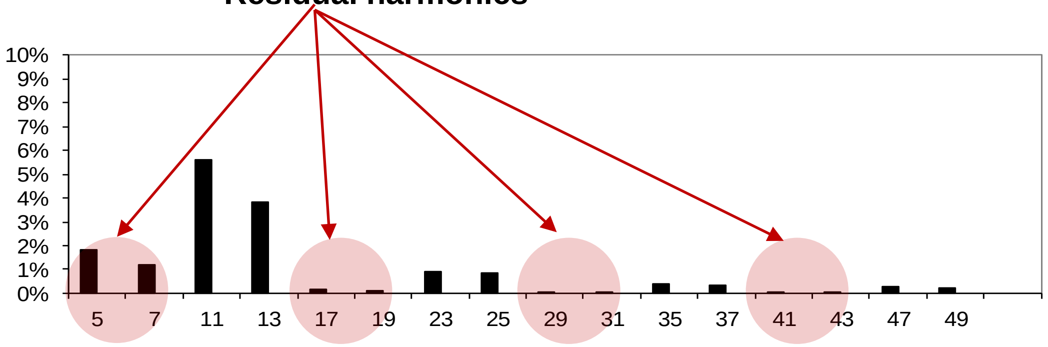
12 pulse topology



But due to tolerances/imperfections of control and converter, those harmonics are not completely cancelled

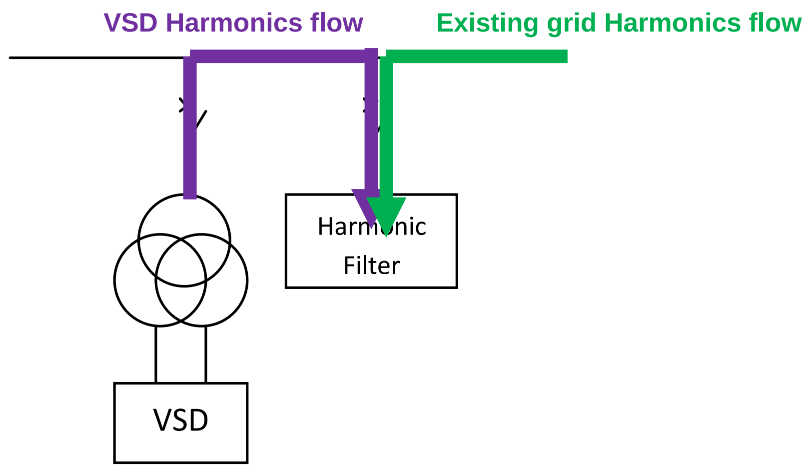
Residual harmonics amplitude can reach from 5% to 15% of those of a 6-pulse converter (IEC 60146-2)

Residual harmonics



RESIDUAL HARMONICS SHALL NOT BE OVERLOOKED WHEN MAKING HARMONICS STUDIES

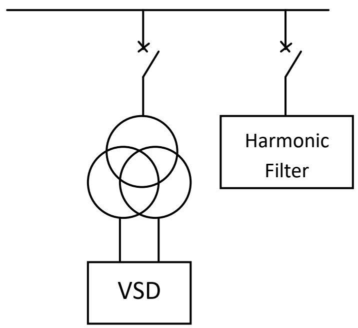
Existing harmonics



Existing grid harmonics shall not be overlooked as well when designing harmonics filter to avoid to overload the harmonic filter in normal operation

Harmonics filter location

Direct connection of the Harmonic Filter(HF) to busbar



Advantages

•Design of the transformer and harmonic filter made in parallel

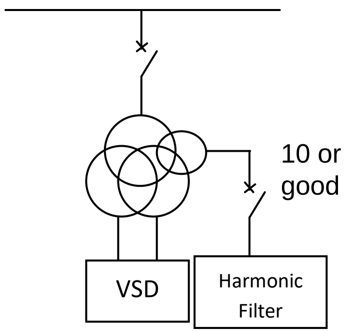
•Cost effective solution for MV grid

Limitation of this solution

•Cost of harmonic filter & HV feeder becomes expensive with voltage increase (shall be <90kV)

Harmonics filter location

Connection of the harmonic filter to 4th transformer winding



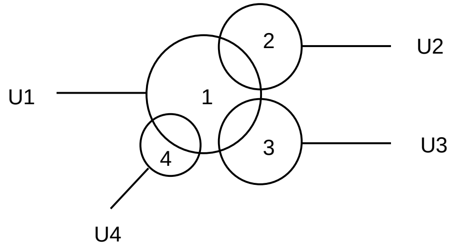
10 or 11kV on 4th winding is a good cost tradeoff

Advantages

•Less HV feeder and cost of harmonic filter reduced

Drawbacks

•Complex transformer where short circuit impedance Ucc tolerances impact harmonic filter performances



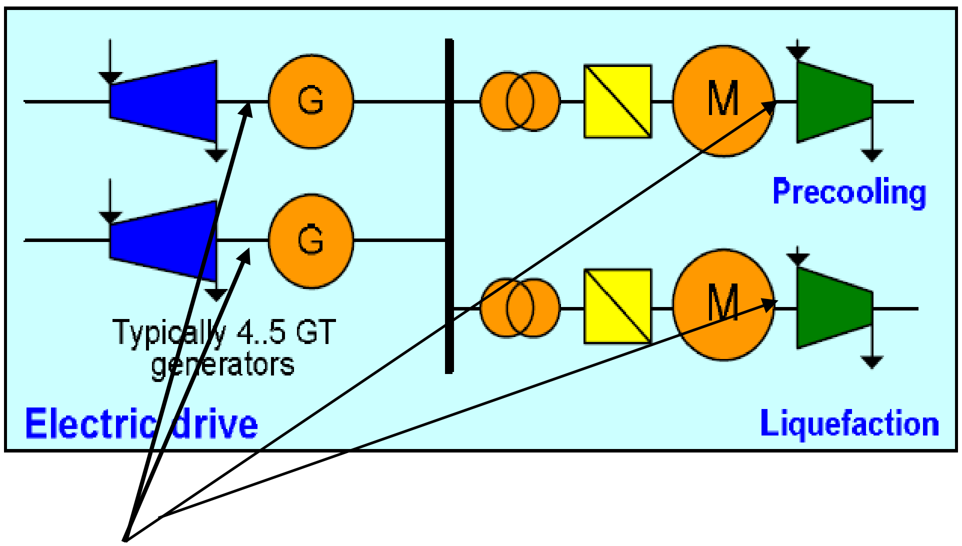
Interharmonics

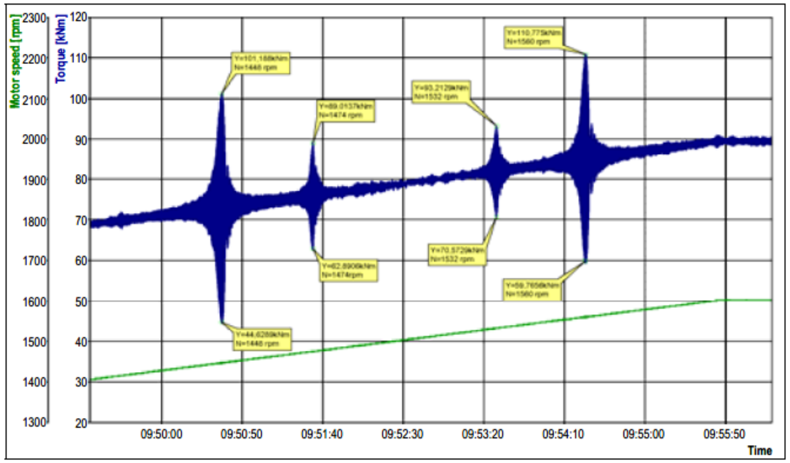
In addition to harmonics, LCI injects as well interharmonics into the surrounding power system.

Interharmonics are non integer harmonic which are the results of combination of grid and motor frequency

Formula is |n*FN +/− m*FM|

where FN: grid frequency, FM: Motor frequency



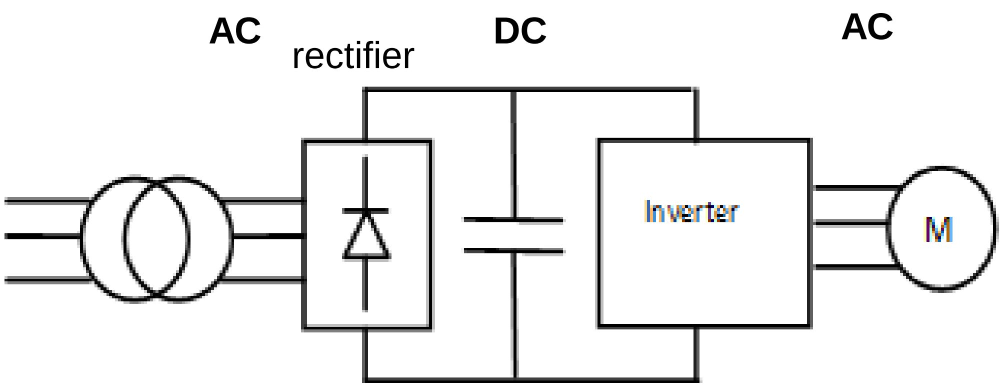


Interharmonics cause torsional oscillations leading to an excess of vibrations

SSTI (Sub Synchronous Torsional Interaction) study to de done to assess potential issues with interharmonics on your plant

VSI Voltage Source Inverter

VSI



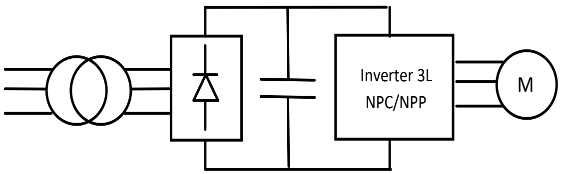
Synchronous motor

Induction motor

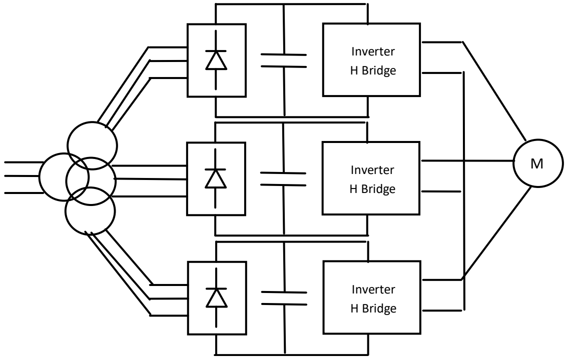
Capacitor smooth DC voltage ripple

VSI Topologies

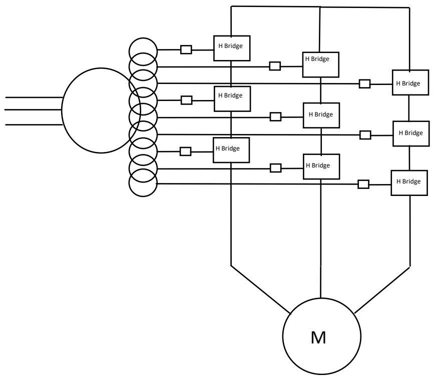
Most commonly used VSI in O&G



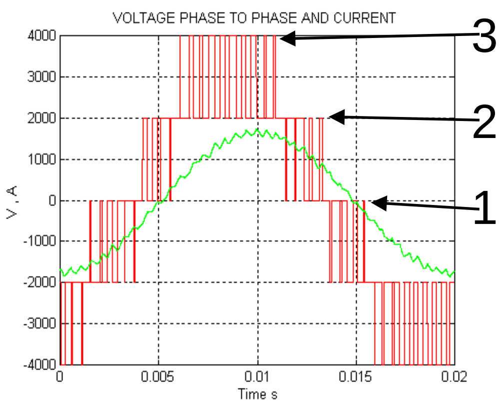
VSI 3 Level NPC or NPP

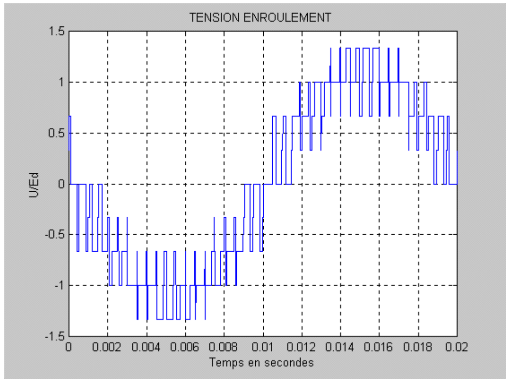


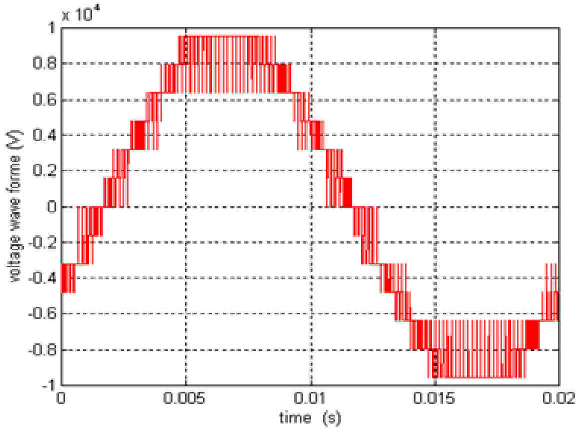
VSI 5 level H bridge



VSI multi level H bridge

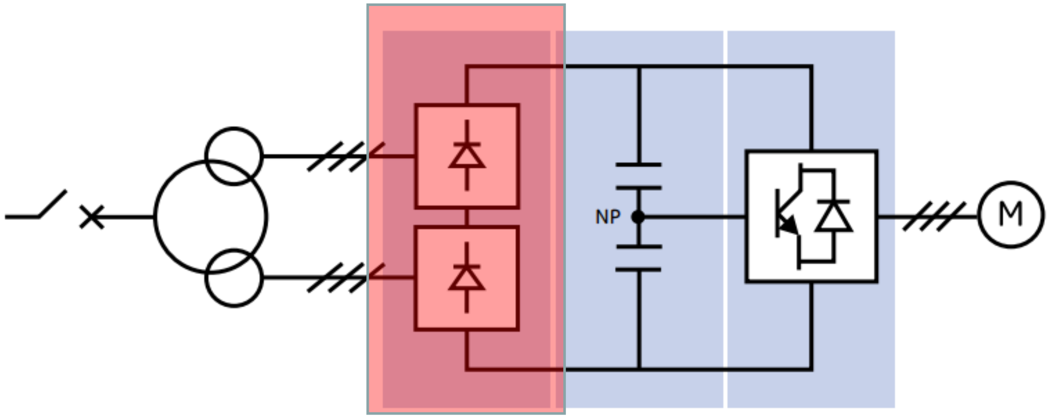






Better current THD

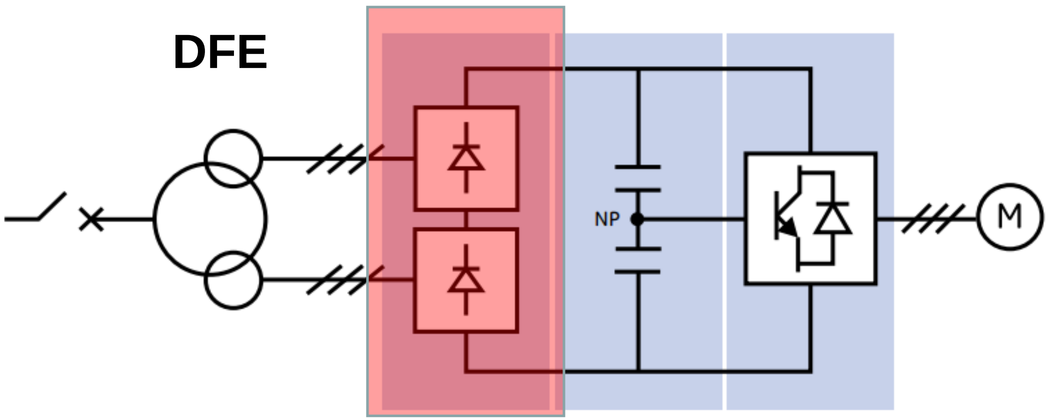
VSI DFE

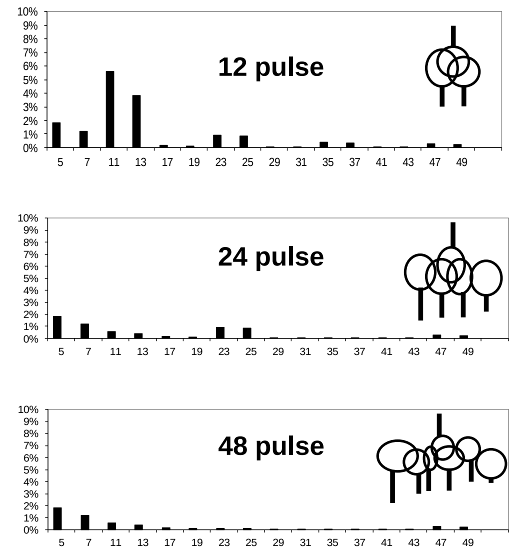


Diode Front End (DFE)

- Cost effective
- No regeneration capability
- Installation of DC chopper for braking if required
- Rectifier configuration (number of pulse), based on use of multi winding transformer to comply to harmonic requirements

VSI DFE & Harmonics Filter



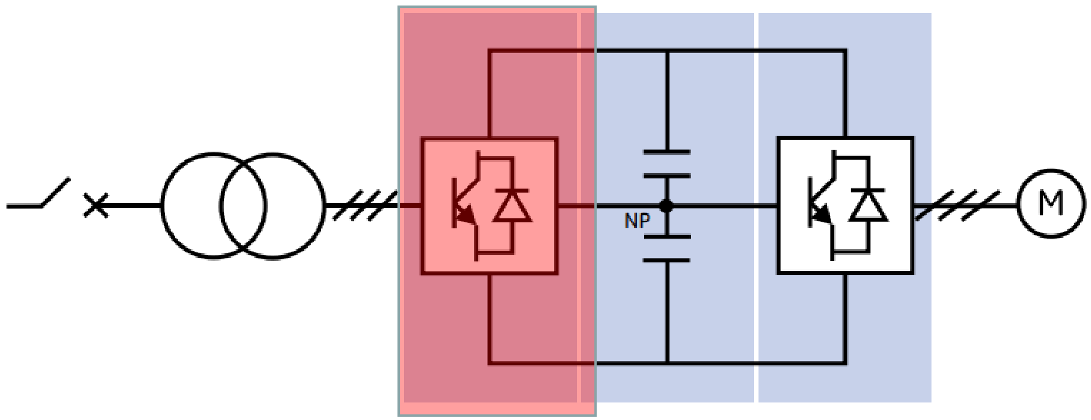


Usually there is no need for an Harmonic Filter (HF) since:

- the power factor is >0.96 for a DFE (No need to compensate the power factor like for LCI)
- the rectifier configuration (number of pulse) of the transformer is calculated to comply with harmonic limitation requirements and therefore to avoid installation of HF

Nevertheless, if there is a large number of VSI installed with DFE rectifier in operation, a filter can be contemplated to comply with harmonic limitation requirements

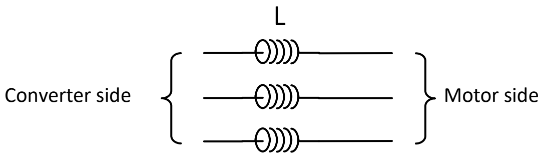
VSI AFE rectifier



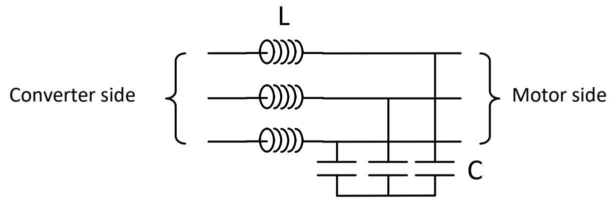
Active Front End (AFE)

- Regeneration capability (4 quadrants)
- Simpler transformer compare to multi winding of DFE (1 secondary only)
- Low harmonic content at input grid side
- Possibility for transformer less (less equipment, space, weight)
- VSD more expensive/complex
- Possibility of Power Factor 1 and reactive power compensation

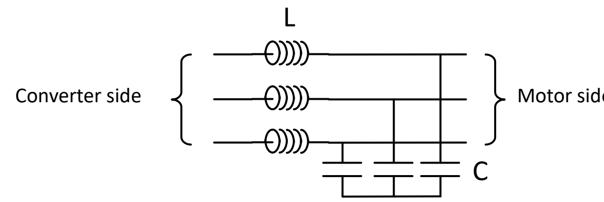
Output filters



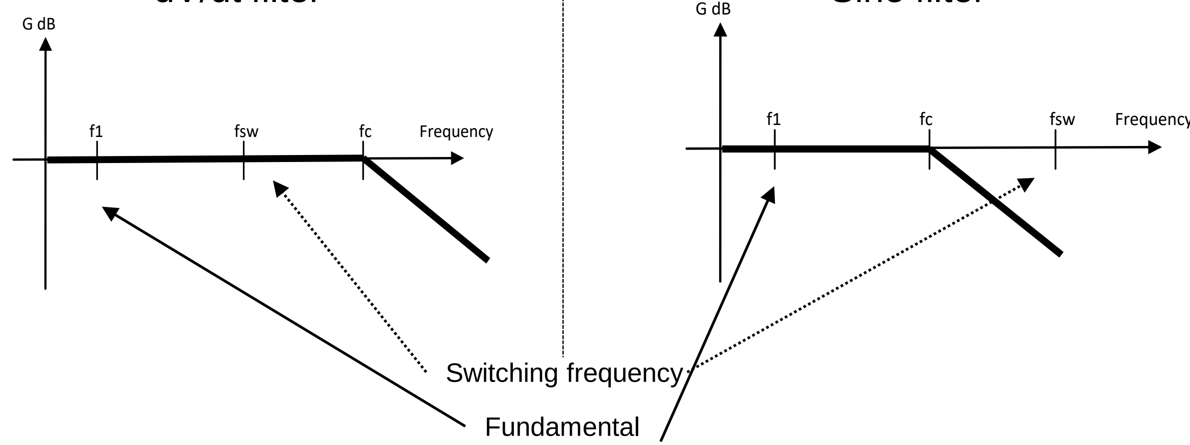
Output choke



dV/dt filter



Sine filter

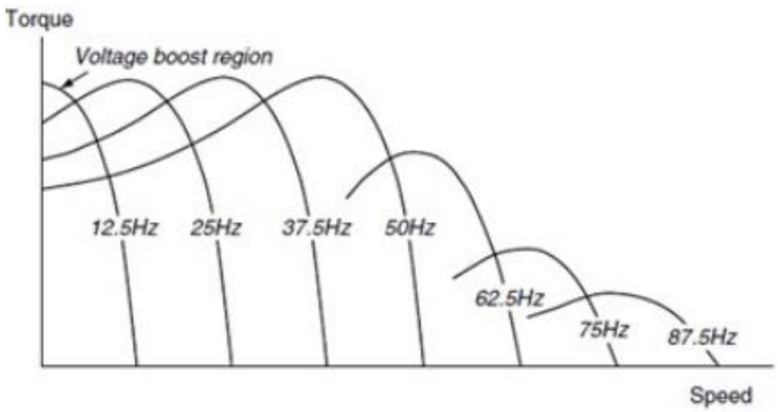


	Output choke	dV/dt filter	Sine Filter
Noise, mechanical vibrations and torque pulsations	--	--	++
Overheating	-	--	++
Overvoltage stress (differential mode)	+	++	++
Overvoltage stress (common mode)	-	+	++
Motor bearing currents	-	+	++

VSD control

Scalar Control

- Voltage controlled according to U/F to keep constant flux
- Voltage boost to improve starting/performance at low speed due to resistive voltage drop



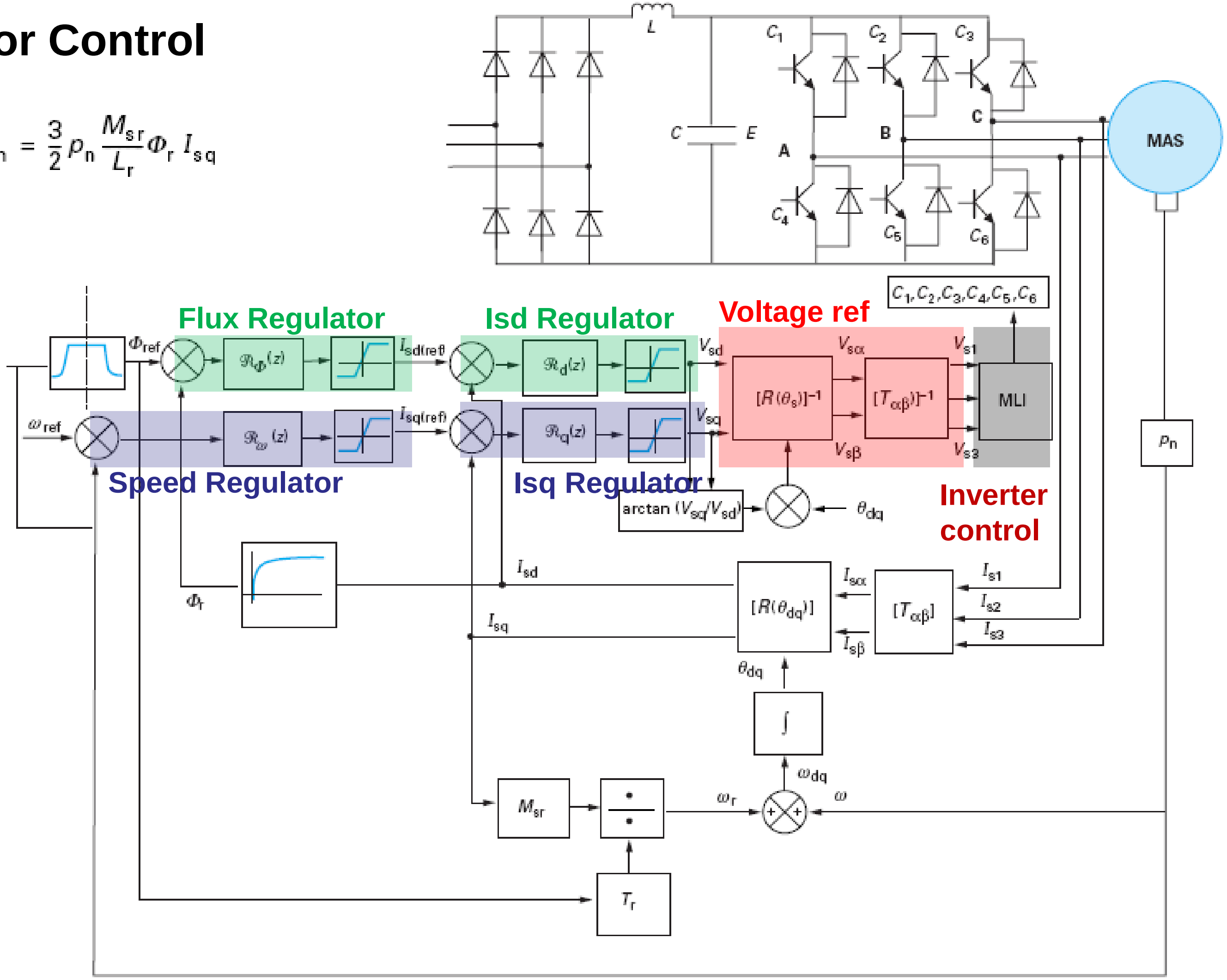
Applied where:

- Fast response to torque/speed **is not** required
- If multiple motors are to be supplied from 1 VSD

VSD control principle

Vector Control

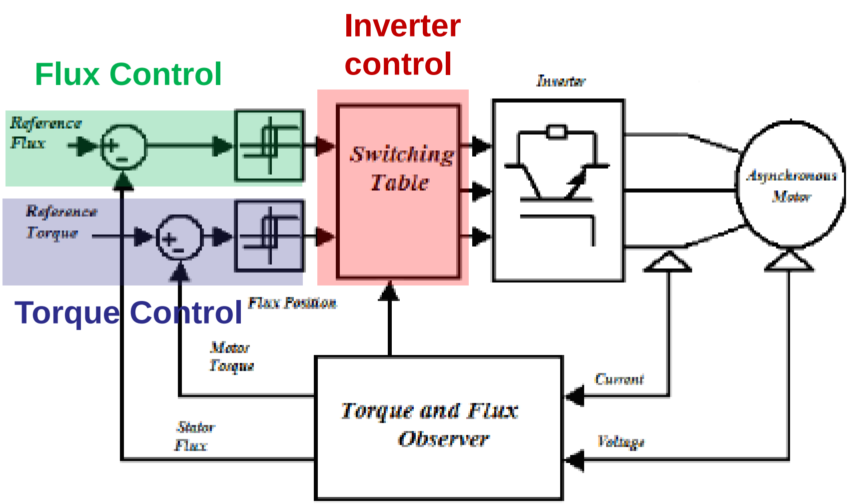
$$C_{em} = \frac{3}{2} p_n \frac{M_{sr}}{L_r} \Phi_r I_{sq}$$

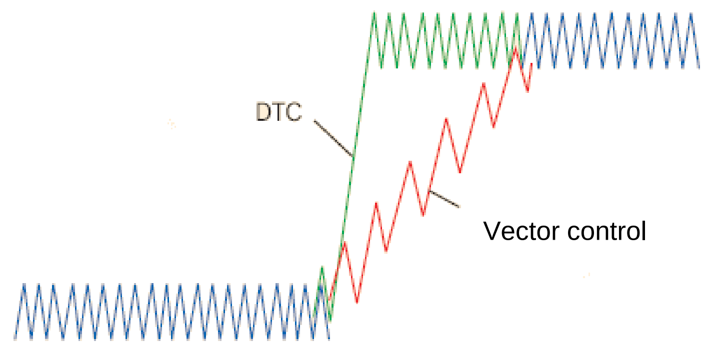


VSD control

DTC (Direct Torque Control)

- Inverter is controlled directly by torque and flux reference
- Usually applied when fast torque and speed responses are required.





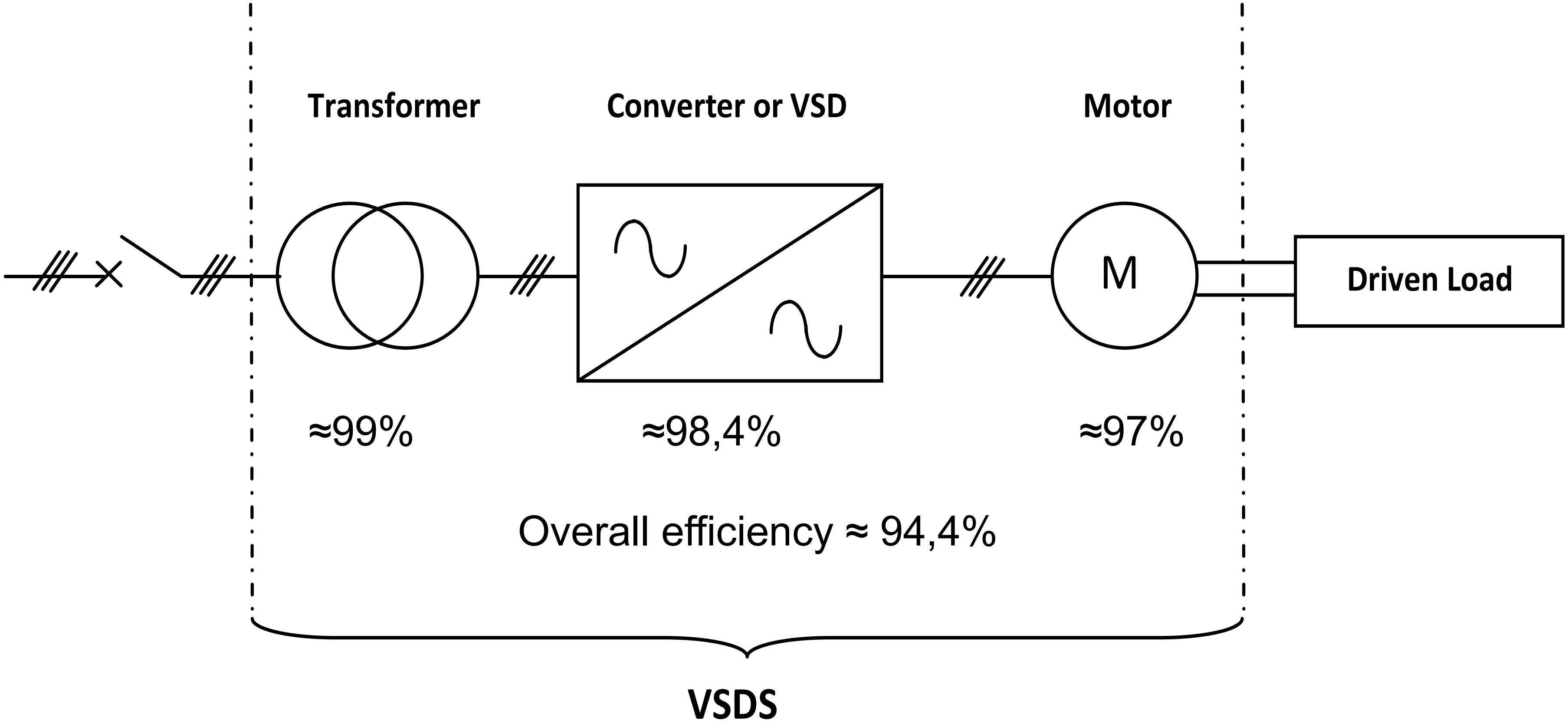
VSD control

	Control Mode	
	Scalar Control	Vector Control or DTC
Torque accuracy Rising Time	~+/-3% ~6 to 10 Cn/s	~+/-1% ~50 to 100 Cn/s
Speed Static Accuracy Dynamic Accuracy	 ~+/-0.01% 3% in 1 sec	 ~+/-0.01% 0.3% in 1 sec

VSD cooling

MV VSD efficiency rules of the thumbs

Rough assessment of VSDS losses



VSD cooling

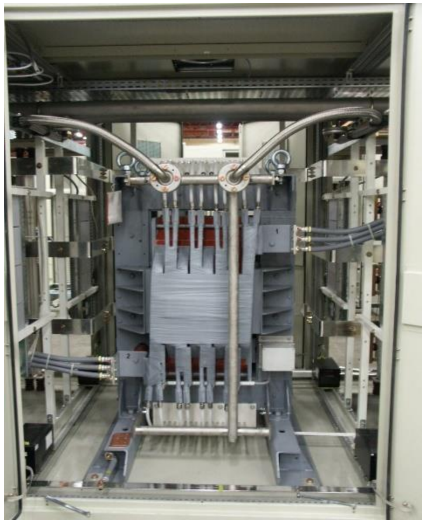
Air cooled MV VSD

- 100% of losses dissipated in air
- Evacuation through duct or HVAC (HVAC to be sized to absorb all losses)
- Arc fault issue (Safety) due to opening in cubicles
- High noise

VSD cooling

Water cooled MV VSD

- Use of deionized water since MV power elements are directly cooled by water
- 95% of losses transfered to water circuit
- 5% of losses dissipated in air (cooling circuit radiation in air) this shall not be forgotten when sizing HVAC unit



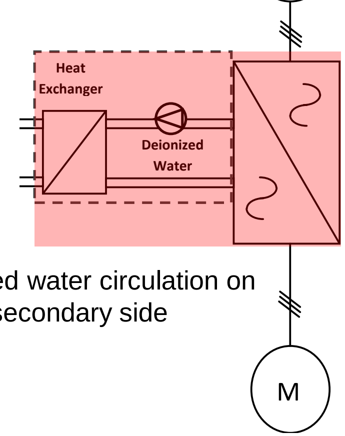
Water cooled typical configurations

Water available on site: Use of water to water heat exchager + pump

Pump integrated to the VSD

Heat exchanger can be integrated to the VSD or can be outdoor

Raw water or sea water circulation on primary side

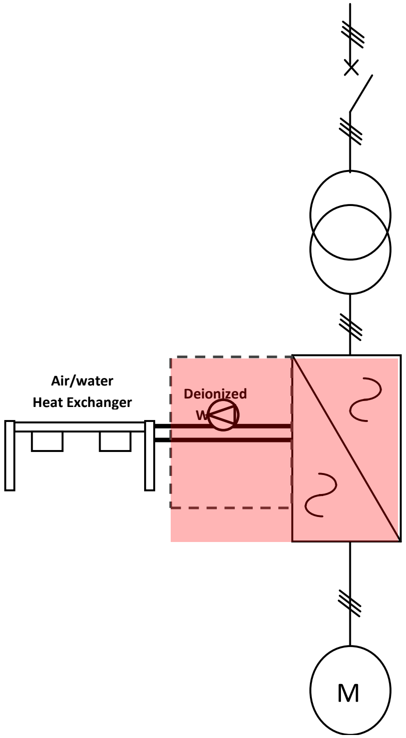


Deionized water circulation on secondary side

Water cooled typical configurations

No water available on site: use of fin fan cooler + pump

Installation of outdoor fin fan air cooler



- Pump integrated to the VSD

For high site temperature (typically >40°C such as Middle East)
Chiller system shall be considered to cool water to avoid VSD large power derating

VSD Cooling in cold ambient <0°C

If the cooling water can experience negative temperature

Glycol shall be added to water to avoid freezing the water

Temperature	Glycol % in volume
+1 °C	0 %
-3 °C	10 %
-10 °C	20 %
-15 °C	30 %
-20 °C	35 %
-25 °C	40 %
-30 °C	45 %

VSD power derating shall be as well checked since glycol heat transfer is less efficient than water

VSD Cooling, dew point risk

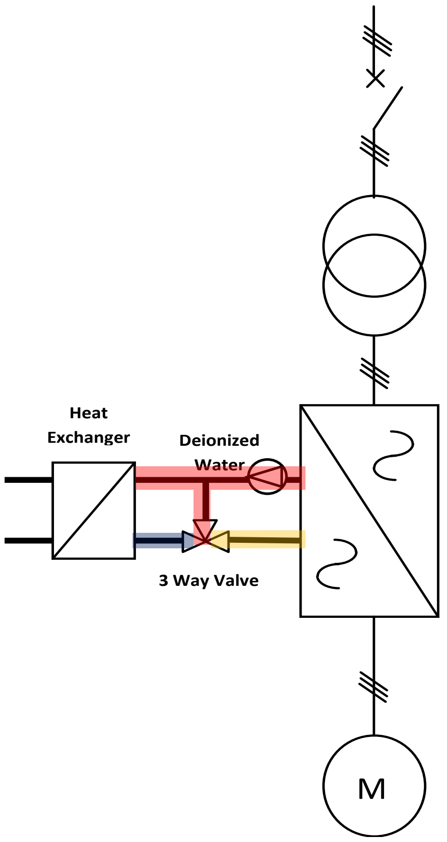
When there is a difference between the room air ambient temperature and the VSD cooling water temperature

↓

Risk of dew point inside the HV section of the converter (arc fault, earth fault)

↓

A 3 way valve shall be installed to avoid dew point by heating up the converter inlet temperature in order to regulate the cooling water temperature above the dew point temperature

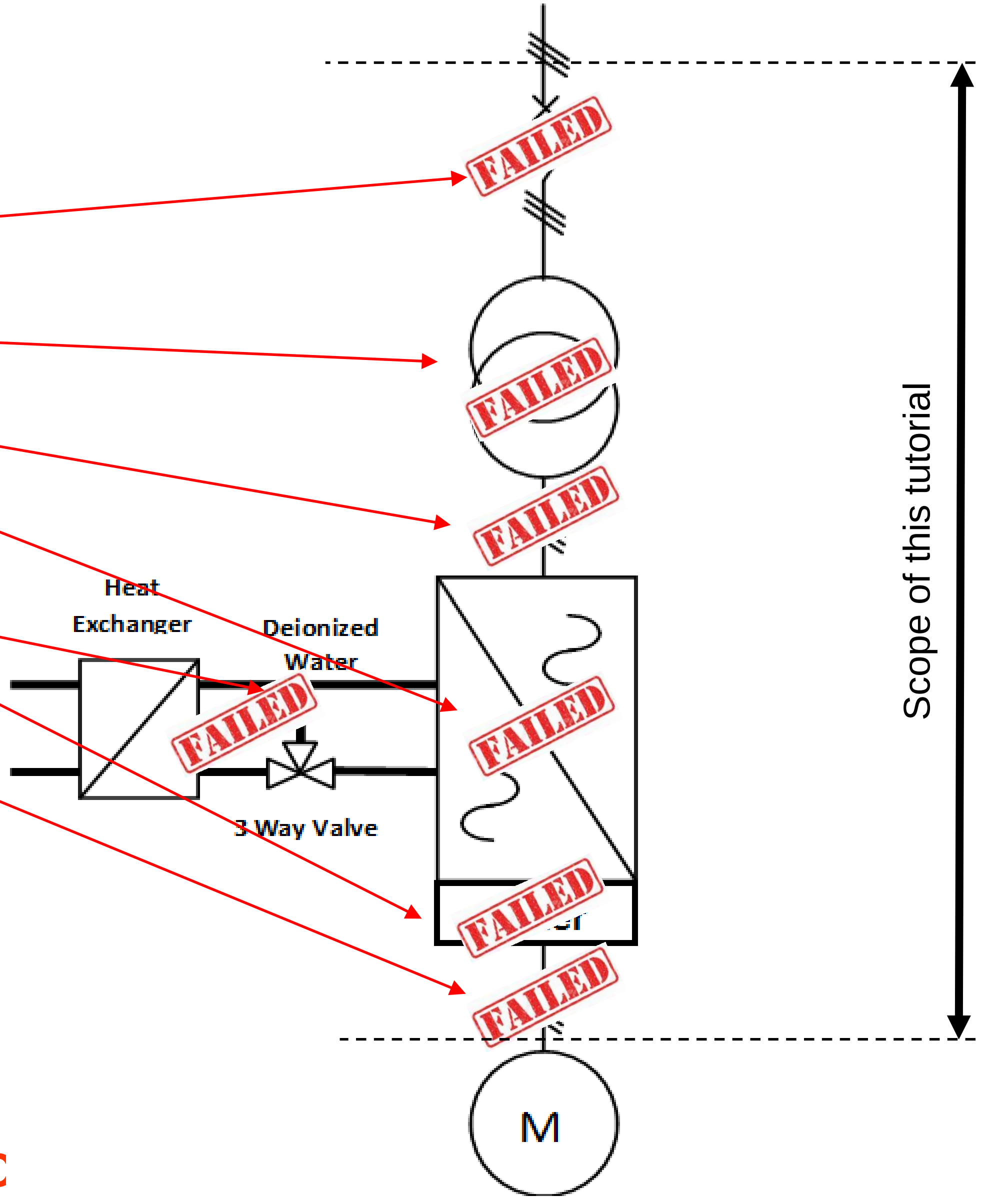


Return of EXperiences REX

Return of EXperiences REX: Summary

Summary:

- HV cells
- Input transformer
- Input Power Cables
- VSD (Power & Control)
- Cooling
- Harmonic filter (next tuto)
- Output power cables



Conclusion

Poor quality control on standard part in the factory

PDCS: Protection relay not properly refresh its data via the network (load shedding priority), loss of parameters, ...

Circuit breaker :Tripping action time not matching with the datasheet

VT 11kV

Voltage transformer 11kV explosion due to a short circuit on secondary side.

Monitoring windows broken

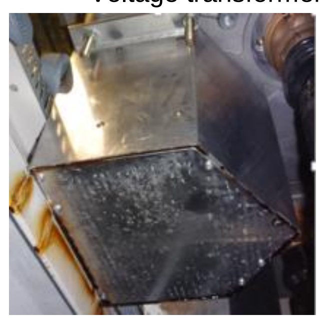
No HV fuse found open.

VT 36kV

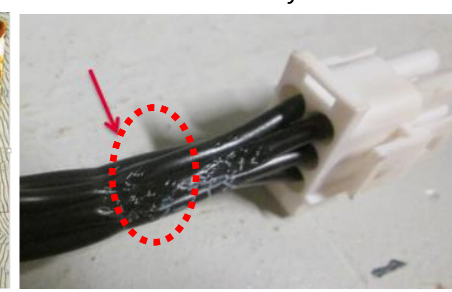
Voltage transformer 36kV explosion due to a short circuit on secondary side.

- zero sequence CT not fixed
- no trefoil trought the MCT
- Earth cable not pulled

Cubicle sealing not matching with cable sizing Dust ingress,…



VT bottom part



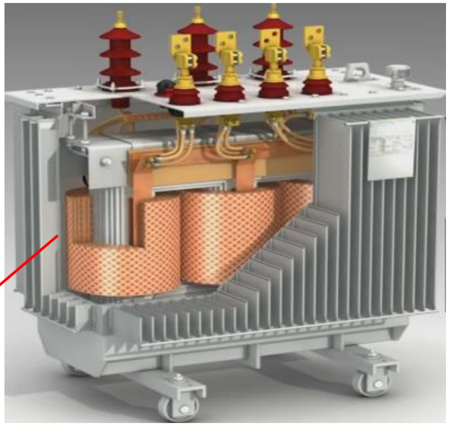
the clip was too tight.

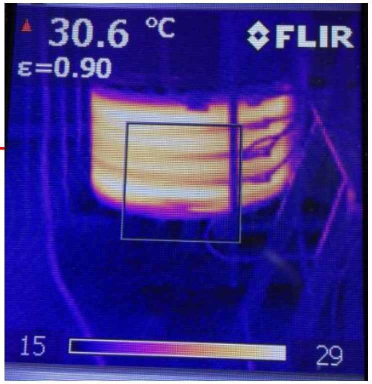
Result:
Overall shutdown due to a significant smoke detection

Power transformer

Poor manufacturing for offshore transformer

Poor assembly made by a “summer worker” and without any quality control in the factory





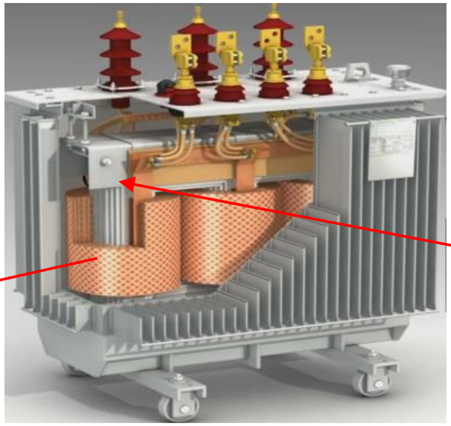
Useless splicing at only 5 cm to the goal

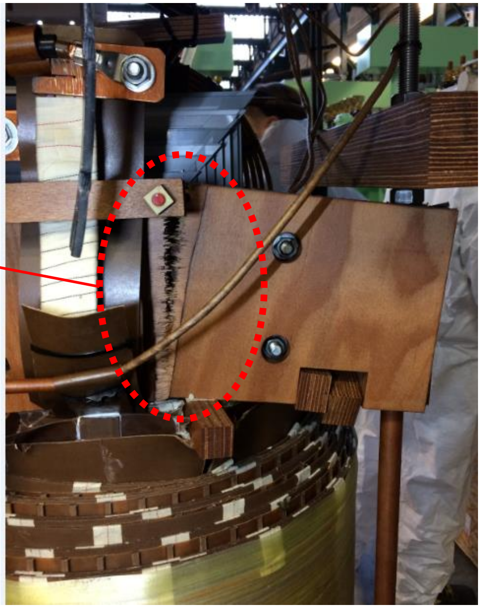
Result:
6 months of flaring and lost production

Power transformer

Real short circuit behavior neglected

VSD input transformer behavior under a real short circuit based on “extrapolation” of a standard transformer used for electrical distribution and a DC component not taken into account.



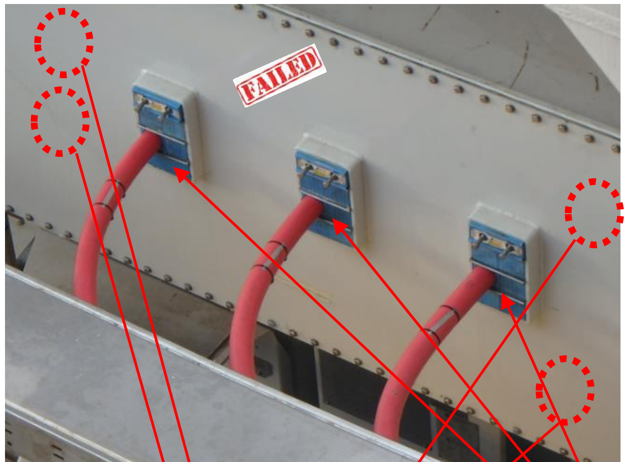


Electrodynamic effect not as per expectation

Result:
6 months of lost production and the critical situation on the similar transformer design deployed on site.

Input Power cables: Junction box

Poor hookup execution found after some years in operation



Transformer JB

Ex"p" box lost due to bad welding

Bad routing on HV cables leading to a gas ingress into the JB

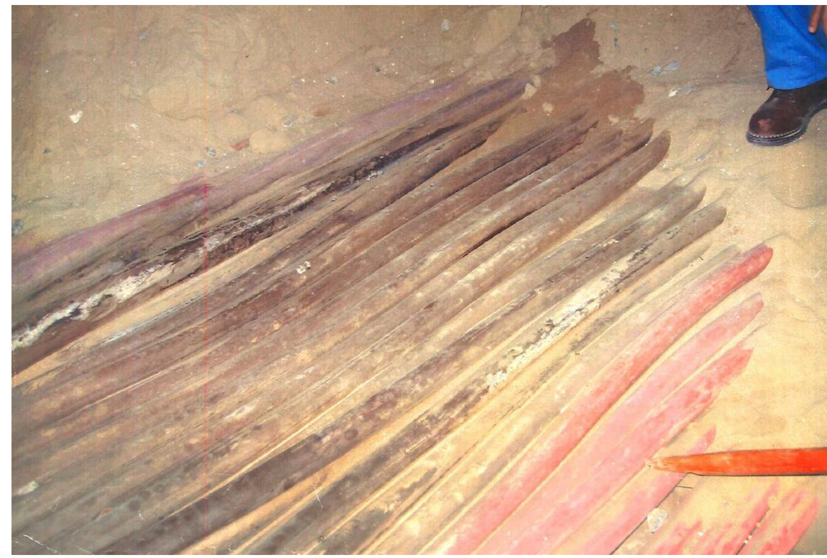
Result:
JB pressure leak

Input Power cables: Termination head

Poor hookup execution found after some years in operation

Before repair

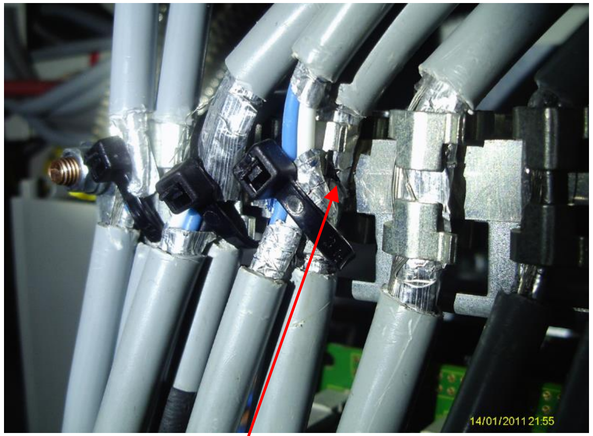
After repair



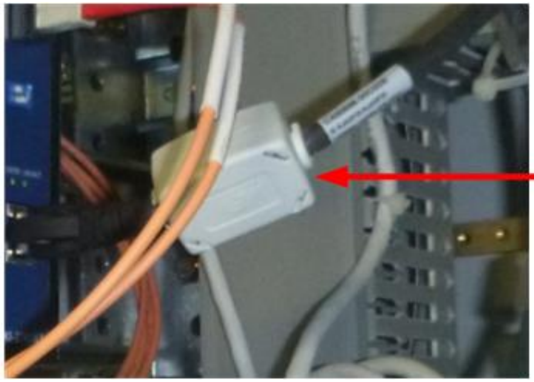
Cables overheating:
Pulling cables not in trefoil increasing significantly the induced current

VSD (Power and Control)

Control command part : Quality and design issues:
EMC issues with spurious trips

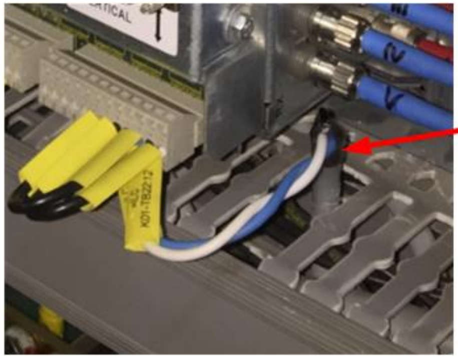


Spurious trip due to a bad cable shield assembly



Common mode filter

Communication failure



Twisted cables
After corrective action

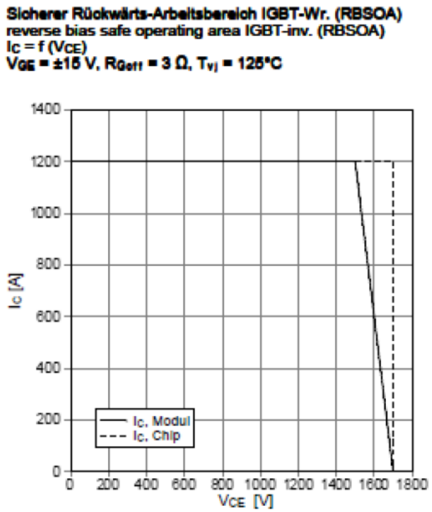
All shield not properly installed

VSD (Power and Control)

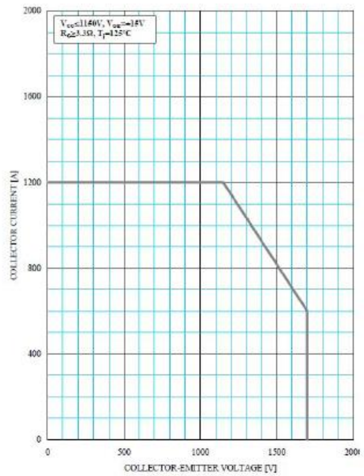
Quality and design issues

Power Electronic parts : Use inside of the same VSD of core power semi conductors components from different vendors with differents characteristics, no traceability from the VSD vendors

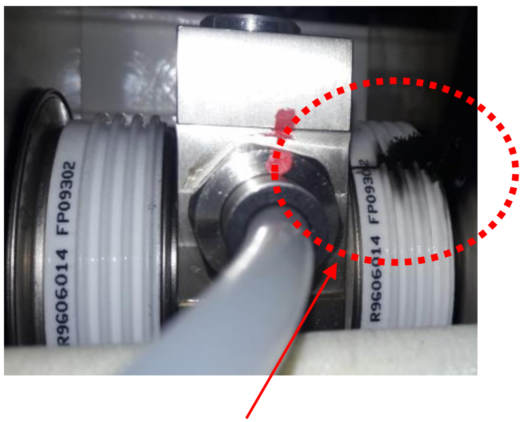
Safe operating area



Infineon FF600R17KE3



Mitsubishi CM600DY-34H

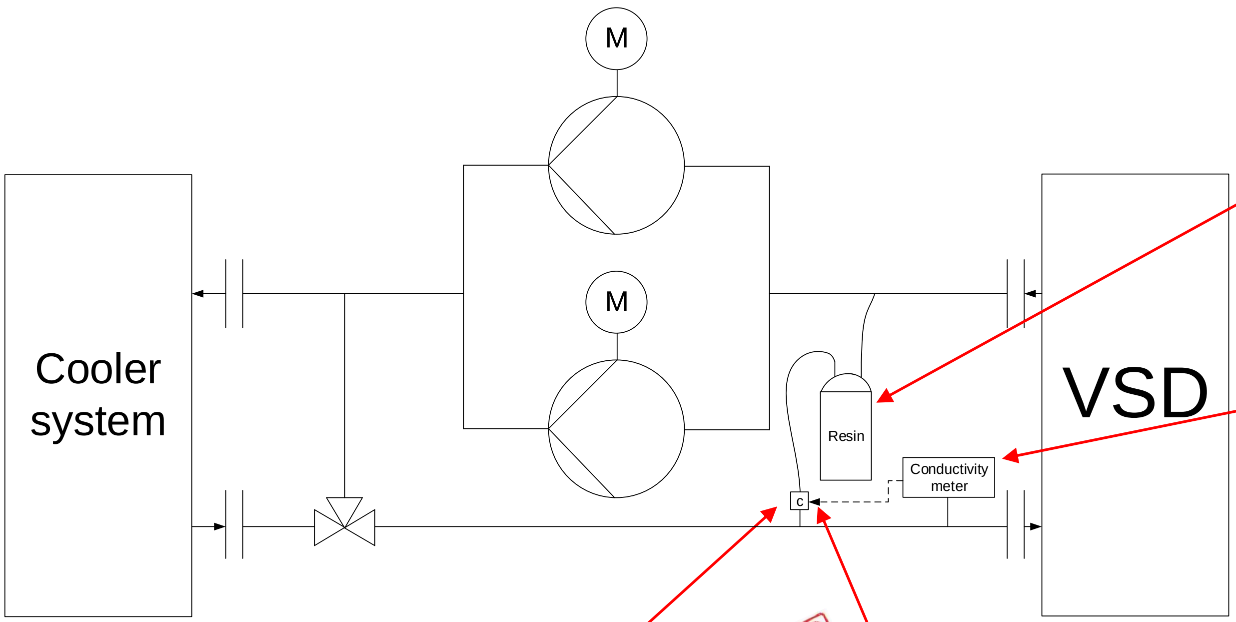


VSD Rectifier: Diode failed led to a DC component into the transformer

- Some functions do not work like controlling the DC bus voltage while the mains voltage dips.
- Discrepancy between drawings and as built VSD

Cooling: VFD liquid-to-liquid cooling system

Several VSD trip due to a bad conductivity control level



Storage more than 1 year

Resin cartridge

Conductivity meter and control if solenoid valve is used)

Better life expectancy of the cartridge but a bit more expensive solution

Solenoid valve

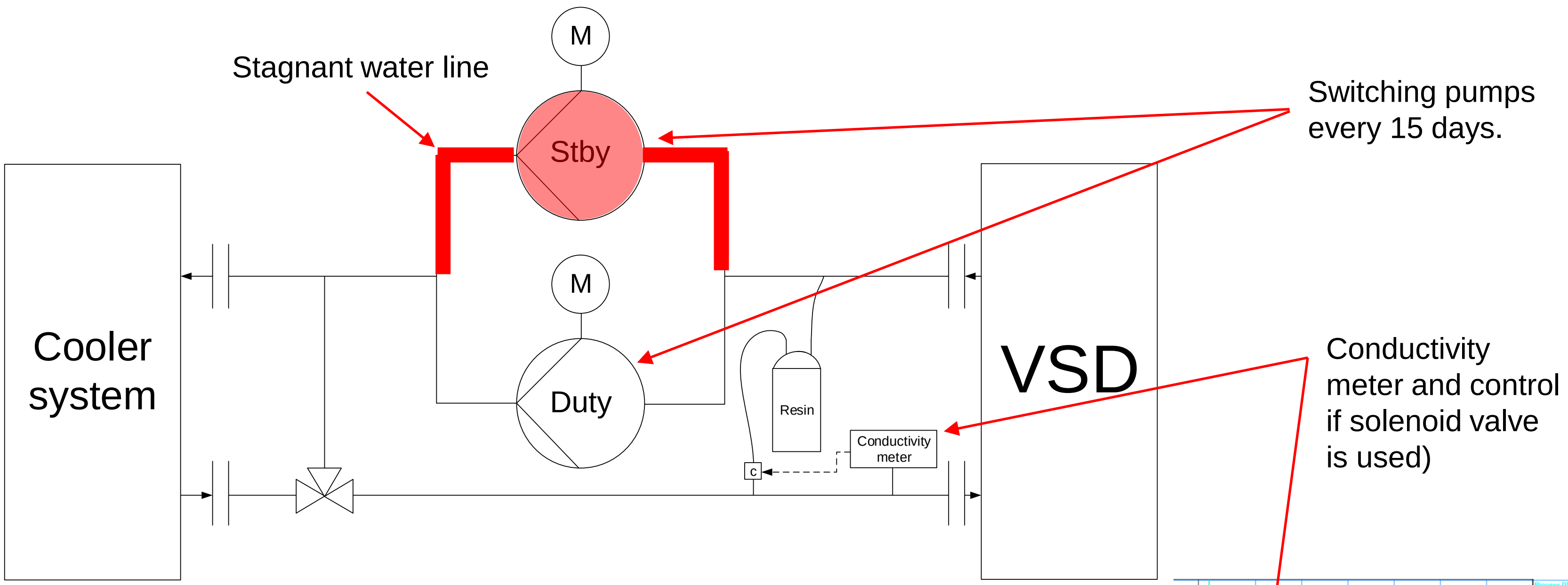
OR

Diaphragm

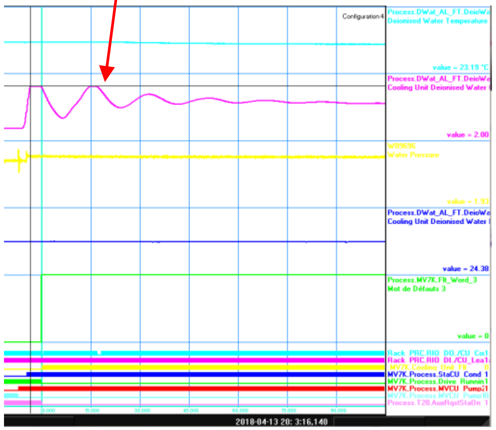
Cheaper but can be forgotten while a cartridge replacement:
As a result: Very low conductivity can be observed and can affect the cooling circuit component.

Cooling: VFD liquid-to-liquid cooling system

Several VSD trip due to a bad conductivity control level



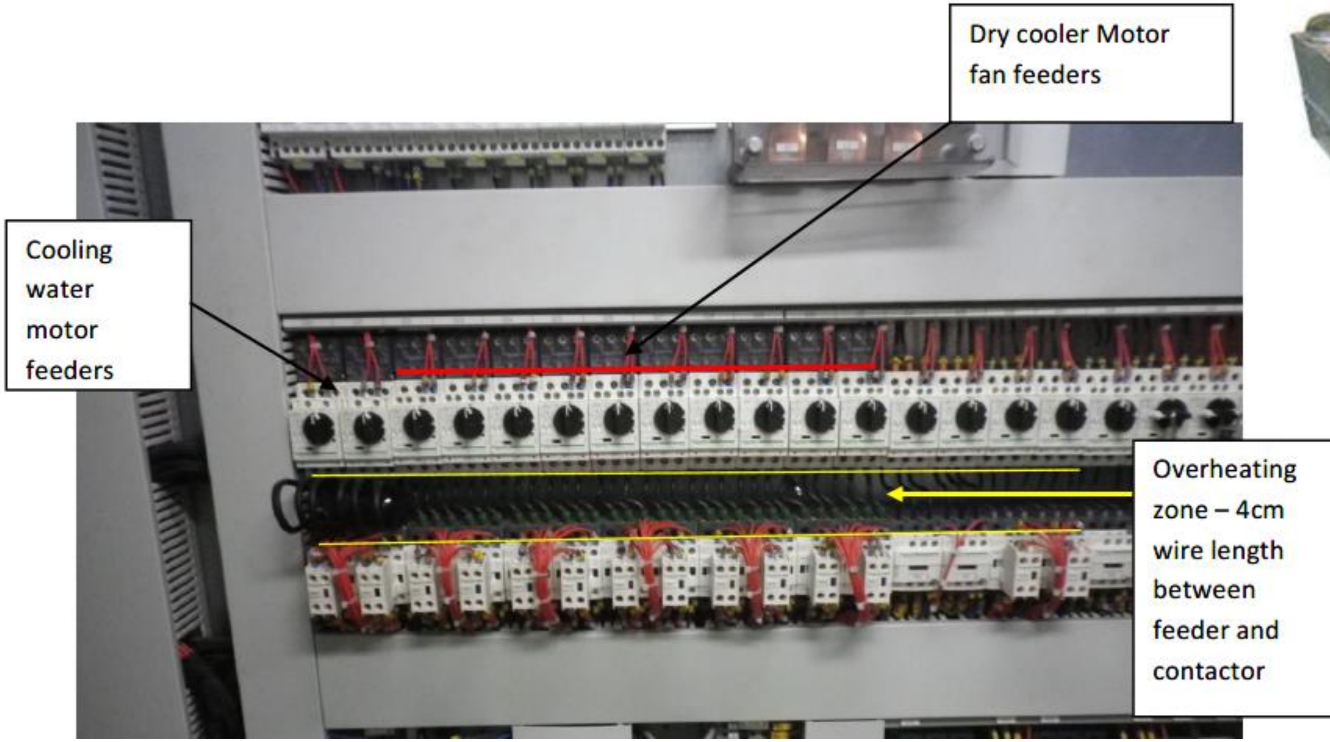
Switching from Duty to Stby generates a transient high conductivity level (above the trip level). Two common phenomena :
- Conductivity level of the stagnant water into the standby line higher
- temperature variation coming from the stagnant line that the algorithm did not take into account



Switching pumps record

Cooling: liquid-to-air cooling system

Overheating issue on HVAC MCC Cabinet



Cooling: Primary side

Quality and design issues

- Need to refill completely cooling circuit when changing power semi-conductor stacks
- Need possibility to change the bottle of resin for deionized water cooling circuit without stopping the drive
- Water cooled VSD need to be refilled regurlarly to compensate micro leakage

Space for repair and maintenance

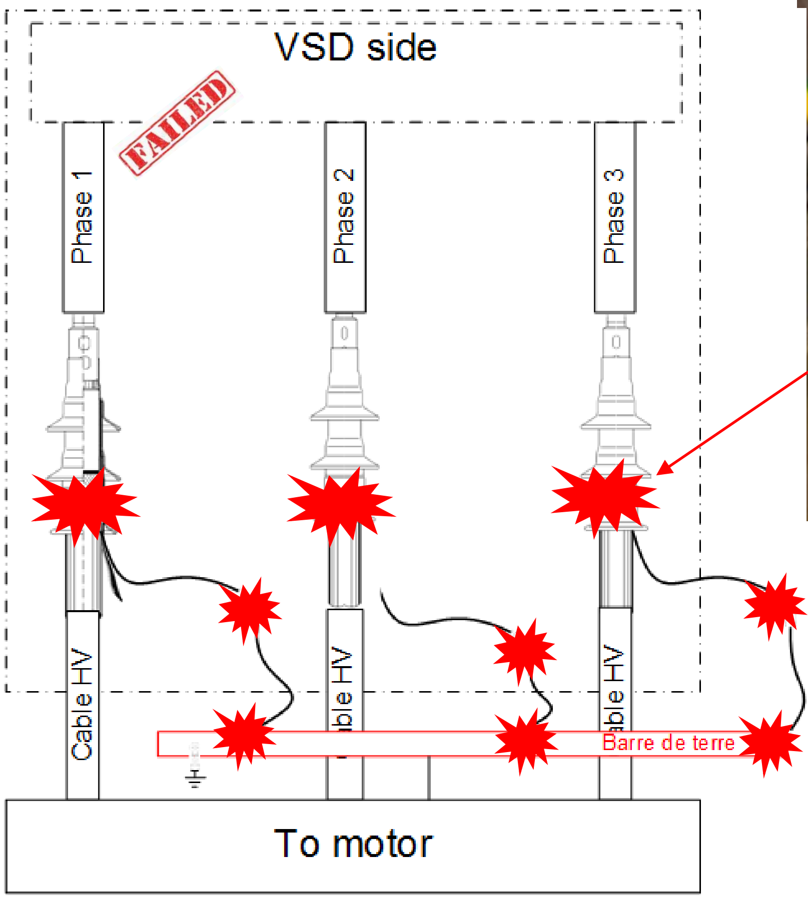
- Need to be able to change of motor or a pump without dismantling piping
- Need space to be able to change power semiconductor when they fail without dismantling other bulky component

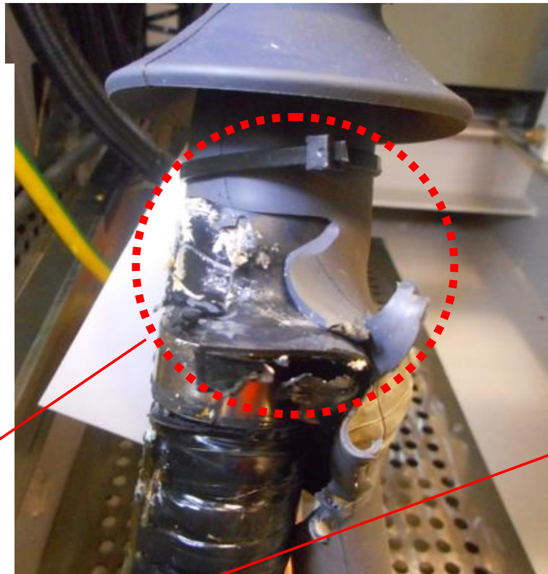




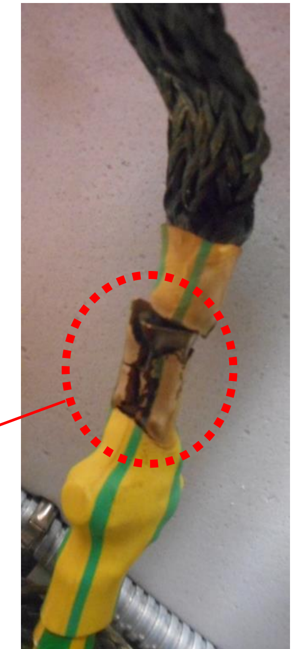
Output Power cables: VSD output termination head

Screen current value neglected while the frequency and the line current are high





Overheating effect



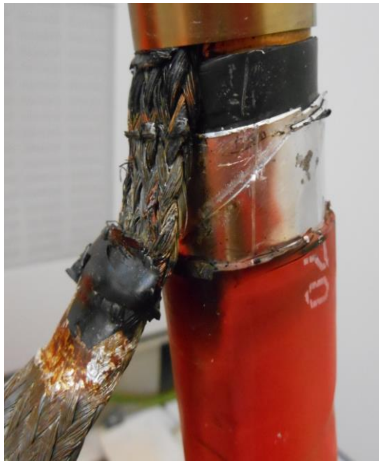
Overheating effect

Overheating effect

The Lugs used are made of stainless material instead of tinned copper and not properly crimped.

Output Power cables: VSD output termination head

Most common failure seen



External failure mark

Earth braid onto the springs

Bad connection of the earth braid because of Insulation tape forgotten

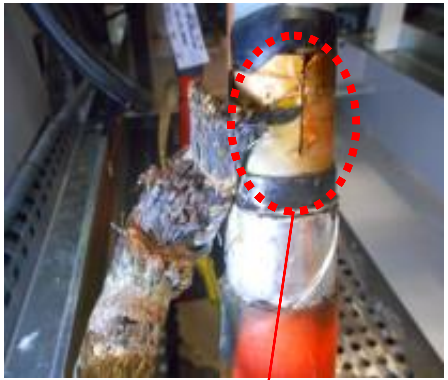
Iscreen = I line

Output Power cables: Termination head

Most common failure seen on site

Poor contact between the cable screen and the ground braid due to a PVC tape forgotten

Poor contact between the cable armor and the ground braid due to the important thickness of the aluminum alloy tapes material.



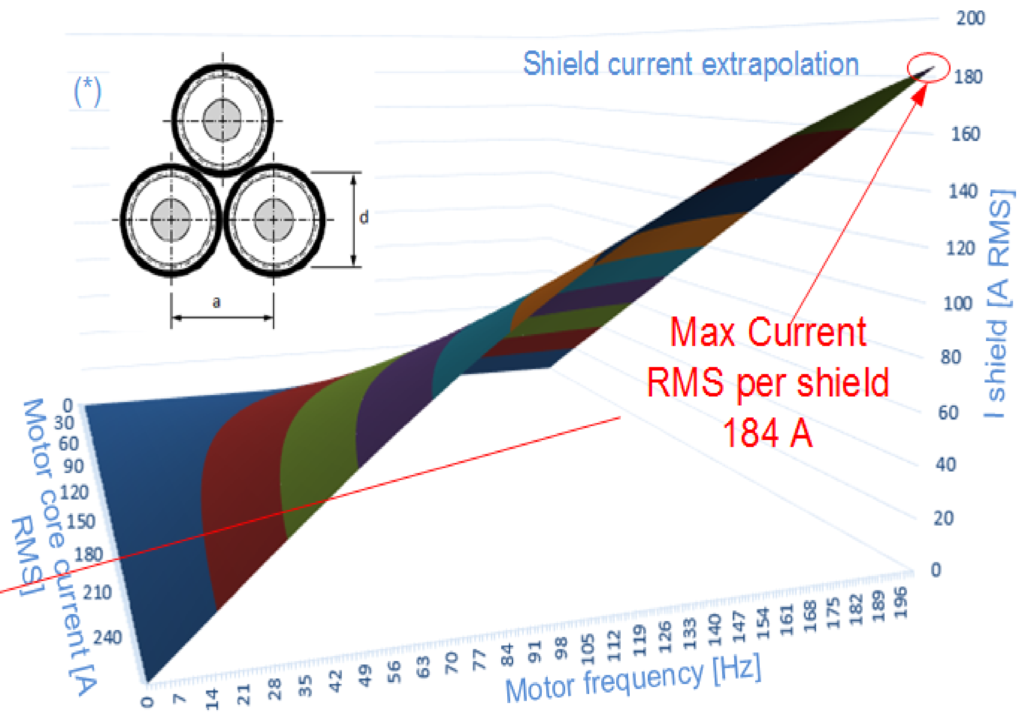
The cable screen has been cut without reason. The effect is to increase the contact resistance, thus overheating.

Kind of Repair

Output Power cables: Termination head

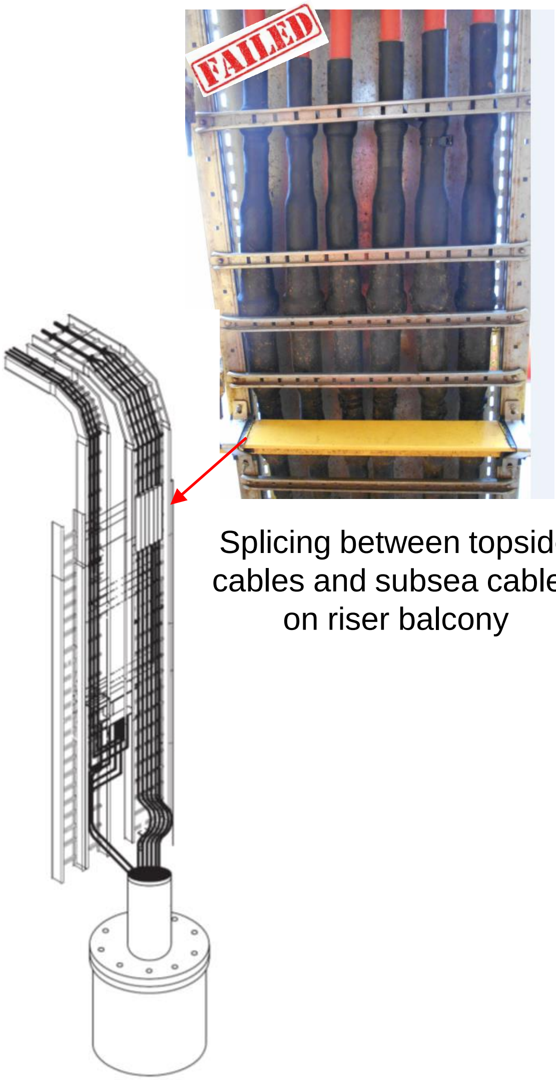
Induced current calculation: a Case study for High-speed motor

Data	Value	Unit	Description
F =	200	[Hz]	Motor frequency
a=	58,9	[mm]	Geometrical data*
d=	44,9	[mm]	Geometrical data*
L=	0,23	[km]	Cable lenght
Icore=	266,00	[A]	Motor current per core
E=	14,83	[V]	Shield Voltage
Rshield=	0,0583	[ohms]	Shield resisctance
Lshield=	0,000993	[H]	
Xshield=	1,2478406	[ohms]	
Zshield=	1,2492018	[ohms]	
X=	0,0557561	[ohms]	Shiled impedance
Ishield=	183,85	[A]	Shield current

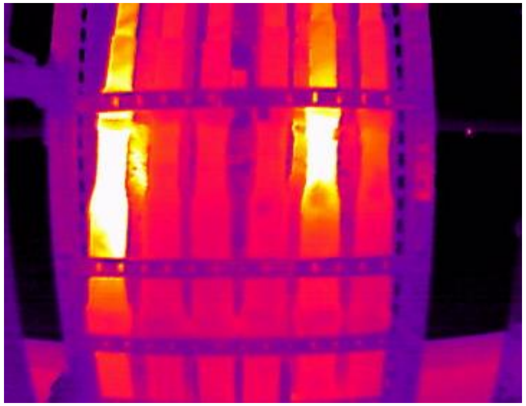


Ishield/Icore=70%

Power cables: Splicing in hazardous area



Splicing between topside cables and subsea cables on riser balcony



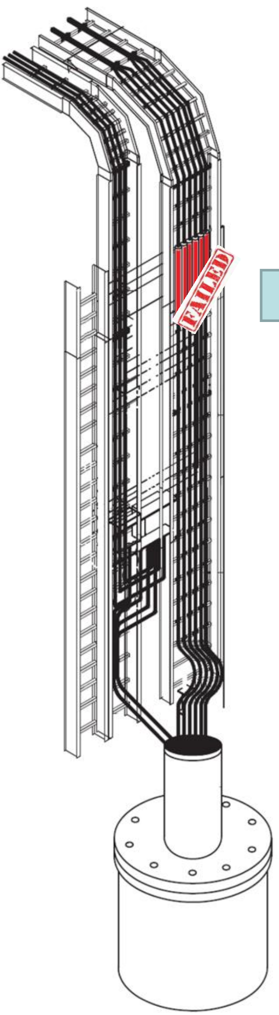
Thermal camera

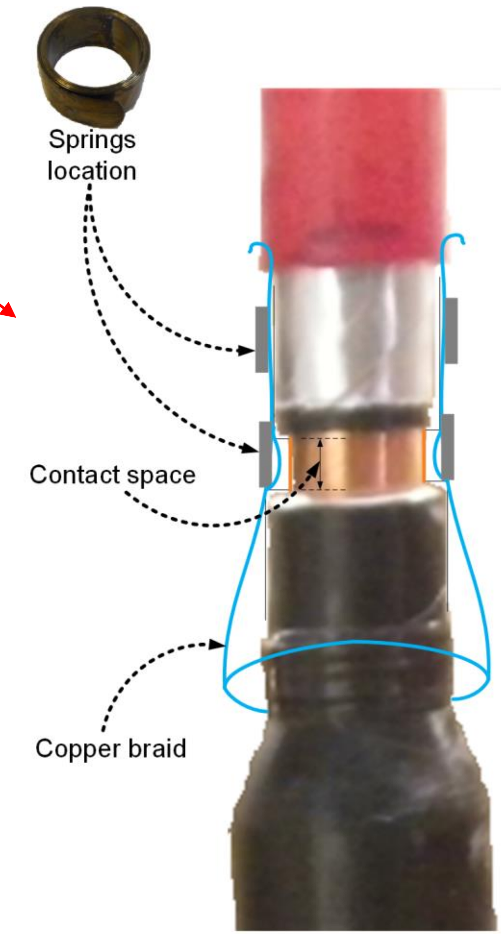
90°C surface temperature at mid load

Result:
Production of the pump line are limited because the problem did not solve yet.

Output Power cables: Splicing in hazardous area

Splicing's dismantling

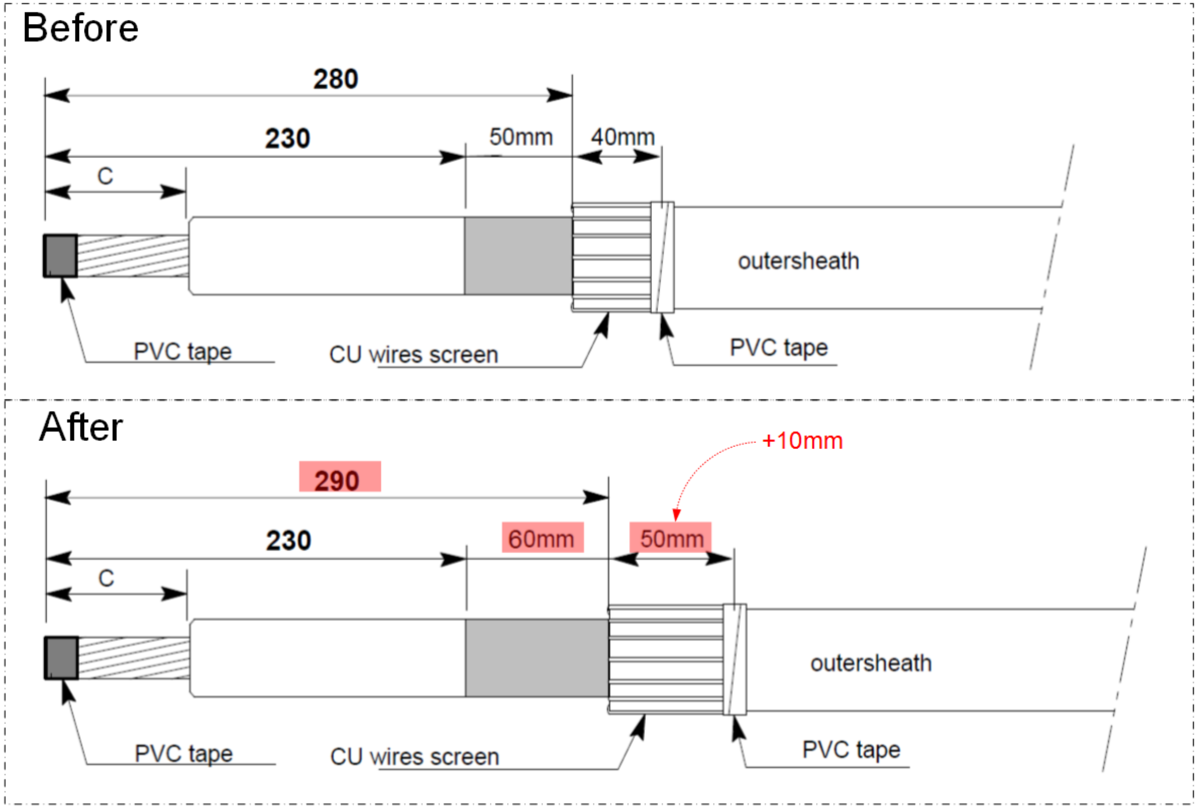


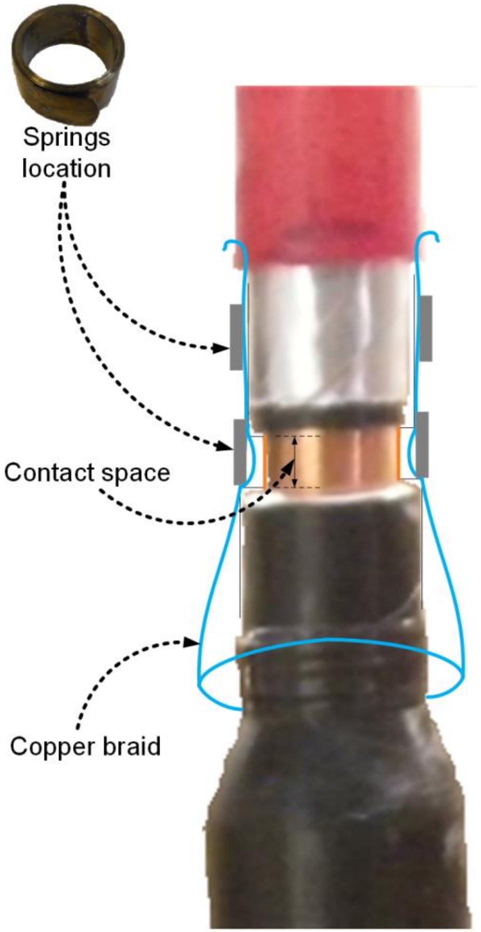


Dismantling

Output Power cables: Splicing in hazardous area

Example of design modification agreed with the manufacturer





Return of experiences

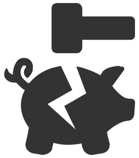
Conclusion

Human ressources issues

- Lack of skilled/experienced commissioning engineer, not able to:
  - Investigate/correct issues
  - Tune properly the VSD

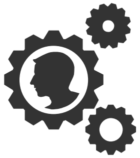
- Significant turnover on site needs to have a very simple VSDS to maintain and troubleshoot

Opex issues



- Cost of spare parts expensive

REX and Lessons learned



- Lessons learned of one project are not reflected or communicated to others projects within contractors/manufacturers organisations.

Software and firmware management

- Lack of proper management of software versions where VSD vendor does not know the versions installed inside the VSD
- Software not properly validated by the VSD vendor before commissioning
- Ride through capability issues with regards to voltage dips
- Factory modifications made without internal validation

Next tuto: ICBM (integrated based monitoring for VSD) A new development that need to be launched.

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