EUR24_03

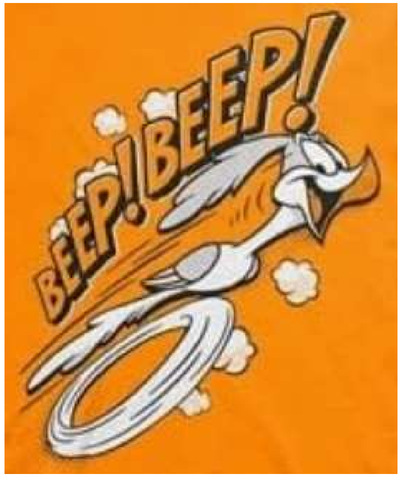
State of the Art of High-speed Motors VSD-fed Technologies for Compression

Rotterdam - Nederland

Dr. Lionel Durantay, GE Vernova Power Conversion
Global Product & Technology Leader

Summary

- **INTRODUCTION → GAS MONETIZATION & GREENHOUSE GAS EMISSION**
- **ELECTRIC TECHNOLOGIES FOR COMPRESSION**
  - (SYNCHRONOUS WOUND) VS (SQUIRREL CAGE) VS (PERMANENT MAGNET) ROTOR FOR SPEED-SPEED MOTOR
  - (LCI) VS (NPC-VSI) VS (NPP-VSI) DRIVES
  - (4-POLE) VS (2-POLE) HIGH-SPEED MOTORS
  - COOLING
  - ACTIVE MAGNETIC BEARINGS

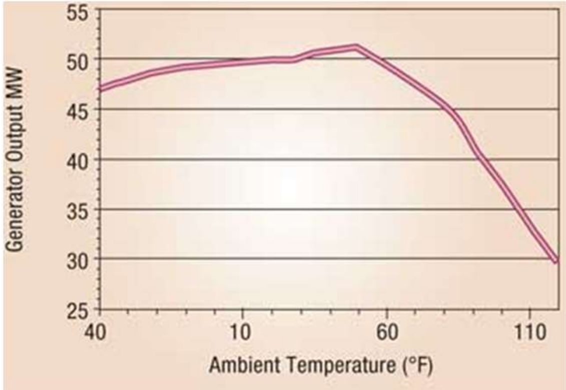


- **ELECTRIC SYSTEMS SOLUTIONS FOR COMPRESSION TRAINS**
  - COMPRESSOR OPEX & CAPEX OPTIMISATION / 80MW & 40MW BUSINESS CASES
  - ELECTRIC SYSTEMS PROS & CONS
  - ELECTRIC SYSTEMS FOR STARTER-HELPER LNG TRAINS
  - ELECTRIC SYSTEMS FOR FULL ELECTRIC LNG TRAINS
  - (GEARED STANDALONE TRAIN) VS (DIRECT-DRIVE STANDALONE TRAIN) VS (DIRECT-DRIVE INTEGRATED TRAIN)
  - TURBINES REPLACEMENTS
- **ELECTRIC COMPRESSION COVERAGE - CONCLUSION & PERSPECTIVES**

INTRODUCTION

Gas Peak ➔ Less Resources over the Time ➔ Gas Monetization

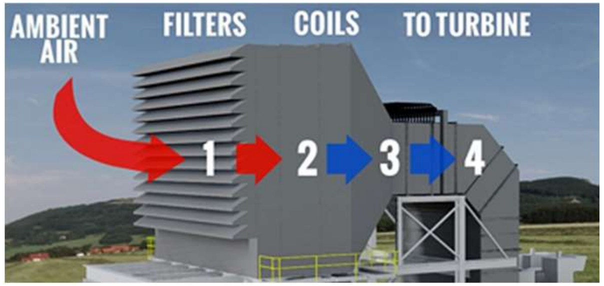
Gas turbine is a thermal machine with rating limitations (speed, temperature, humidity, pressure …) coming from the physics of the gas (thermodynamic and combustion)



Gas Turbine Output highly derated in harsh climatic conditions

&

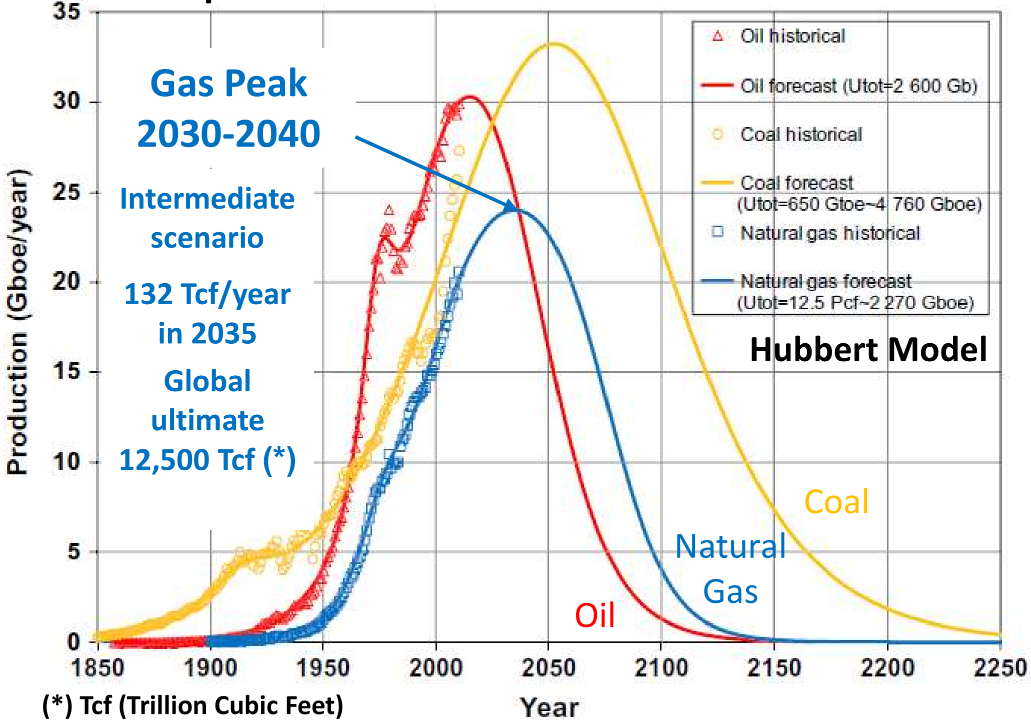
Greenhouse gases emission (New Regulations are coming …)



1. Ambient air enters chilling coils
2. Thermo process between coils & ambient air removes sensible & latent heat from ambient air
3. Resulting air is at design inlet temperature
4. Chilled air is ingested into the compressor of the turbine

G. Maggio, G. Cacciola / Fuel 98 (2012) 111–123

Expected Production vs **Limited Resources**



(*) Tcf (Trillion Cubic Feet)

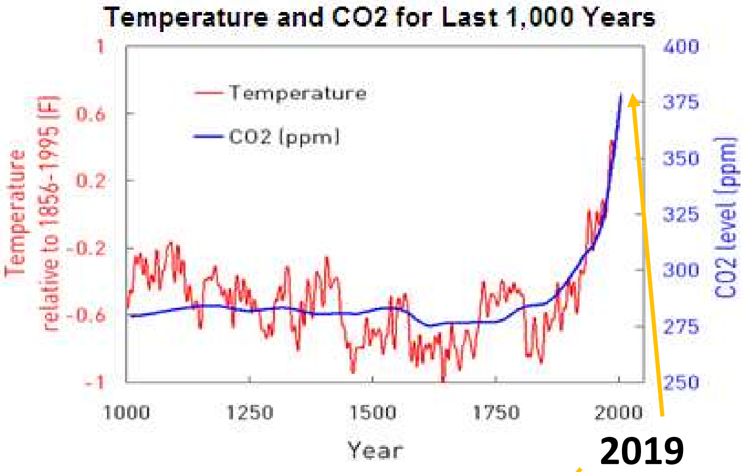
(**) Gboe (Giga Barrels of Oil Equivalent)

Fig. 16. Comparison of fossil fuel forecasts calculated for intermediate Ultimate scenarios.

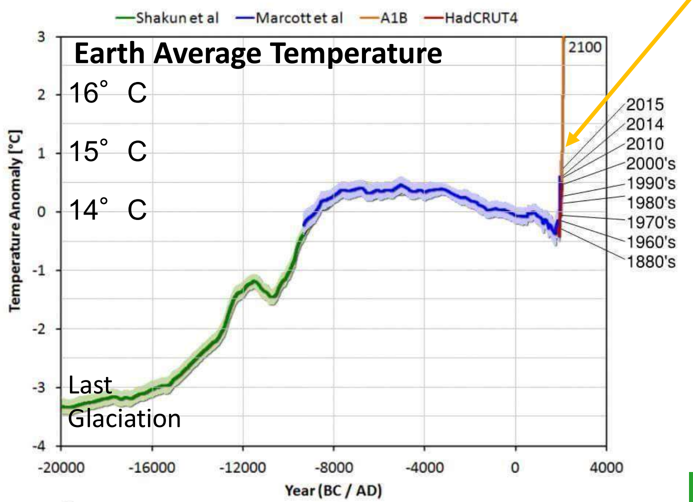
Low OPEX (Efficiency) & High Gas Emission

CAPEX (New Investments Costs) will increase

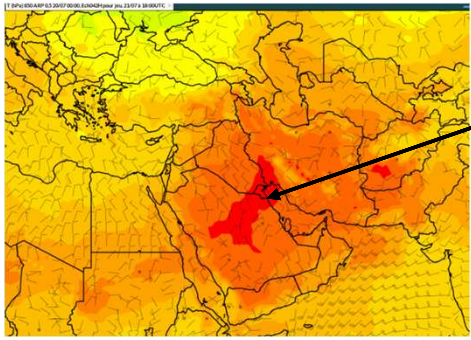
Greenhouse Gases (GG) Emission ➔ Decarbonization Investments



2019

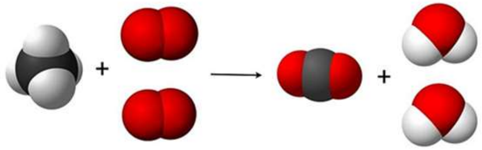


Sources:
http://www.antarcticglaciers.org/glaciers-and-climate/climate-change/
http://data.giss.nasa.gov/gistemp/tabledata_v3/GLB.Ts+dSST.txt



Record of Temperatures …
54° C, July 2016, Mitribah, Koweit
54° C, August 2020, Dead Valley, USA
46° C, June 2020, Avignon, France
38° C, June 2020, Verkhoïansk, Russia (Arctic Circle) …

In 2019, Earth Mean Temperature = 15° C



$CH_4 + 2O_2 \longrightarrow CO_2 + 2H_2O$

(GG) (GG) (GG)

Tax arising in EEC ≈ 40$ Norway ≈ 90$ per Ton of (GG) Emission

Greenhouse Gas Emission

4 billions Tons of CO_2 Emission per year coming from Fugitive Gas Process Emissions (source Energy Institute & The Shift Project) :

- Fleet of 100000+ Steam & Gas Turbines in operation around the world
  - Gas Turbine ≈ 5kTons of CO_2 Emission per MW per year
  - Steam Turbine ≈ 10kTons of CO_2 Emission per MW per year

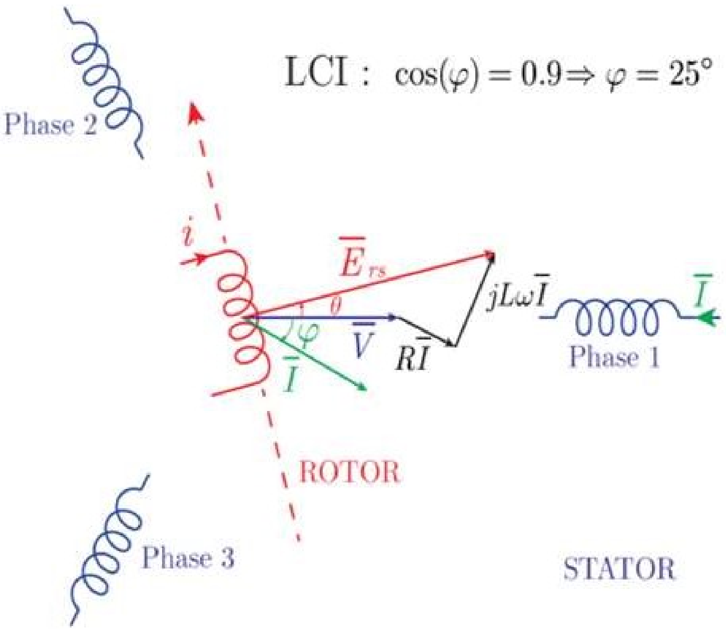
- Flaring
- Dry Gas seals leakage of rotating equipment as compressors
- Pipeline leakage
- Shale Gas pits
- …

10% of the Global CO_2 Emission comes from Gas Process Fugitive Emission

ELECTRIC TECHNOLOGIES FOR COMPRESSION

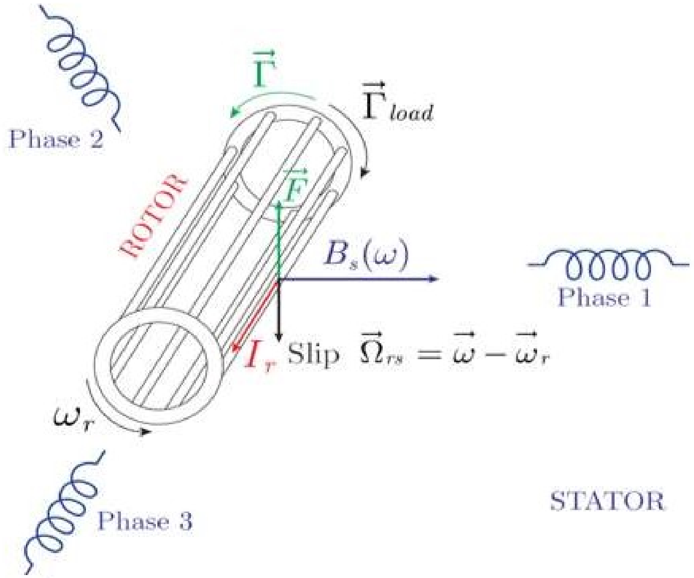
Synchronous vs Induction

Principle of Torque Generation & Control



The rotor is supplied with DC current and creates a rotor magnetic field following the stator rotating field with an angular phase lag θ related to the load with a torque:

$$\overline{\Gamma} = K_1.\ \overline{I_r} \wedge \overline{\emptyset_s} = K_1.I_r.\emptyset_s.\sin\theta \qquad (5)$$



If Resistant torque $\vec{\Gamma}_{load}$ inducing a rotor slippage:

$$\overrightarrow{\Omega_{rs}} = \vec{\omega} - \overrightarrow{\omega_r} \qquad (9)$$

The Lorentz Force induces rotor current into the cage:

$$\overrightarrow{I_r} = K_1.q.\overrightarrow{\Omega_{rs}} \wedge \overrightarrow{B_s} \quad \text{where } K_1 \text{ is a coefficient} \qquad (10)$$

The Laplace Force induces Motor Torque generation:

$$\vec{\Gamma} = K_2.\overrightarrow{I_r} \wedge \overrightarrow{B_s} \quad \text{where } K_2 \text{ is a coefficient} \qquad (11)$$

LCI – Thyristor Turn Off Control

During bridge commutation, the **Total Recovery Time Tq** turning off one thyristor is the sum of:

- the **Reverse Recovery Time** for current falling down to zero
- the **Gate Recovery Time** for draining the residual of charges trapped in the junction, avoiding any risk of thyristor conduction

For efficiency concern, Tq has to be minimized reducing :

- the **Reverse Recovery Time** with low motor sub-transient reactance X'' design
- the **Gate Recovery Time** by the selection of the thyristor

Minimizing Tq & X'' require the Capacitive Reactive Power from the motor designed **below Power Factor 0.92**

Synchronous vs Induction

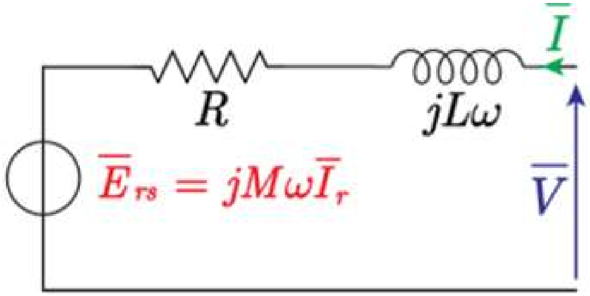


Fig.11 Equivalent Circuit

$$\overline{V} = (R + jL\omega).\overline{I} + (jM\omega).\overline{I_r} \quad (6)$$

$$\overline{V} = f_{syn}\left(\overline{I_r}, \overline{I}, \theta\right) \quad (7)$$

$$\varphi = g_{syn}\left(\overline{I_r}, Load\right) \quad (8)$$

The power factor angle φ is adjustable at a fixed load with the rotor current I_r.

Power Factor Control

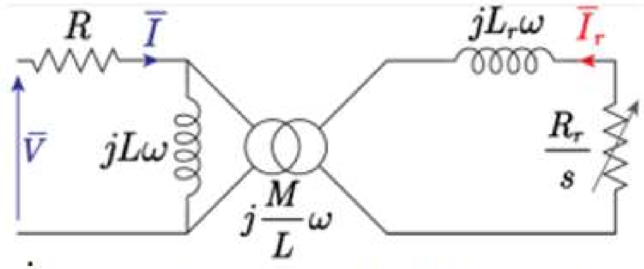


Fig. 14 Equivalent Circuit

$$\overline{V} = \left(R + jL\omega + \frac{M^2.\omega^2}{\left({R_r}/{s}\right) + jL_r\omega}\right).\overline{I} \quad (12)$$

$$\overline{V} = f_{ind}\left(\overline{I}, s\right) \quad (13)$$

$$\varphi = g_{ind}(Load) \quad (14)$$

The power factor angle φ is not adjustable at a fixed load.

Induction Motor not controllable with LCI

Compression Systems

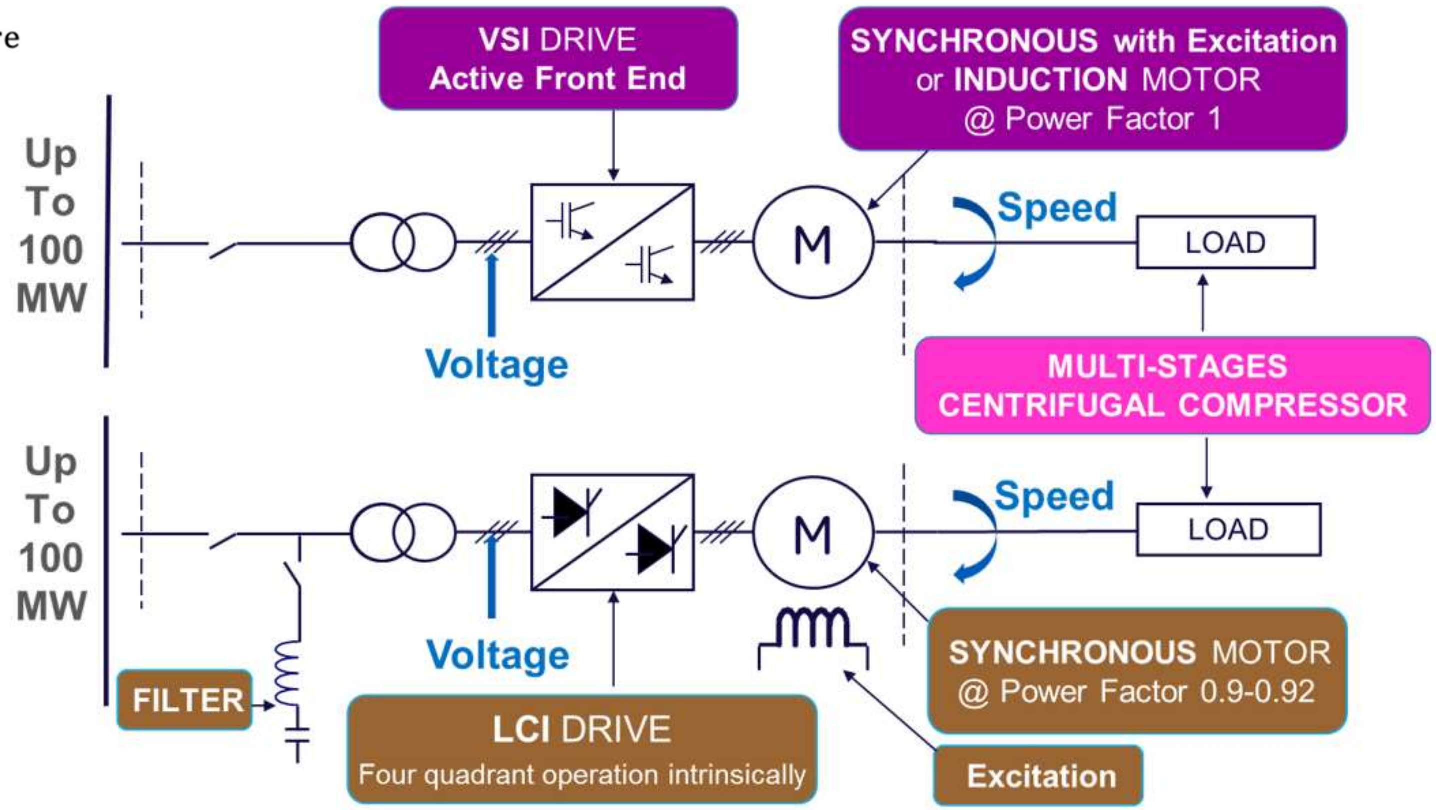
$$\Gamma = \frac{P}{(\omega/p)} \approx \left(D^{Outer}_{Stator}\right)^2 . L_{Magnetic\ Core}$$

2 Key System Drivers:

- Speed ω_r
- Voltage $\overline{V}$

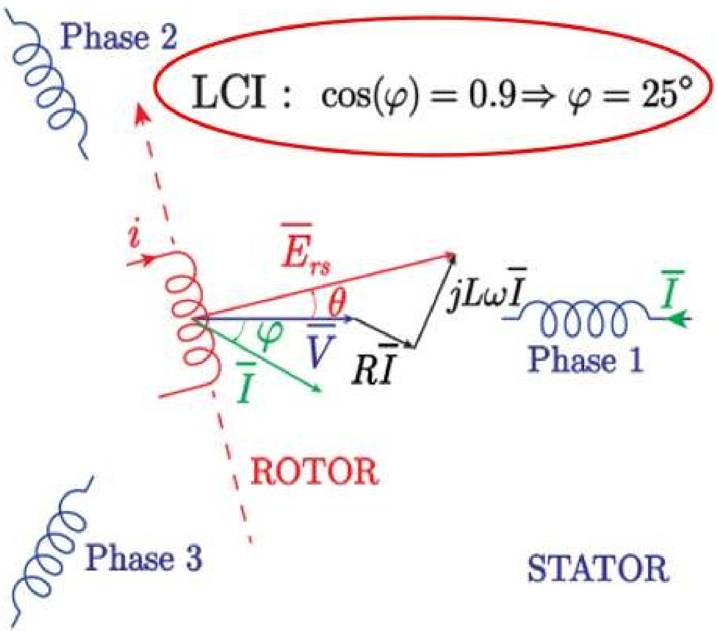
3 Possible Systems:

- LCI + Synchronous
- VSI + Synchronous
- VSI + Induction



Torque Density ≈ Volume of Active Parts ➔ Increase Speed for Compactness
Torque Control possible for Induction Motor with IGBTs (VSI), not with Thyristors (LCI)

LCI vs VSI for Synchronous Motor



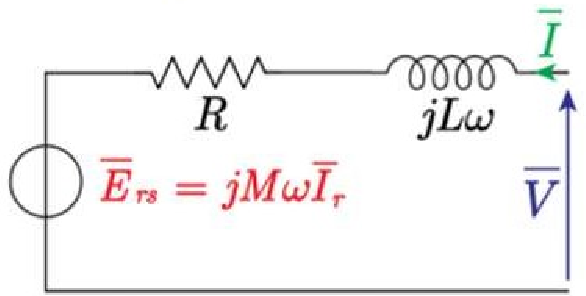
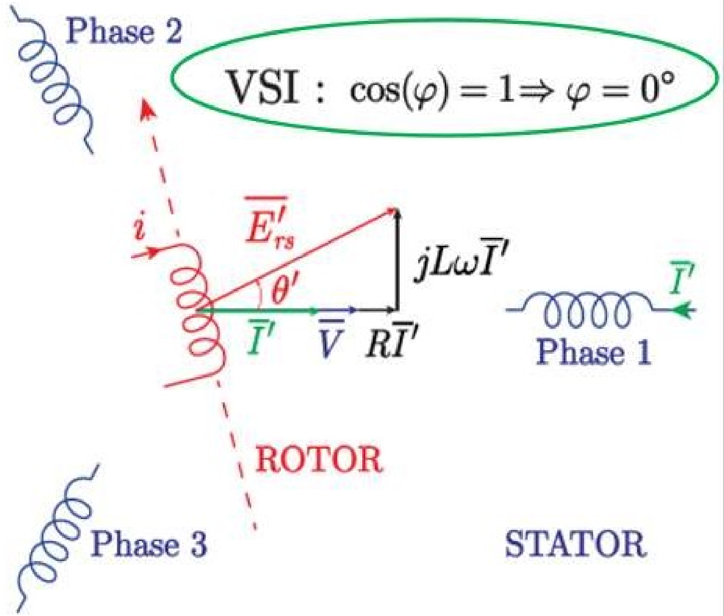


Fig.11 Equivalent Circuit



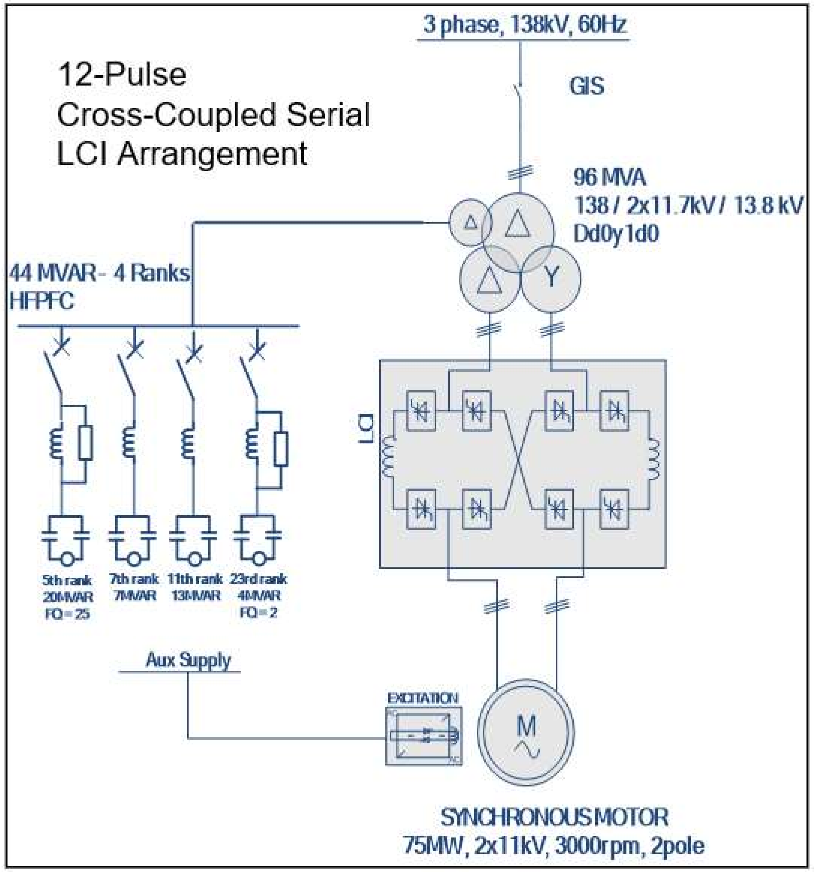
Torque

$$\overline{\Gamma} = K_1 .\ \overline{I_r} \wedge \overline{\emptyset_s} = K_1 . I_r . \emptyset_s . \sin\theta$$

Compared to VSI@PF=1, LCI@PF=0.9 requires more Stator Current $\overline{I}$
& more Electromotive Force $\overline{E_{rs}}$ thus more Rotor Current $\overline{I_r}$
increasing the Active Parts by 15% to 25% !

LCI - Load Commutated Inverter

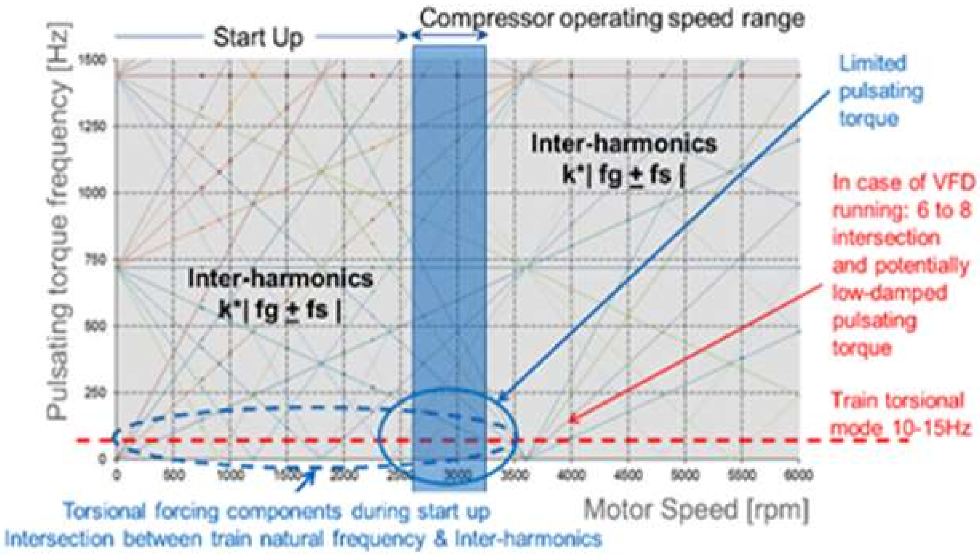
- Current source based on thyristors cells
- Well known and reliable technology
- References for tens of Megawatts
- But … generating significant Current Harmonics
  ➔ **12 or 24 Pulse Cross-Coupled Serial LCI needed**
  - Motor side: **k * 6.fs ± 1** where **fs** Stator Frequency with Double Winding Synchronous Motor fed by a 6 Pulse Thyristors Inverter @ 30° phase shift thus generating Torque Pulsations only at **k*12f_s** order
  - Grid side: **k * 6.fg ± 1** where **fg** Grid Frequency with Harmonics Filters sizing for **k*12f_g** harmonics order
  - Inter Harmonics: | **(k*12)* f_g ± (k'*12)* f_s** | **"60Hz Grid Frequency"** imposes **"50 Hz Stator Frequency"** avoiding excitations



LCI - Load Commutated Inverter

Even with 12 or 24 Pulse Arrangement, there are well known issues:

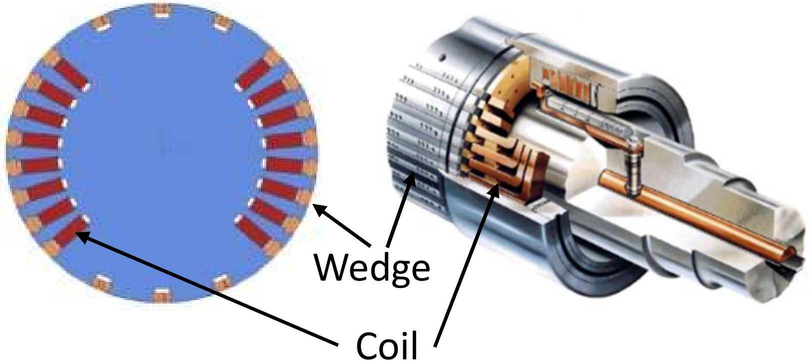
- Reactive Power consumption
  - Reactive Power consumption
  - Requires Power Factor Compensation
- Harmonics
  - Torque pulsations – Rotor dynamics study
  - Requires Harmonic Filters – Network study
- Sub-Synchronous Harmonics
  - Limited compressor speed range
  - Requires Grid screening



Pulsating Torque Campbell Diagram
for a 2 Poles Motor

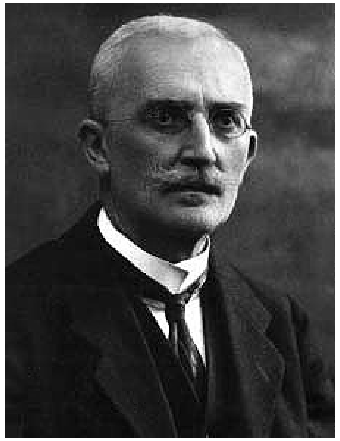
High-Speed 2-Pole Synchronous Rotor Technologies

Technology SM#1: Wound Rotor



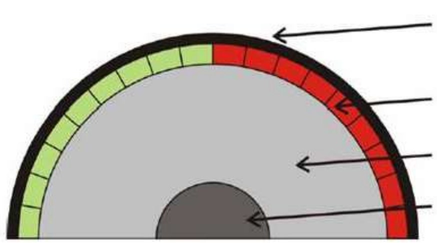
< 7,000 rpm
Wound Synchronous Rotor
Fed by Exciter + Diodes Rectifier
with insulated coils inserted in slots close by wedge

Limited to 200 m/s peripheral speed due to mechanical stress of wedges



The three-phase synchronous motor was invented first by **Friedrich August Haselwander** in 1887.

Technology SM#2: Permanent Magnet Rotor



> 15,000 rpm
Permanent Magnet Rotor
with surface mounted arrangement
surrounded by a composite bandage or a stainless-steel retaining ring

Limited by over-sizing the amount of magnet and the retaining ring thickness.

Existing Synchronous Rotor Technologies → Complex, Not Covering All Speed Range

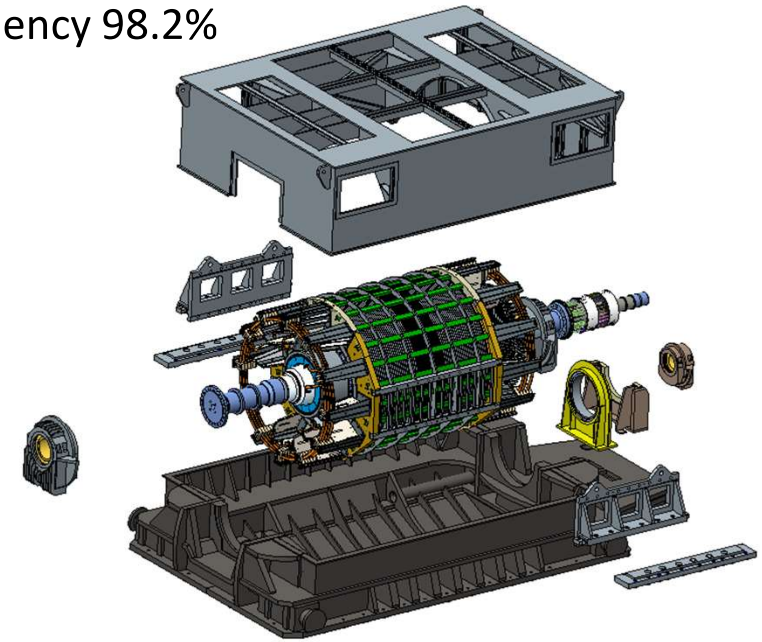
Full Electric LNG **75MW** 2-pole **synchronous** fed by **LCI**

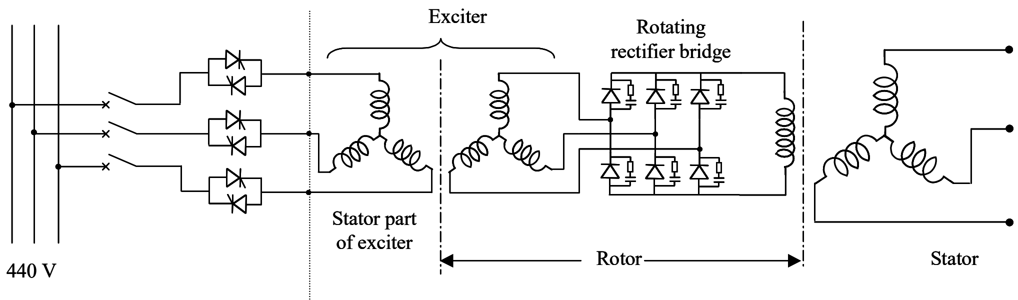
75MW @ 3000rpm 2-pole Synchronous Motor

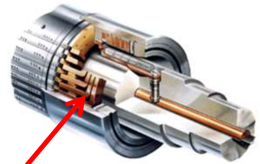
Two-star 11kV

Weight **260 tons** - Power Factor 0.9

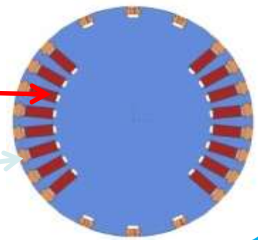
Motor Efficiency 98.2%



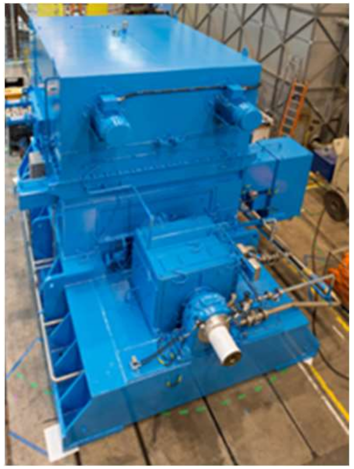




- Complex rotor (diodes & exciter)
- Insulated coils
- Max peripheral speed **200 m/s** limited by slot wedges



Examples of 2-pole Turbo Wound Synchronous Motor


61 MW @ 3 600rpm VSI-fed


18 MW @ 4 800rpm VSI-fed


25 MW @ 3 600rpm VSI-fed


25MW @ 3 600rpm LCI-fed


13 MW @ 3 600rpm LCI-fed


27 MW @ 5 200rpm LCI-fed

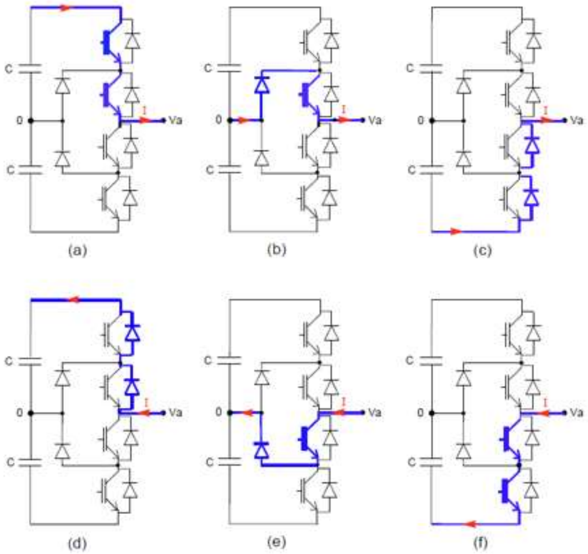

75 MW @ 3 000rpm LCI-fed

Drive Techno for Large High-speed Motor : NPC vs NPP

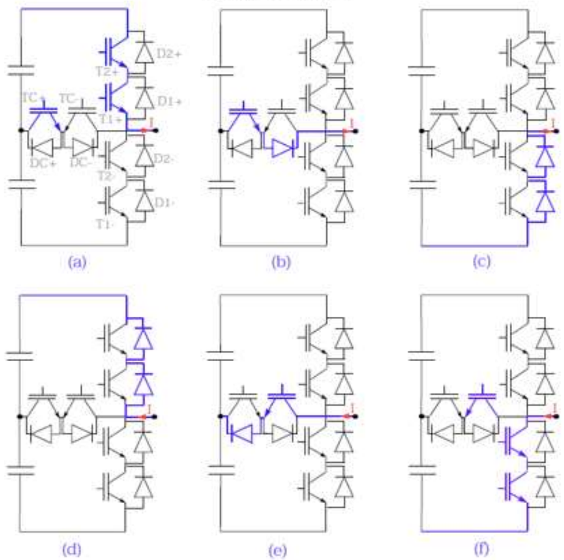
Neutral Point Clamped (NPC) Inverter

versus

Neutral Point Piloted (NPP) Inverter



NPC	Converter Type	NPP
+	Level #	+
++	IGBT #	+
+	Diodes #	+
+	Output Voltage THD	+
+	Max commutation voltage	++
+	Max commutation frequency	++
+	Max current	++
-	(N+1) redundancy	++

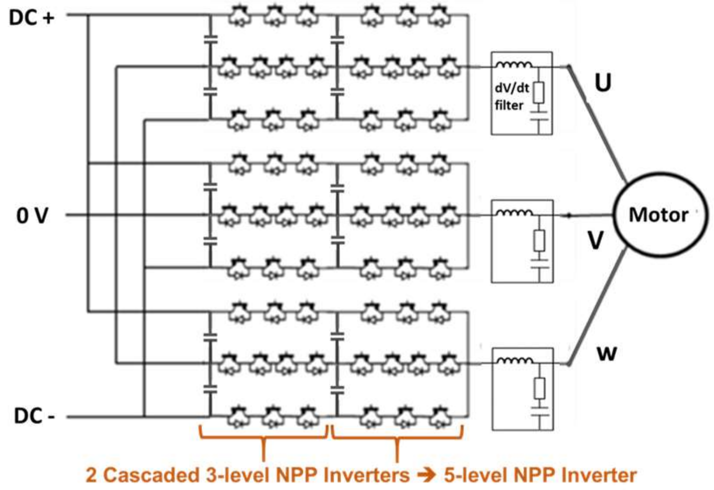


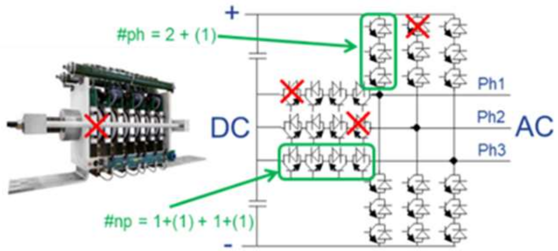
For NPP, each valve is commutating with only half the DC bus voltage reducing the devices commutation losses by three compared to NPC

Drive Techno for Large High-speed Induction or Permanent Magnet Motor

Up to 45MVA / 13.8kV / 5-level NPP for one thread

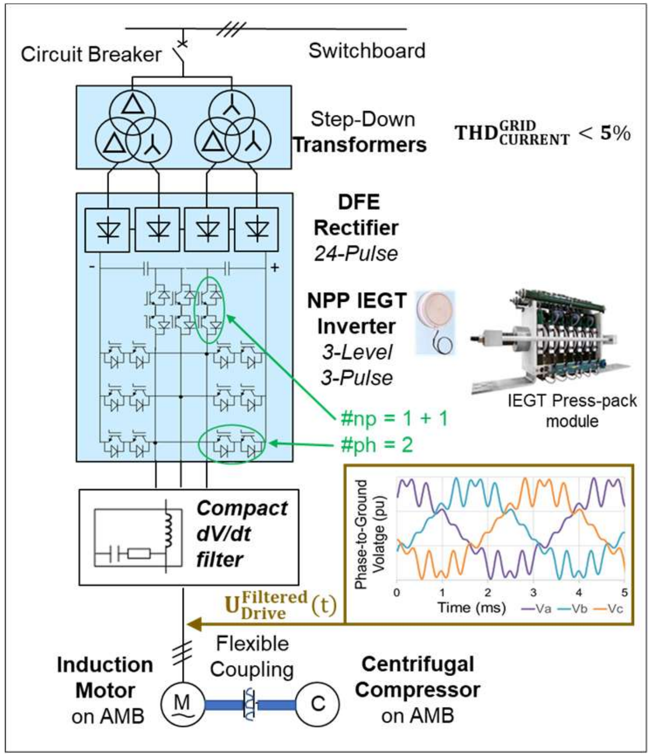
Example of 9kV-30MVA Neutral Point Piloted (NPP) Voltage Source Inverter

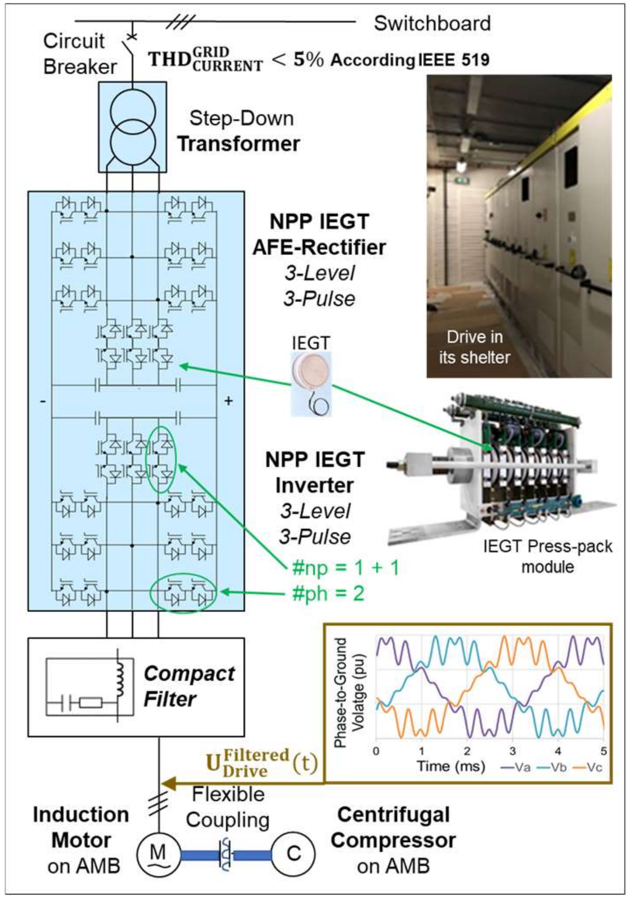




(N+1) IEGT Redundancy

NPP: Neutral Point Piloted
DFE: Diode Front End
AFE: Active Front End





(N+1) IEGT Transistor Press-pack Techno is used in NPP Arrangement for both Inverter & Rectifier

Induction Motor Torque Generation

Load Resistant Torque $\vec{\Gamma}_{load}(t)$

⇓

Stator-Rotor Slippage $\Omega_{rs} = \omega(\text{inverter}) - \Omega_r > 0$

⇓

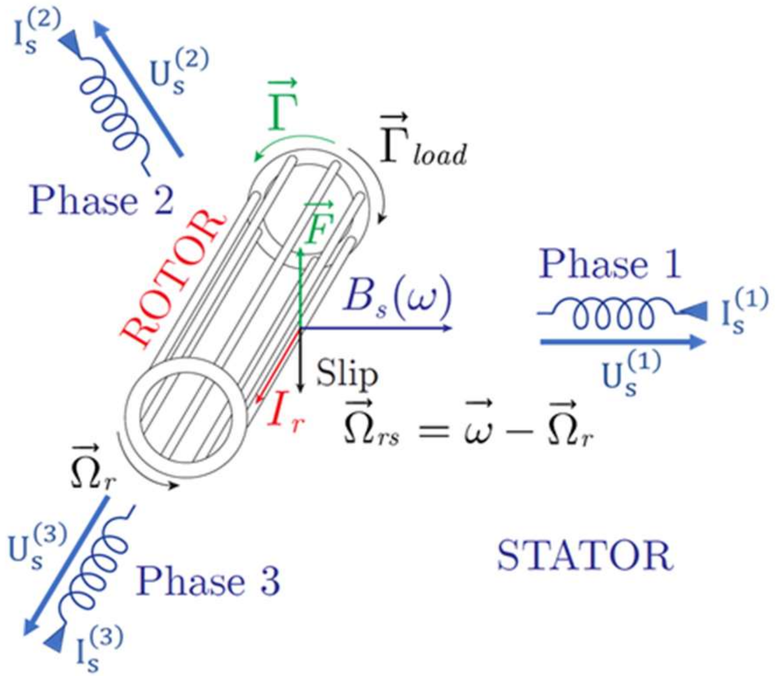
Lorentz Force $\overrightarrow{I_r} = \kappa_1 . q . \overrightarrow{\Omega_{rs}} \wedge \overrightarrow{B_s}$

⇓

Laplace Force $\vec{\Gamma} = \overrightarrow{F} . \text{Radius}_{\text{Rotor}}^{\text{Outer}} = (\kappa_2 . \overrightarrow{I_r} \wedge \overrightarrow{B_s}) . \text{Radius}_{\text{Rotor}}^{\text{Outer}}$

⇓

Steady State Condition $\vec{\Gamma}_{load} + \vec{\Gamma}_{elec} = \vec{0}$

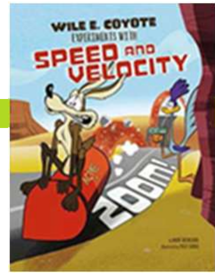


Stator pulsation ω

Rotor pulsation Ω_r

Maximum Achievable Electric Torque by Maximizing Radius, Stator Induction, Rotor Current

High-speed Squirrel Cage Rotor Selection



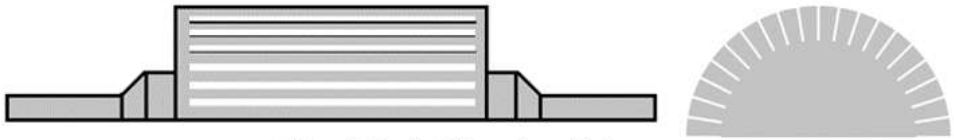


Fig.11(a) Slitted solid rotor.

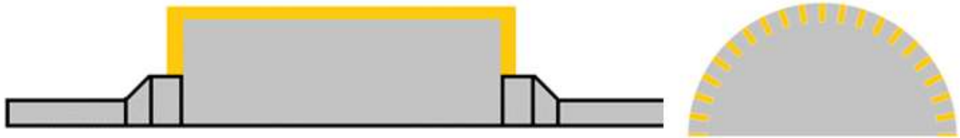


Fig.11(b) Cage welded to solid rotor.

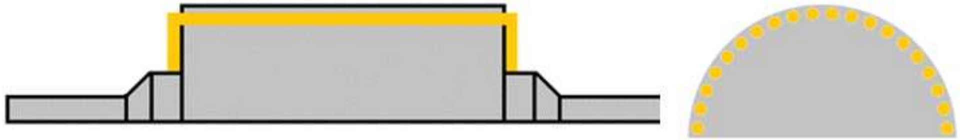
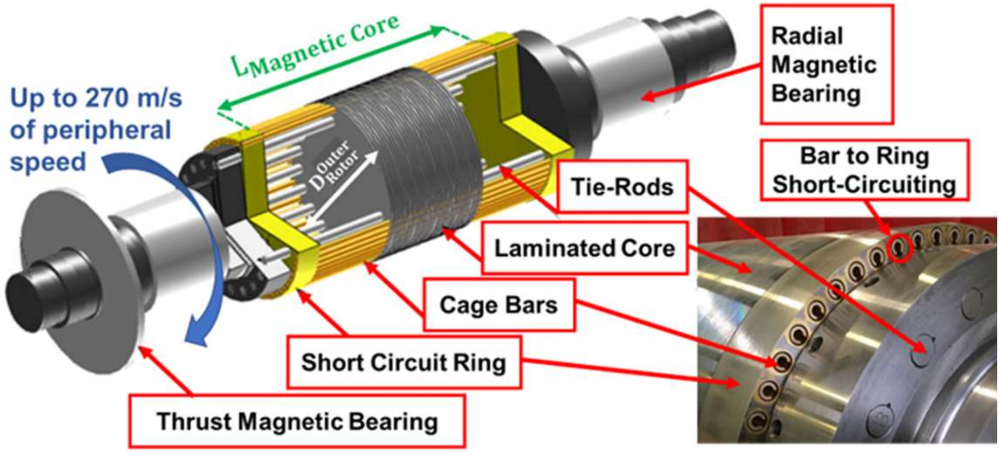


Fig.11(c) Cage inserted to solid rotor.

Lower Power Factor
Cage Temperature limitation ≈ 130° C

Cage inserted inside laminated core with tie-rods

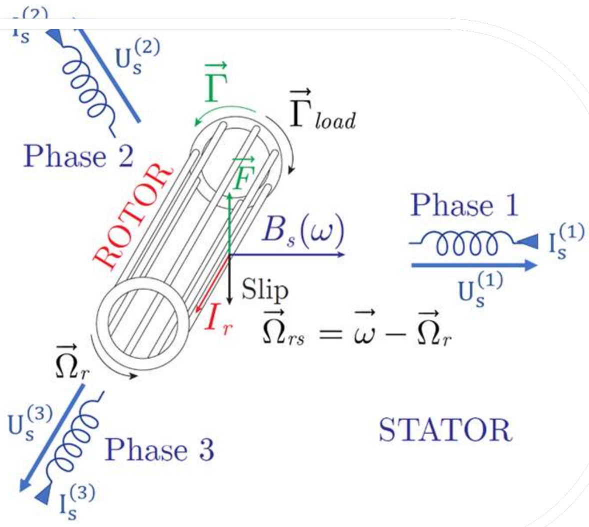


Higher Power factor
Cage Temperature up to 200° C

Cage inserted inside laminated core with tie-rods maximizing Torque & Tip speed (up to 270 m/s)
➔ Power = Torque * Speed ➔ High Power Density

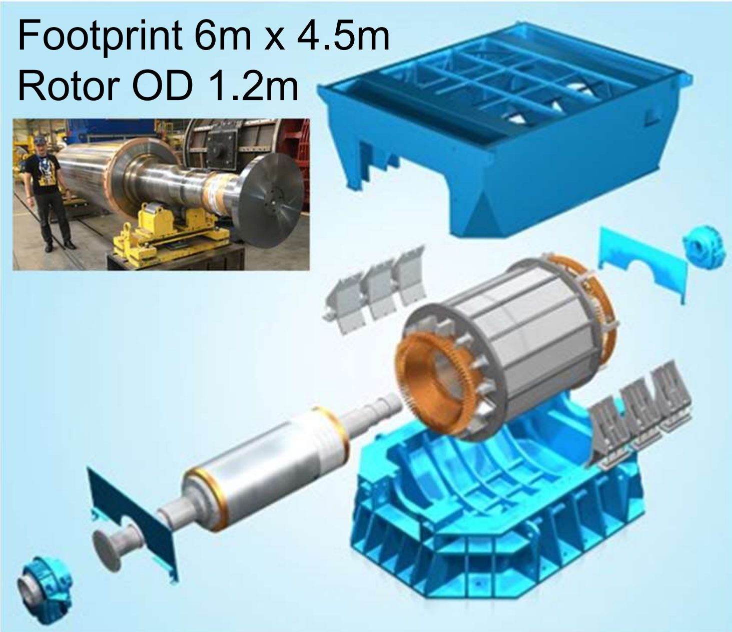
2-pole **Induction** Motor **VSI-fed for Starter Helper LNG Train**

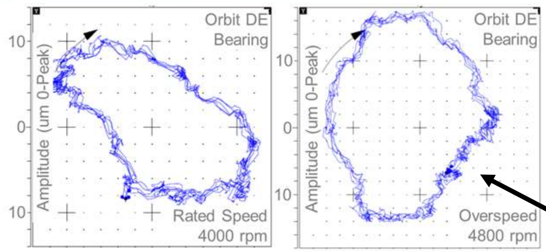
Motor fed by **VSI**
Induction – Squirrel Cage
23MW@3600rpm
59 tons
One-star 9.2kV
Power Factor 0.87
Efficiency 98.2%



2-pole Squirrel Cage Rotor

80MW @ Rated Speed 4,000 rpm – Max Continuous Speed 4,200 rpm





Shaft Displacement at overspeed 4800 rpm

Thermal Unbalance < 5umpp

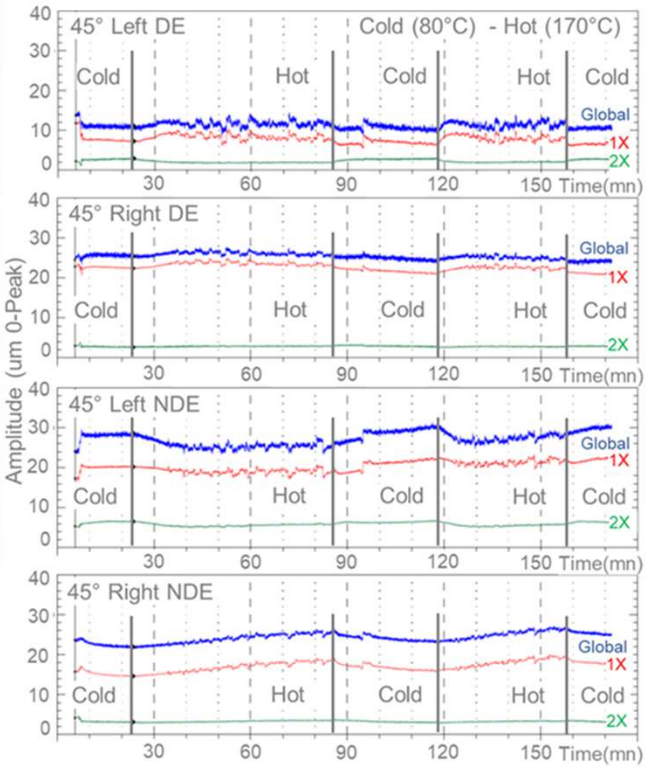


TABLE I
MAIN OUTPUTS OF THE MOTOR PERFORMANCE

Parameters	Acceptance Criteria	Tests Conditions or Results
Rated speed	100%	4000 rpm
Max Continuous Speed	105%	4200 rpm
Over speed	120%	4800 rpm
Motor Power	/	80 MW
Fundamental Motor Voltage	/	11 kV
Motor Current	/	4800 A
Weight	/	150 tons
Rated Winding Temperature	F-Class < 120°C	113°C
Max Rotor Temperature	200°C	< 160°C
Rated Efficiency	/	98.3%
Vibration Thermal Unbalance	API 541 ≤ 15 um pk-pk	Max 5 ump pk-pk
Radial Vibration @ Squirrel Cage at 170°C	API 541 ≤ 38 um pk-pk	Max 30 um pk-pk
Radial Vibration @ 4800 rpm Overspeed	/	Max 32 um pk-pk

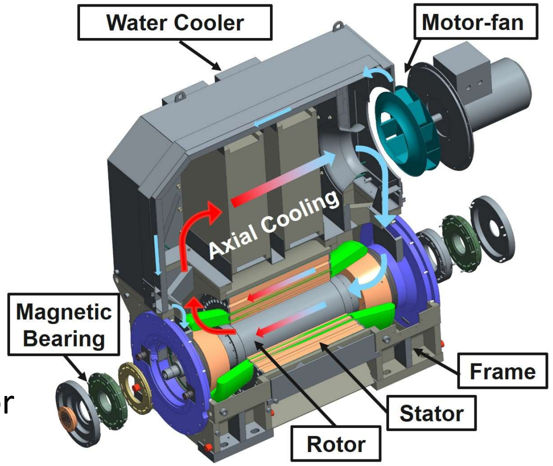
API 541 Compliance

Higher Speed than Synchronous Motor Improving Compressor Efficiency & System Layout

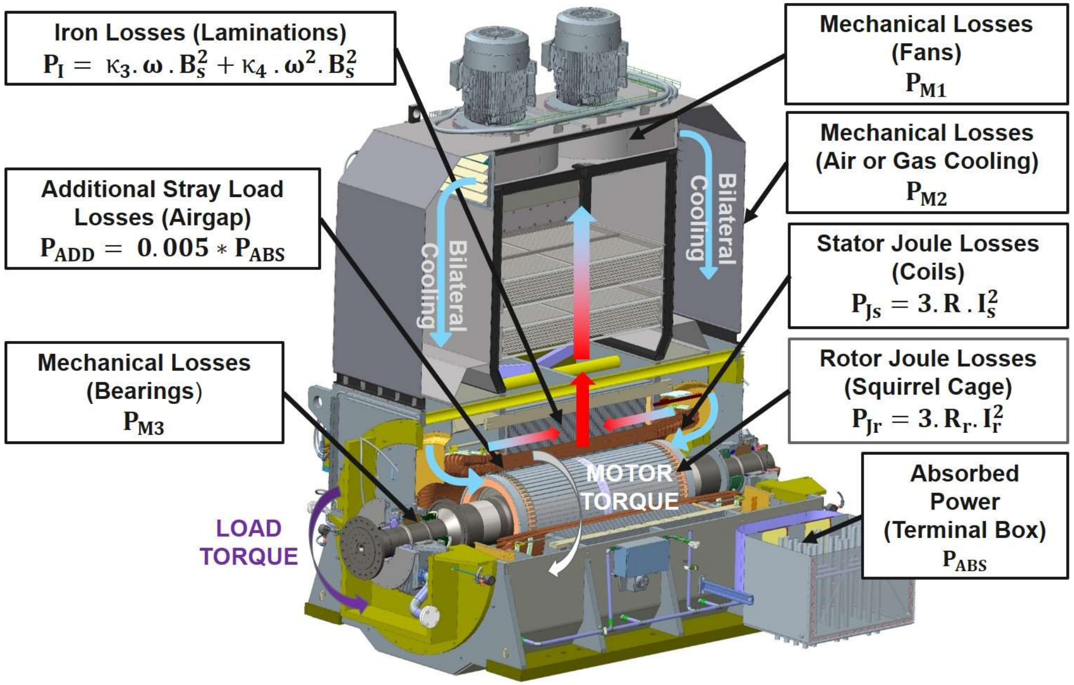
Induction Motor ➔ Limitations & Losses & Cooling

- **Limitation #1**: Maximum **Temperature** of the wound **Stator** at 120 C for Class-B, or 155 C for Class-F, limiting induction ➔ **Bs**

Induction Motor 11kV – 80MW Stator
Vacuum-Pressure-Impregnated
with Class-H Epoxy Free Resin



- **Limitation #2**: **Rotor** hot spot of **Temperature** at 200 C for Class1 Div2 T3 Hazardous Location, limiting rotor current ➔ **Ir**
- **Limitation #3**: Maximum peripheral **Speed** of the rotor by design defining the **Key Driver #A,** limiting speed ➔ **Ωr**



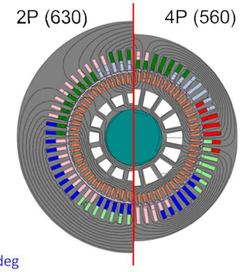
Motor Efficiency ➔ $\eta = \frac{P_{ABS}(1-0.005)-(P_{Js}+P_{Jr}+P_I+P_{M1}+P_{M2}+P_{M2})}{P_{ABS}}$

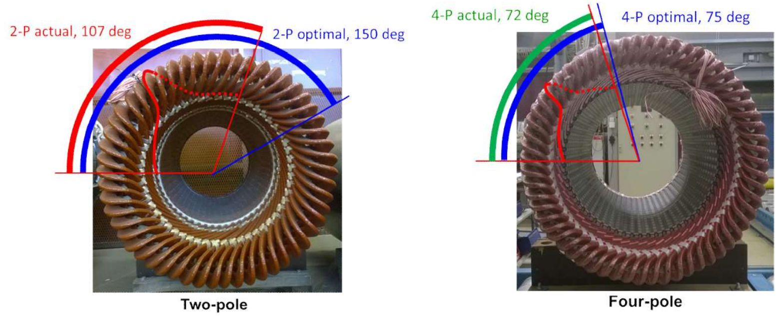
4-pole high-speed Motor Versus 2-pole high-speed Motor

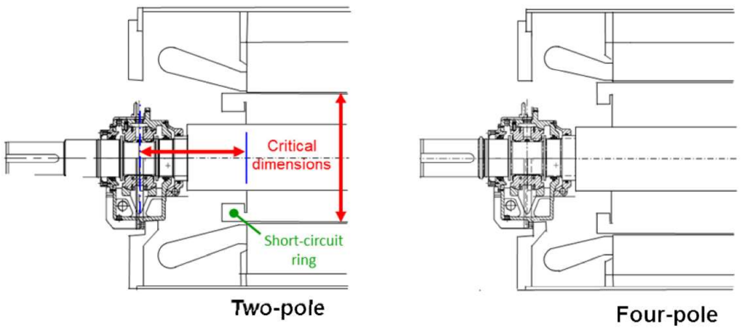
45TH TURBOMACHINERY & 32ND PUMP SYMPOSIA
HOUSTON, TEXAS | SEPTEMBER 12 – 15, 2016
GEORGE R. BROWN CONVENTION CENTER

COMPARISON OF TWO- AND FOUR-POLE VSD MOTORS UP TO 4000 RPM

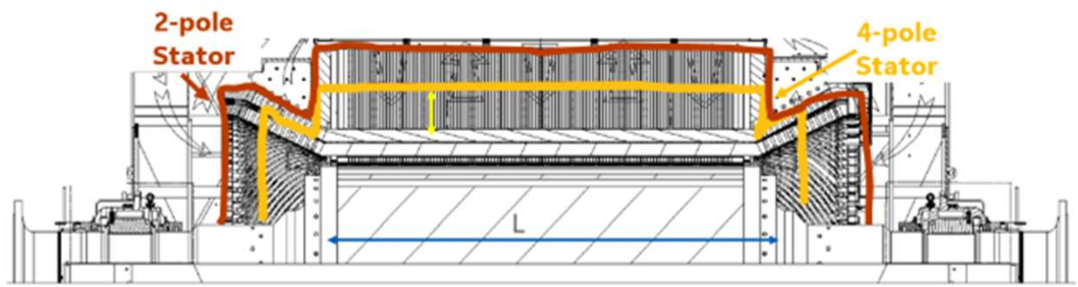
Timo P. Holopainen, Olli Liukkonen, Pieder Jörg (ABB)

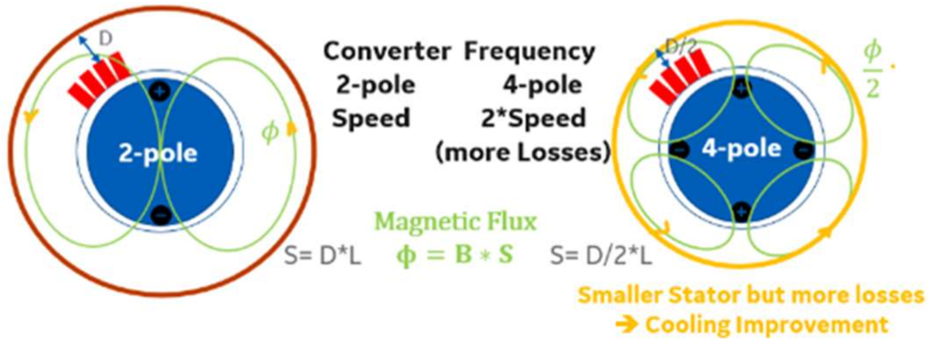






80MW@4000 rpm : 2-pole vs 4-pole





4-pole Smaller footprint / More iron losses and Stray Load Losses 2*Fs / More commutation losses in the inverter

Cooling Capacity

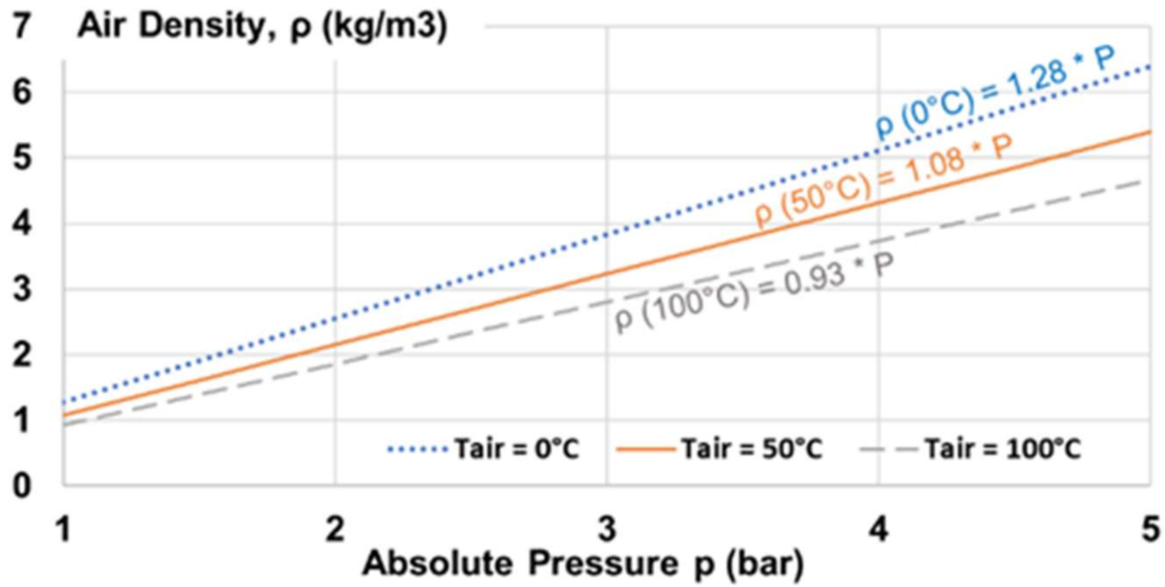
The cooling capacity is driven by:

- Axial or Bilateral cooling path
- Cooling Gas Inlet Temperature set by the cooler
- Heat Transfer related to Gas Nature and Flow

Static Pressure p

Gas Density $\rho(\mathbf{p},\mathrm{T})_{(g)} = \alpha(g,\mathrm{T}).\mathbf{p}$

Reynolds $\mathrm{Re}(\mathbf{p},\mathrm{T})_{(g)} = \dfrac{\rho(\mathbf{p},\mathrm{T})_{(g)}\,.\,\mathrm{U}_{(g)}\,.\,\mathrm{D}_{\mathrm{H}}}{\mu_{(g)}}$



Absolute Static Pressure p → Key Factor for Heat Transfer Efficiency & Friction Losses Dissipation

Cooling Capacity

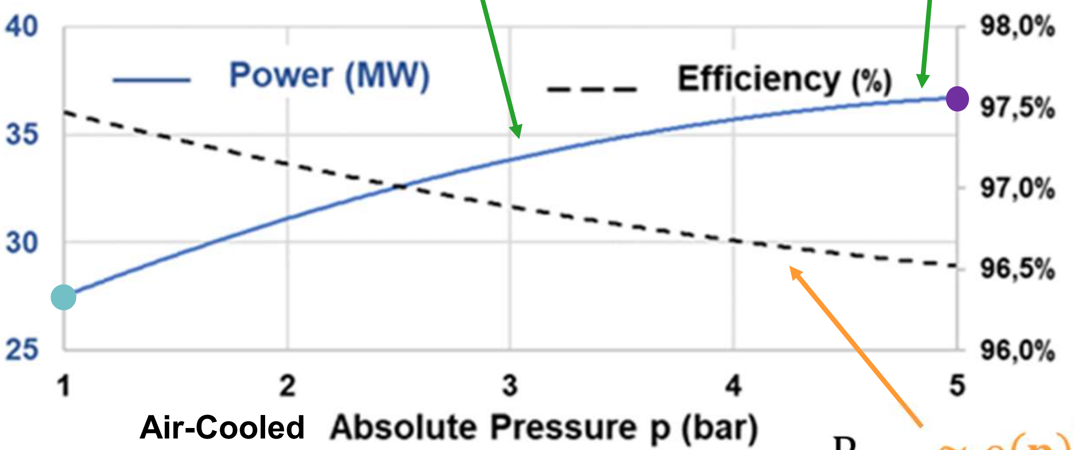
Gas Temperature Rise

Convection Transfer (K)

$$\Delta T_{c(g)}(\mathbf{p}) \approx \frac{1}{Q_{v(g)} . Cp_{(g)} . \rho(\mathbf{p})_{(g)}^{1-\beta 1}}$$

Friction Losses (K)

$$\Delta T_{fr(g)}(\mathbf{p}) \approx \frac{1}{Q_{v(g)} . Cp_{(g)} . \rho(\mathbf{p})_{(g)}^{\beta 3}}$$



$$P_{fr(g)} \approx \rho(\mathbf{p})_{(g)}^{1-\beta 3}$$

Friction Losses (W)

Example of
5-bar air-cooled induction motor

6 MW @ 12 000 rpm
on active magnetic bearings

Air Pressurized Cooling Media ↗ Torque Density by 30% with < 1% of Efficiency Reduction

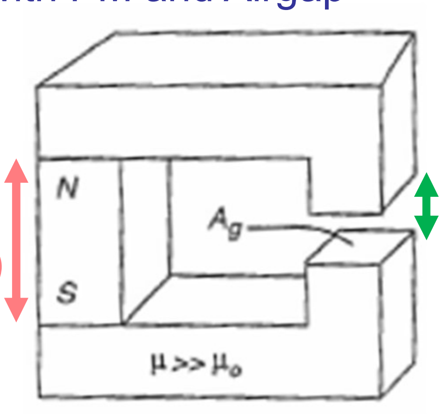
High-speed Permanent Magnet Rotor Optimisation

How to maximize the airgap induction Bm ?

$$B_m = -\mu_0 \frac{A_g l_m}{A_m l_g} H_m$$

Basic equivalent flux Circuit with PM and Airgap

Lm (PM)



Lg (Airgap)

Lm high → Withstand demagnetization

Lg low → Small Airgap

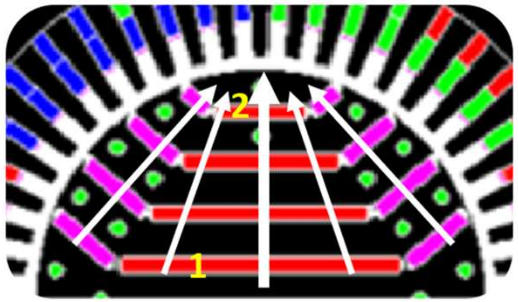
→ Thin thickness of retaining ring

Ag / Am high → Flux Concentration

$$\Phi_1 = B_1 * A_1 = \Phi_2 = B_2 * A_2$$

with $A_1 \approx 4 * A_2$

$B_2 \approx 4 * B_1$ without saturation



High Torque Density → Maximizing the volume of Permanent Magnets inside the rotor

High Torque Density for Permanent Magnet Motor

738 IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, VOL. IA-22, NO. 4, JULY/AUGUST 1986

Interior Permanent-Magnet Synchronous Motors for Adjustable-Speed Drives

THOMAS M. JAHNS, MEMBER, IEEE, GERALD B. KLIMAN, SENIOR MEMBER, IEEE, AND THOMAS W. NEUMANN

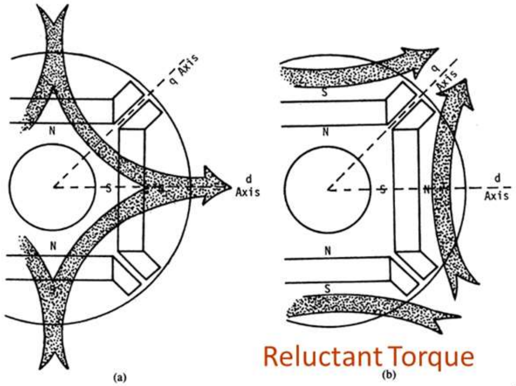
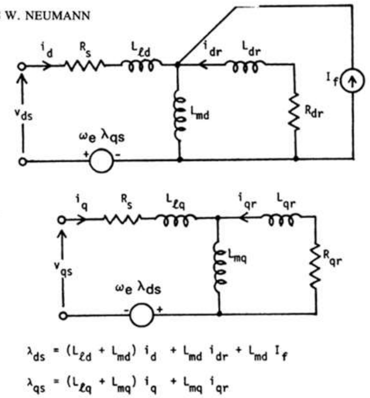
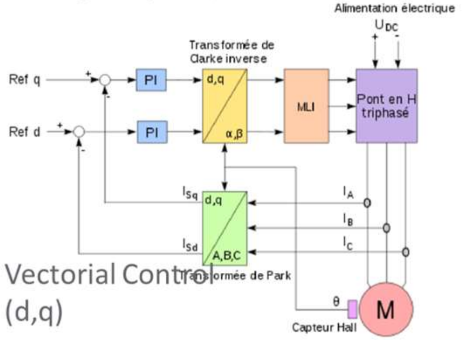


Fig. 3. Principal IPM magnetic flux paths. (a) d axis. (b) q axis.



5. IPM synchronous motor equivalent circuit in rotor reference fram



Exemple de commande vectorielle d'un moteur triphasé, où l'angle de Park (la position du rotor) est mesuré par un capteur à effet Hall

For steady-state operation when the damper transients have decayed to negligible levels, the average torque T_e developed by the IPM synchronous motor can be expressed in terms of the Fig. 5 equivalent circuit d–q currents as

$$T_e = 1.5p[I_{qs}\Psi_{mag} + (L_d - L_q)I_{qs}I_{ds}] \quad (1)$$

where **Field Alignment Torque** + **Reluctant Torque**

- Ψ_{mag} permanent magnet flux linkage ($= L_{md}I_f$),
- L_d, L_q total d axis ($= L_{md} + L_{ld}$) and q-axis ($= L_{mq} + L_{lq}$) stator inductances,
- p number of pole pairs,
- I_{qs}, I_{ds} steady-state q-axis and d-axis stator currents.

Each of the two terms in this equation reflects an important aspect of the torque production in an IPM synchronous motor. First, the magnet flux oriented along the rotor d axis interacts with the q-axis stator current to produce a field-alignment torque proportional to the ($\Psi_{mag}\, I_{qs}$) product. This is the same process by which torque is produced in a conventional surface PM synchronous motor. In addition, the current-induced magnetic fluxes along the two axes L_dI_{ds} and L_qI_{qs} interact with the orthogonal current components to contribute a second torque term. The rotor saliency is clearly responsible for the presence of this reluctance torque term, which is proportional to the axis inductance difference ($L_d - L_q$). Thus the torque equation suggests that, for purposes of conceptualization, the IPM motor can be interpreted as a hybrid combination of the conventional synchronous-reluctance and surface PM machines.

+ / =

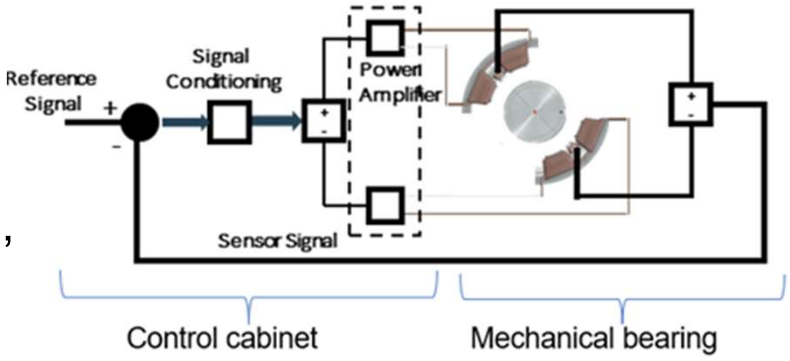
February 13, 2024 18

Control @ PF ≈ 0.97 ➔ Maximizing Torque = Aligment Torque + Reluctant Torque

Active Magnetic Bearings

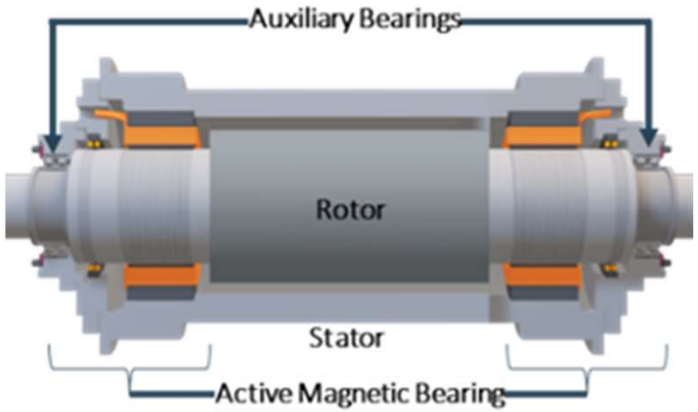
Main components of the control cabinet:

- the oscillator PC board to feed the sensors,
- the PC boards for the PID control,
  for the automatic balancing system and for securities,
- the power amplifiers and their cooling device,
  the power supply and associated battery pack.



Main components of the mechanical bearing:

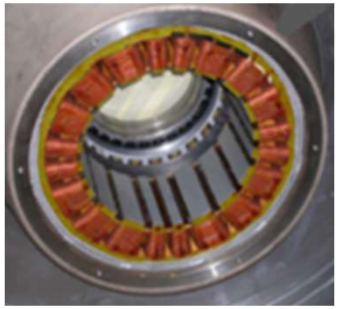
- the laminated rotor,
- the stator electromagnets,
- the auxiliary (landing bearings).



Simple Technology

Active Magnetic Bearings

- No wear, so no mechanical maintenance and unlimited lifetime, moreover no bearing noise,
- 200 m/s tip speed achievable with very low friction losses,
- No process fluid contamination by the bearing,
- No need for seal, oil lube system and accessories,
- Ability to work in vacuum or hostile environments,
- Permanent control of rotation axis,
- Automatic balancing system, rotor spinning around its inertial axis instead of its geometrical axis,
- Adapting static and dynamic stiffnesses for high accuracy of rotation,
- Vibration free control,
- Permanent monitoring of the system.



AMB Actuator

AMB Ceramic Landing Bearing

500 compressors & 800 turboexpanders (stand-alone, high-speed motors driven & hermetically sealed solutions) are equipped with AMB around the world

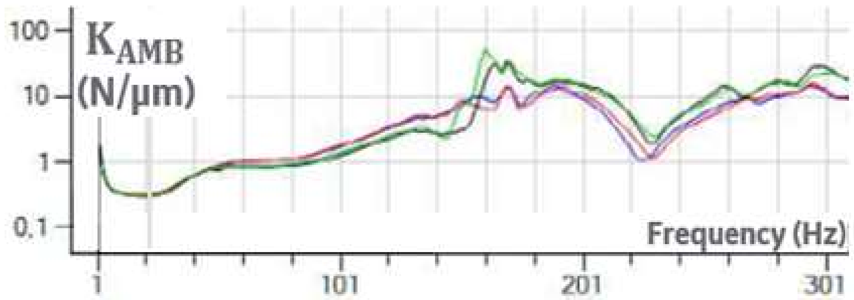
Active Magnetic Bearings

$$F_{pull} = (\sigma_{mag}).Area = \left(\frac{B^2_{airgap}}{8\pi\ 10^{-7}} \right).Area$$

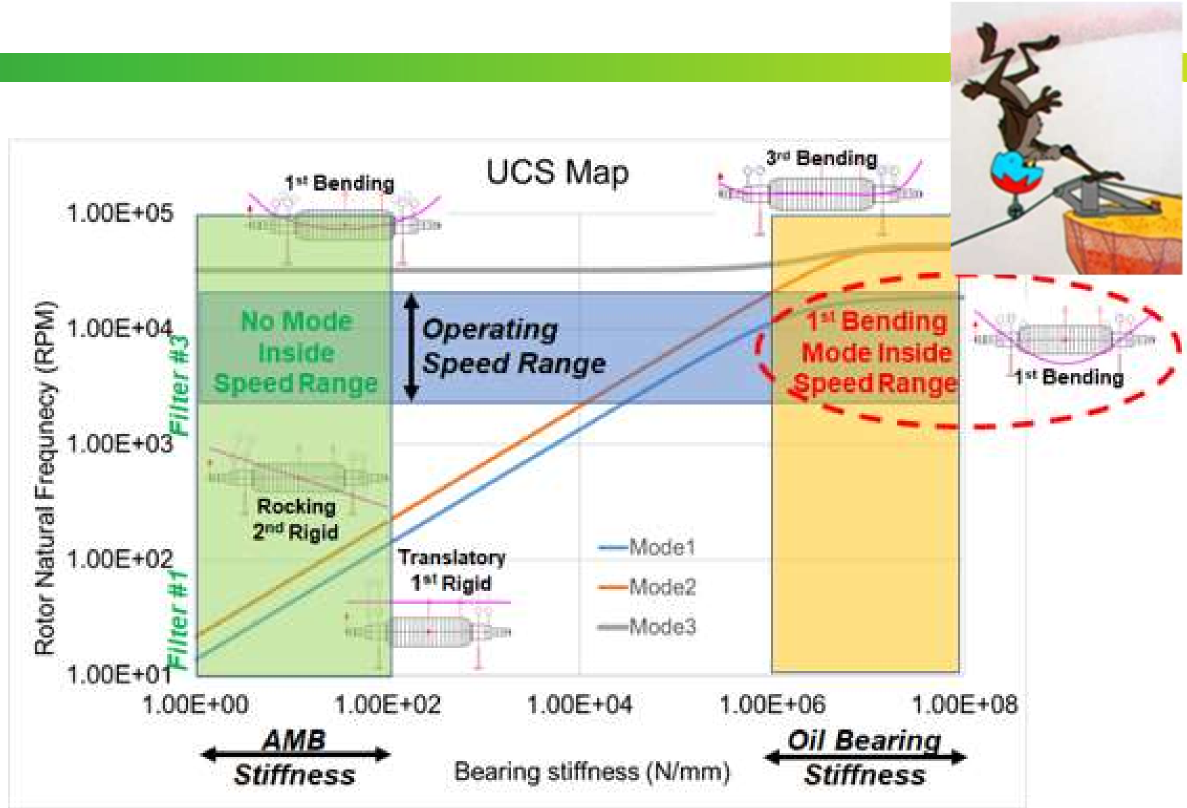
B_{airgap} is of the order of 1.5 Tesla

Magnetic pressure ≈ 1 N/mm²

Magnetic stiffness ≈ 10^{-3} to 10^{-6} N/m



Active magnetic stiffness vs Frequency



6.9MW @ 13200rpm rpm Motor for export compressor
Undamped critical speed map

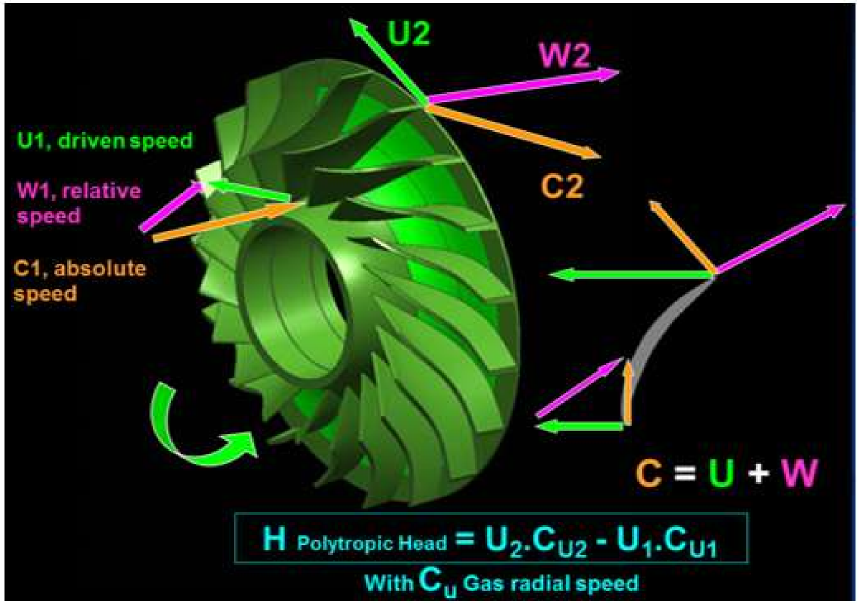
Low controllable stiffness

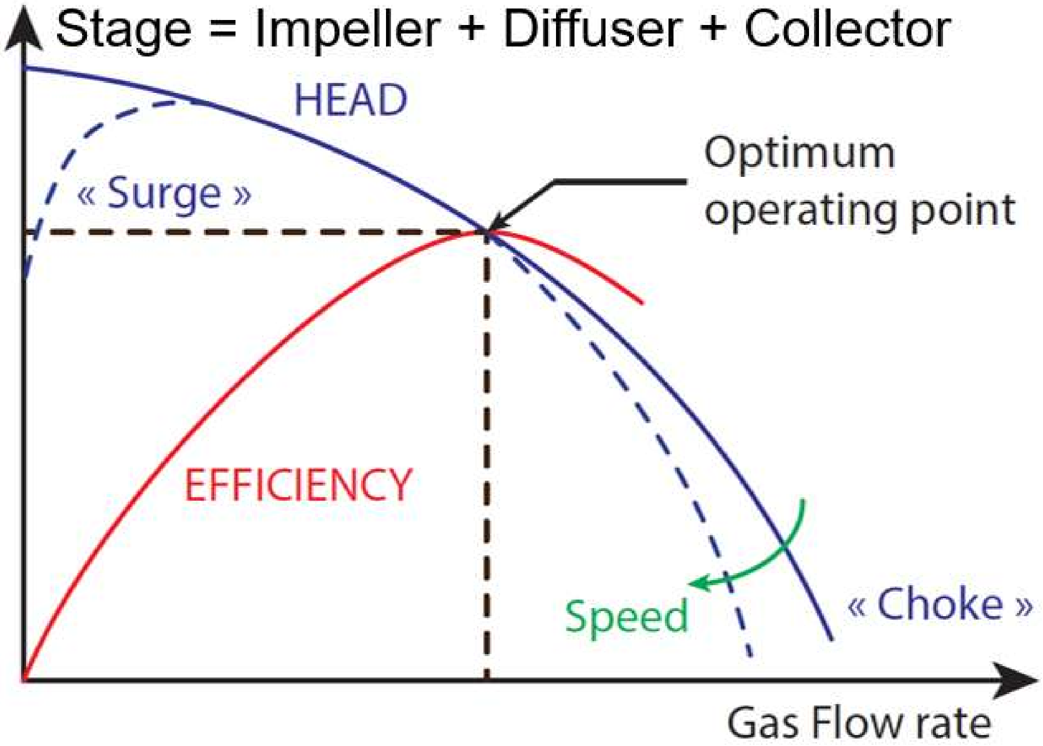
→ No rotor bending mode in the operating speed range

→ Low Unbalance force transmission to foundation

ELECTRIC SYSTEMS SOLUTIONS FOR COMPRESSION TRAINS

Compressor @ One Stage Design

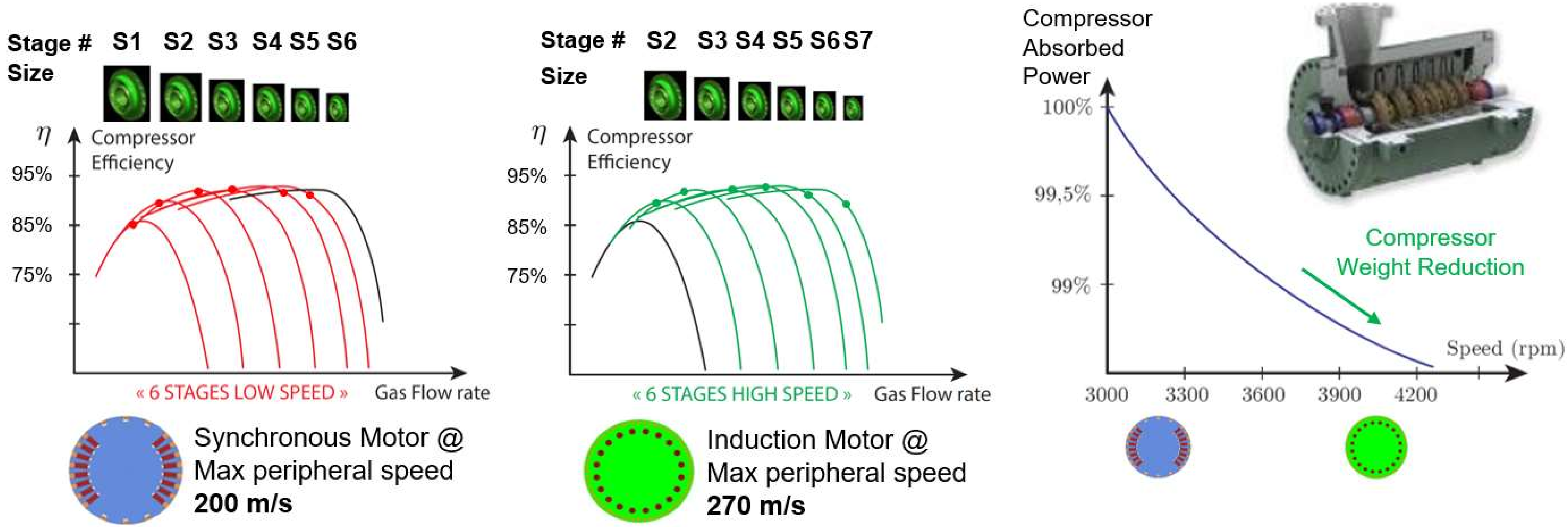




3 Main Drivers for One Stage Design:

- Mass Flow Rate [Kg/s]
- Polytropic Head [m] (Rotor Impellers) ➔ Static Pressure Ratio (Diffuser/Collector)
- Isentropic Efficiency [%] (including Aerodynamic-Polytropic & Thermodynamic Losses)

Multi-stages Compressor vs Speed



Operating at high-speed condition (ω_r) for the System improves the Multi-stages Compressor Efficiency (η) up to 2% (OPEX) and downsizes the Stages and the Layout (CAPEX)

40MW (54MHP) Business Case

TABLE V
40MW BUSINESS CASE - CAPEX

Case / Power Drive Motor		A/ 40MW LCI SYN	B/ 40MW VSI SYN	C/ 40MW VSI IND
Compressor Power	MW	35,0	34,7	34,5
Compressor Speed	rpm	3000	3600	4600
Motor Power	MW	40,0	40,0	40,0
Motor Weight	Ton	125	100	90
Max Load	kN	120 000	80 000	65 000
CAPEX		**PRICES**		
Step Transformer	PU $	8	9	9
Filters & Breakers	PU $	3	-	-
Converter	PU $	13	16	18
Excitation cubicle	PU $	1	1	-
E house	PU $	27	25	26
Motor	PU $	48	46	42
Total	**PU $**	**100**	**97**	**95**
Delta	**%**	**0%**	**3%**	**5%**

TABLE VII
40MW BUSINESS CASE - OPEX

Case / Power Drive Motor		A/ 40MW LCI SYN	B/ 40MW VSI SYN	C/ 40MW VSI IND
Compressor Power	MW	35,0	34,7	34,5
Compressor Speed	rpm	3000	3600	4600
Motor Power	MW	40,0	40,0	40,0
Transformer Efficiency	%	99,00%	99,00%	99,00%
Filter Efficiency	%	99,60%	100,00%	100,00%
Drive Efficiency	%	98,80%	98,40%	98,30%
Motor Efficiency	%	97,60%	98,20%	98,00%
Auxiliary Efficiency (**)	%	97,60%	97,70%	97,90%
System Efficiency	%	92,80%	93,46%	93,37%
Grid Absorbed Power (*)	MW	37,72	37,13	36,95
Cost of energy	$/kwh	$0,06	$0,06	$0,06
Overall Opex @ 5yrs	**k$**	**99 116**	**97 570**	**97 106**
savings @ 5 years	**k$**	**0**	**1 545**	**2 009**

(*) based on Compressor power and system efficiency
(**) Cooling, Oil, Rotor Excitation

For 60Hz Grid, {VSI+Induction @ 4600 rpm} compared to {LCI+Synchronous @ 3000 rpm} :

- 5% CAPEX Saving for the Electrical System (not including Compressor CAPEX Saving)
- Efficiency (η) improvement by 2% (-500 kW) for Compressor & by 0.5% for Electrical System
  2.0M$ OPEX Saving @ 5 years (not including Grid OPEX Saving)

80MW (107MHP) Business Case

TABLE IV
80MW BUSINESS CASE - CAPEX

Case / Power Drive Motor		A/ 80MW LCI SYN	B/ 80MW VSI SYN	C/ 80MW VSI IND
Compressor Power	MW	70,0	69,5	69,2
Compressor Speed	rpm	3000	3600	4000
Motor Power	MW	80,0	80,0	80,0
Motor Weight	Ton	225	180	155
Max Load	kN	220 000	150 000	120 000
CAPEX		**PRICES**		
Step transformer	PU $	9	10	10
Filters & Breakers	PU $	2	-	-
Converter	PU $	24	28	29
Excitation cubicle	PU $	1	1	-
E house	PU $	27	25	26
Motor	PU $	37	34	30
Total	**PU $**	**100**	**98**	**95**
Delta	**%**	**0%**	**2%**	**5%**

TABLE VI
80MW BUSINESS CASE - OPEX

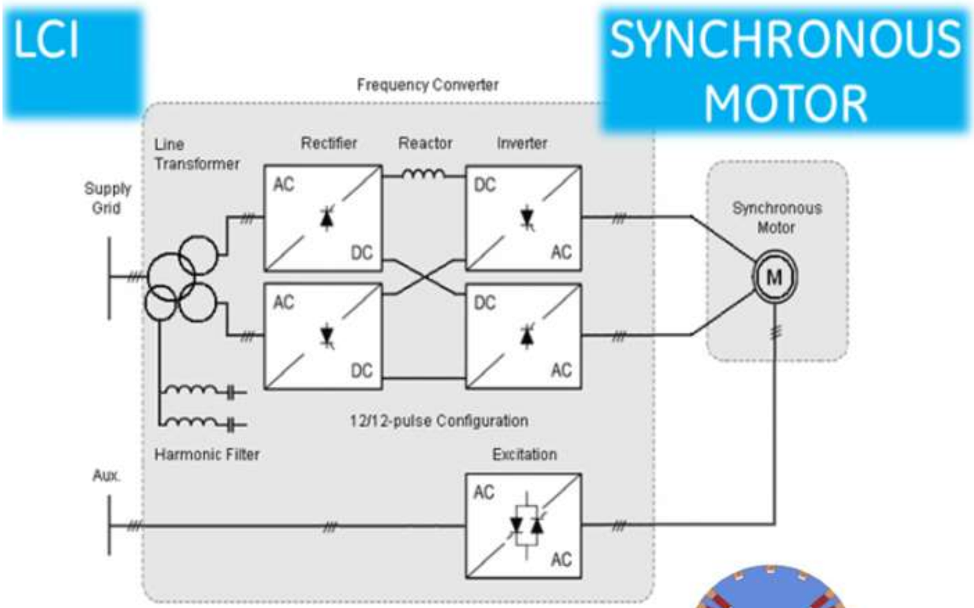
Case / Power Drive Motor		A/ 80MW LCI SYN	B/ 80MW VSI SYN	C/ 80MW VSI IND
Compressor Power	MW	70,0	69,5	69,2
Compressor Speed	rpm	3000	3600	4000
Motor Power	MW	80,0	80,0	80,0
Transformer Efficiency	%	99,00%	99,00%	99,00%
Filter Efficiency	%	99,60%	100,00%	100,00%
Drive Efficiency	%	98,80%	98,40%	98,30%
Motor Efficiency	%	98,00%	98,20%	98,10%
Auxiliary Efficiency (**)	%	97,60%	97,70%	97,90%
System Efficiency	%	93,18%	93,46%	93,46%
Grid Absorbed Power (*)	MW	75,12	74,36	74,04
Cost of energy	$/kwh	$0,06	$0,06	$0,06
Overall Opex @ 5yrs	**k$**	**197 422**	**195 422**	**194 577**
savings @ 5 years	**k$**	**0**	**2 000**	**2 845**

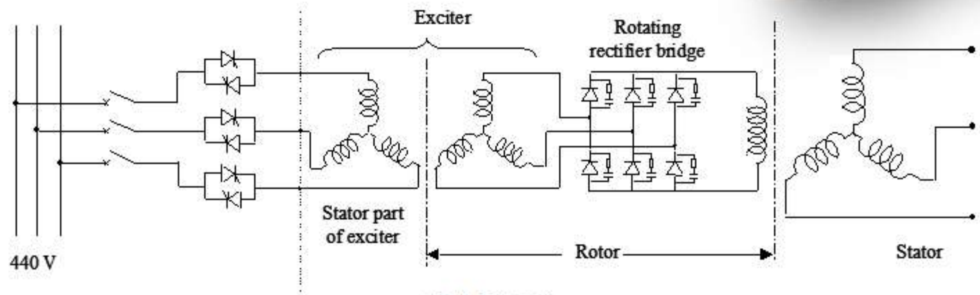
(*) based on Compressor power and system efficiency
(**) Cooling, Oil, Rotor Excitation

For 60Hz Grid, {VSI+Induction @ 4000 rpm} compared to {LCI+Synchronous @ 3000 rpm} :

- 5% CAPEX Saving for the Electrical System (not including Compressor CAPEX Saving)
- Efficiency (η) improvement by 1% (-800 kW) for Compressor & by 0.3% for Electrical System
  2.8M$ OPEX Saving @ 5 years (not including Grid OPEX Saving)

Pros & Cons: LCI + Synchronous





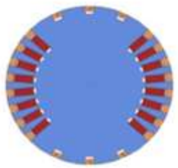
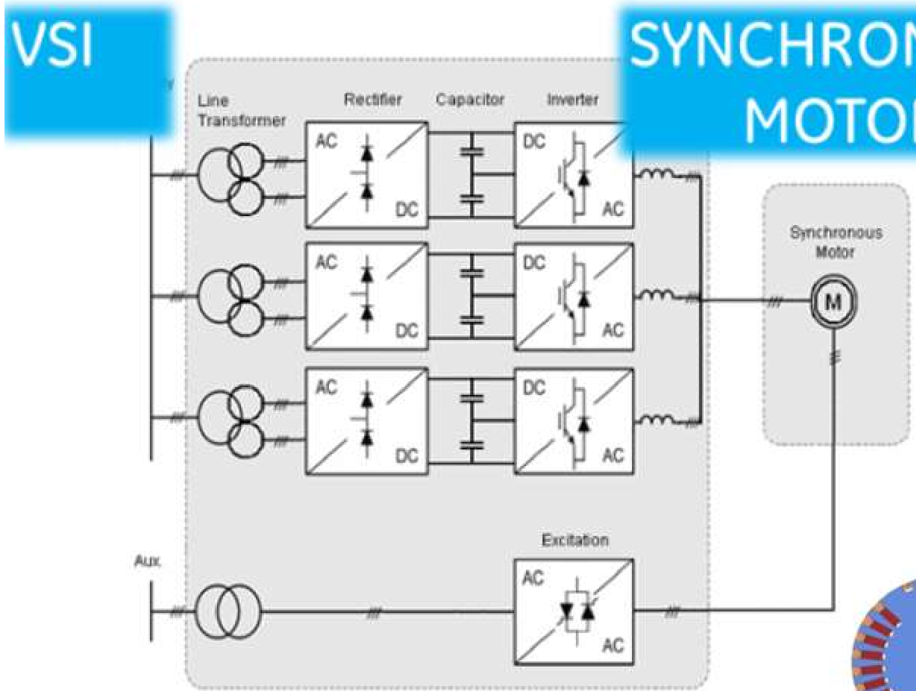


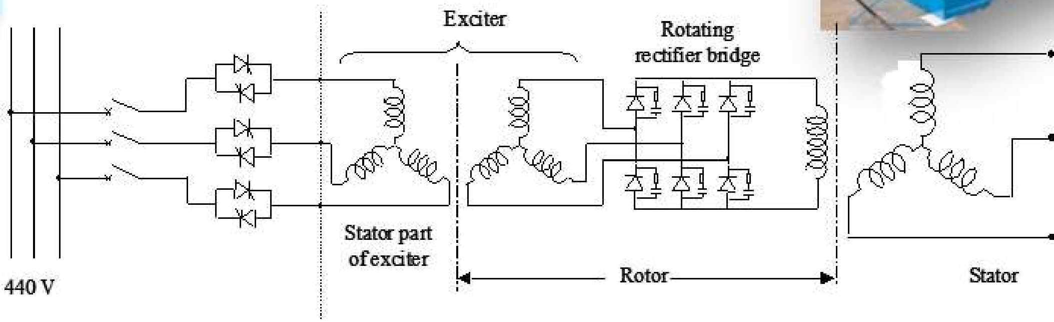
TABLE I
LCI SYNCHRONOUS MOTOR SYSTEM PROS & CONS

PROS	Lot of references up to 75MW
CONS	Weak network stability and utilities integration
	Large harmonics pollution to the grid
	Critical torque harmonics on shaft line
	Required external harmonics filter
	Motor Layout & Weight oversizing at leading PF=0.9
	Large static & transient loads oversizing foundations

The Baseline Solution

Pros & Cons: VSI + Synchronous





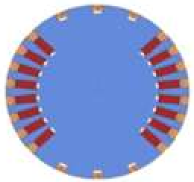
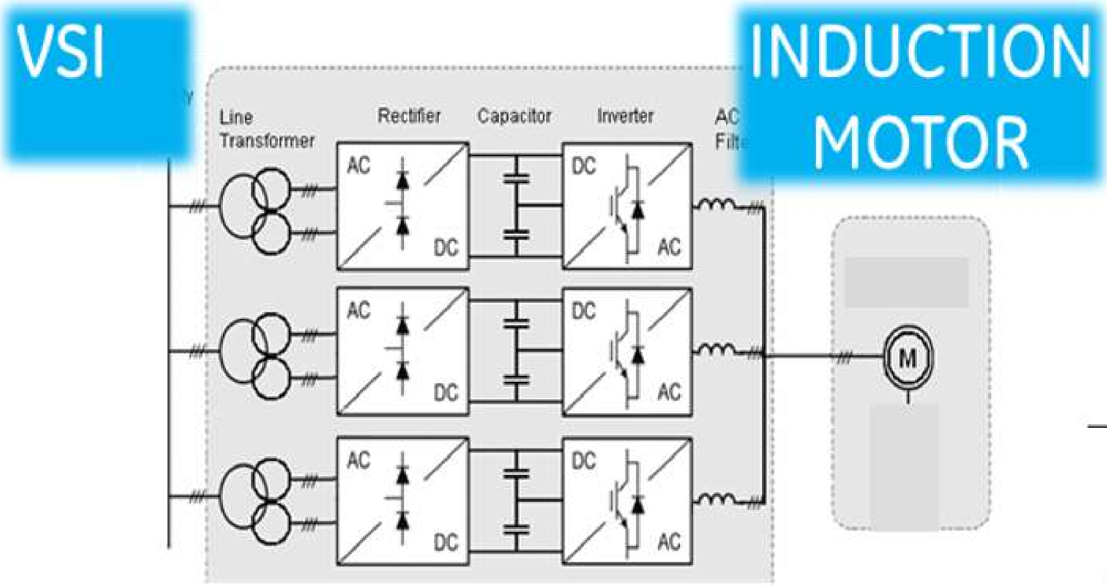


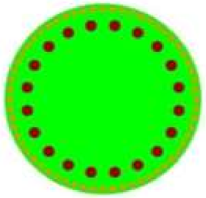
TABLE II
VSI SYNCHRONOUS MOTOR SYSTEM PROS & CONS

PROS	Low harmonics content … external filter not required
	Improved network stability and grid integration
	Reduced torque ripple at shaft level
	No risk of torsional vibration
	Operability in Power Factor one, leading or lagging
CONS	System new references up to 60 MW

The Transient Solution

Pros & Cons: VSI + Induction





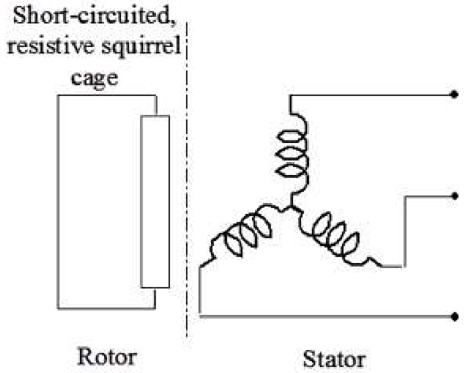


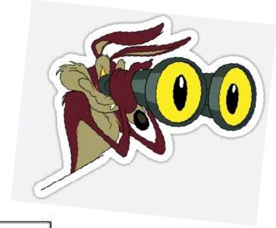
TABLE III
VSI INDUCTION MOTOR SYSTEM PROS & CONS

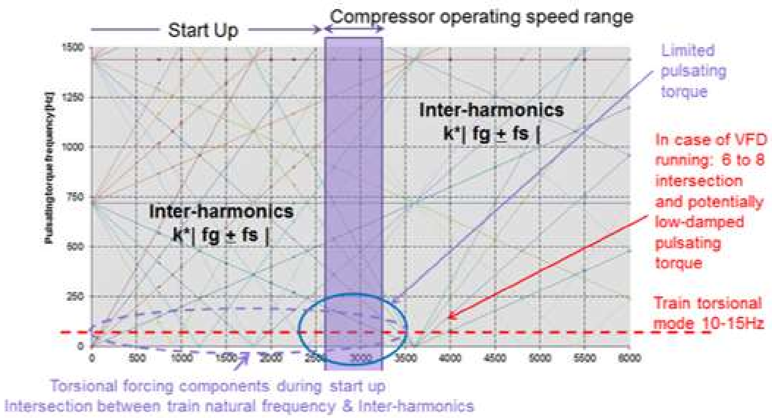
PROS	Low harmonics content … external filter not required
	Improved network stability and grid integration
	Reduced torque ripple at shaft level
	No risk of torsional vibration
	Simpler rotor technology w/o excitation system
	Increased motor and system availability
	Low static & transient loads downsizing foundations
	Less rotor natural frequencies interactions because no exciter
	Highest speed operability for best compressor Capex & Opex
CONS	Induction new references up to 23 MW

The Ultimate Solution : Induction Rotor or PM Rotor

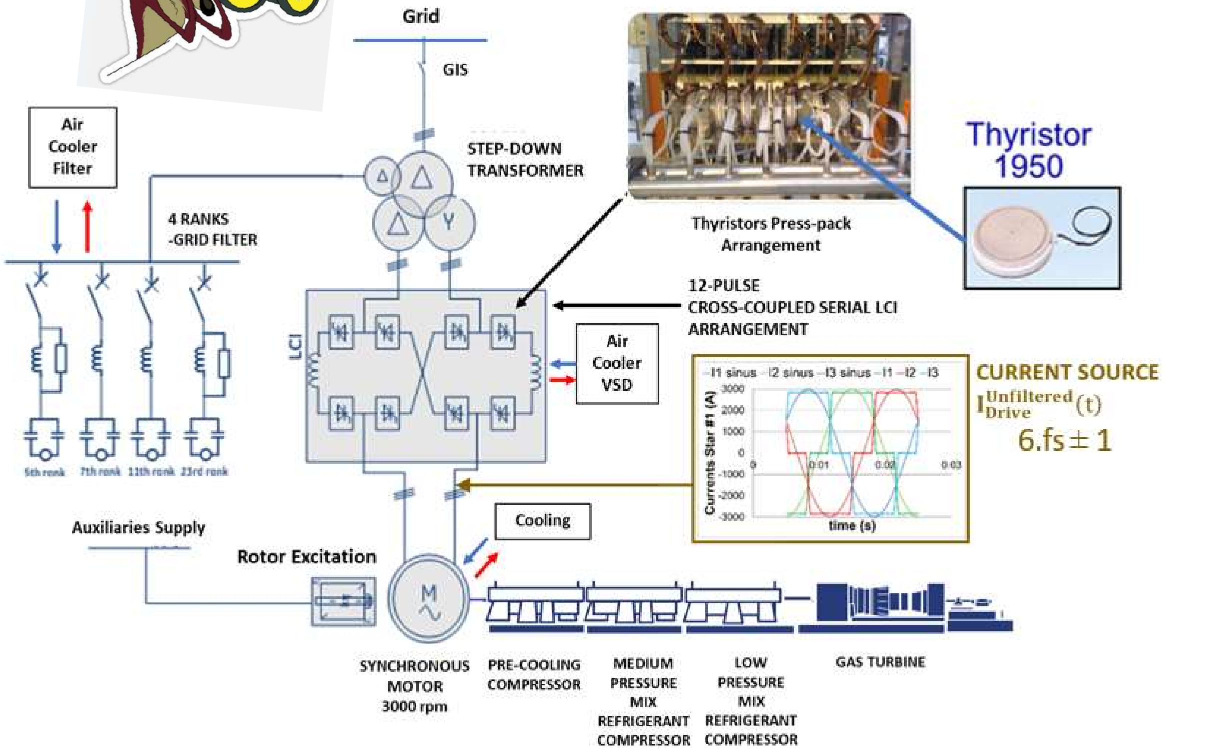
LCI + Synchronous motor + (Gearbox if 4-pole) for Starter Helper LNG Train

Thyristor is a diode needing reactive power from the motor and the grid for its commutation
➔ Load Commutated Inverter (LCI)





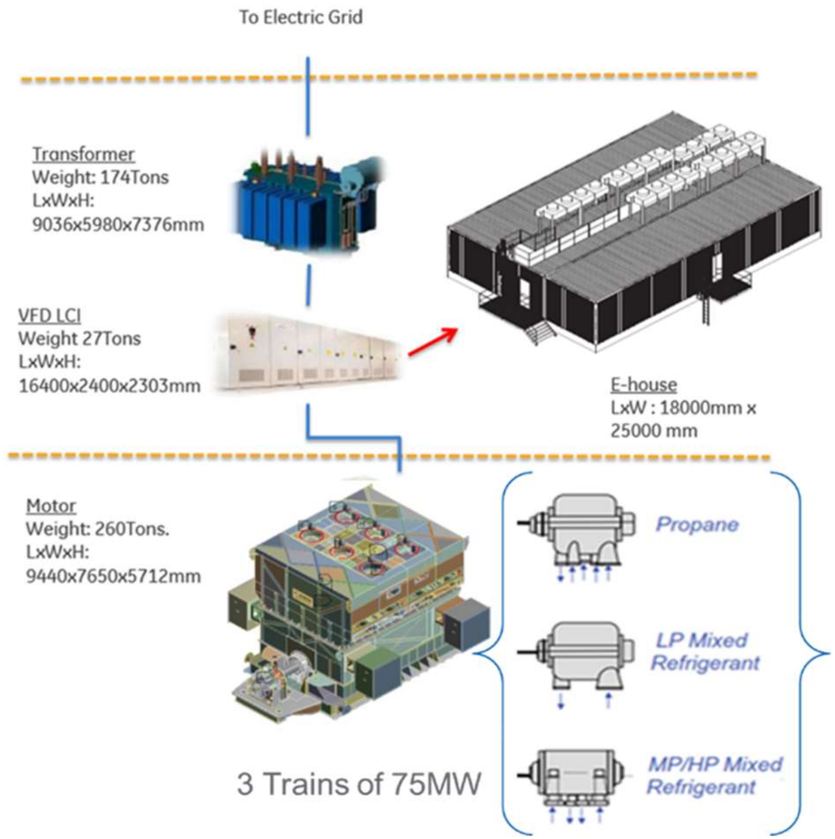
Diodes Press-Pack proven arrangement



LCI generates inter-harmonics and absorbs reactive power
3 constraints ➔Harmonic filter, Large capacitors bank, Synchronous motor

Full Electric LNG **Biggest** 2-pole **synchronous** motor fed LCI ➔ **75 MW**

In 2019, GTGs are totally eliminated
in some plant designs as
2-pole synchronous motors fed by LCI are used instead
with the highest reference at 75MW



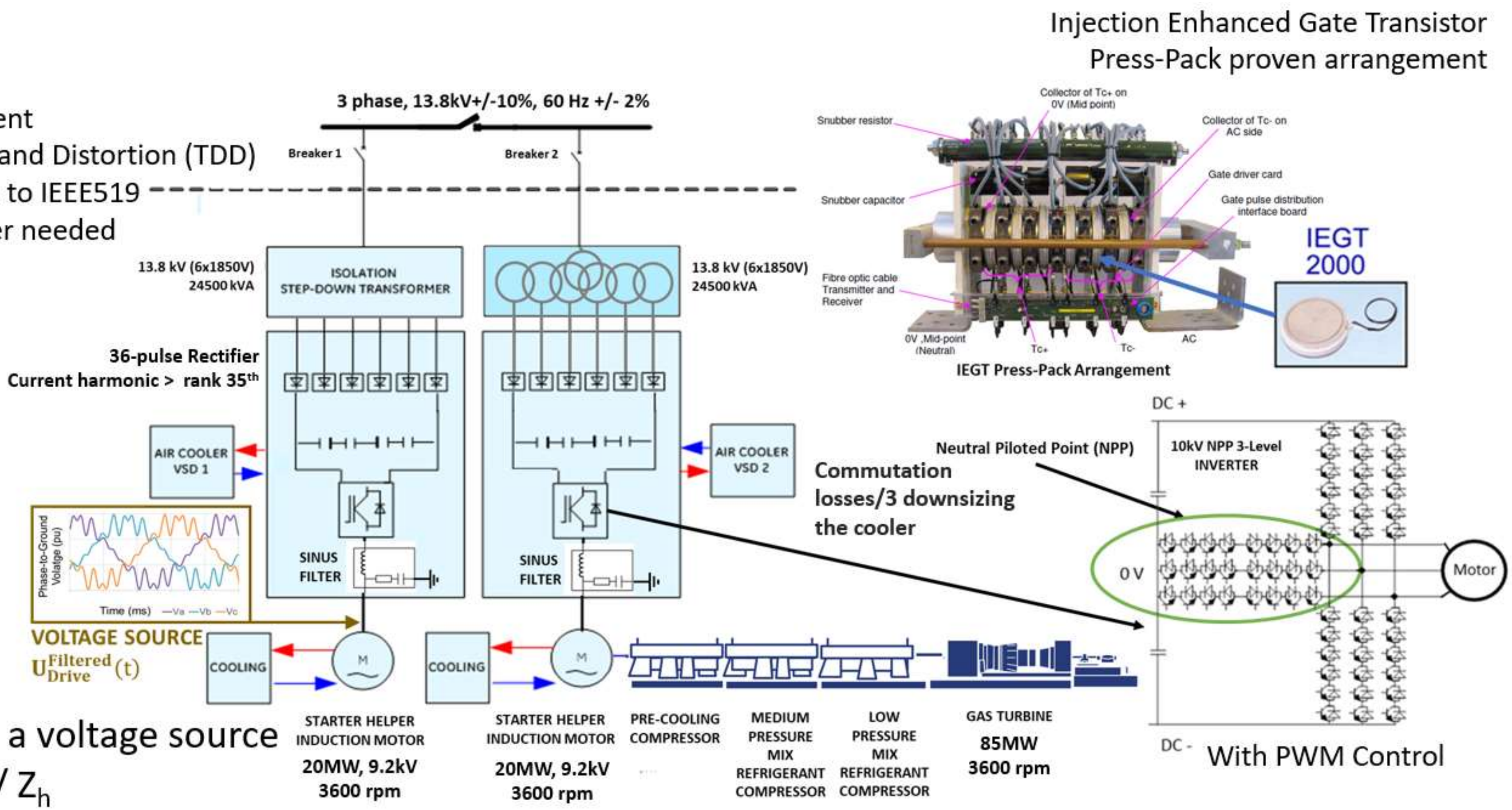
Electric motor has less constraint of rating limitations (temperature, speed) coming from the electromagnetic physics (photon, electron)

Compressors Test bench : 2-pole Synchronous Motor VSI-fed ➔ 61MW@3600 rpm

- 2 pole synchronous motor 9kV fed PWM VSI Converter
- 3 bearings – Oil lubricated
- 7-phased exciter
- Watercooler
- 2 shaft-ends
- Operating at full load since the 2 May 2013

VSI + Induction motor + (Gearbox if 4-pole) for Starter Helper LNG Train

< 8% Current
Total Demand Distortion (TDD)
Compliant to IEEE519
➔ No filter needed



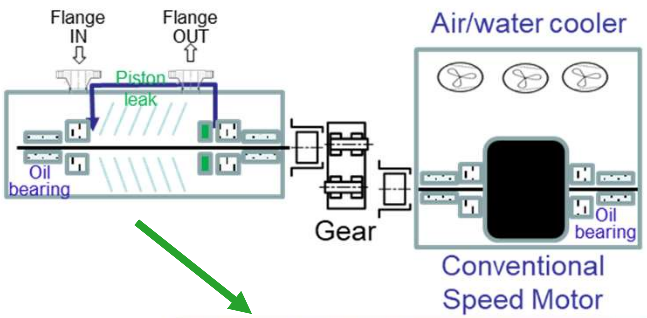
IEGT is a voltage source

$I_h = V_h / Z_h$

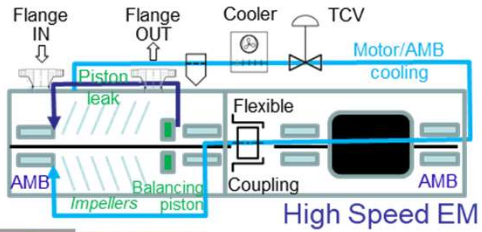
DFE-VSI ➔ No Constraint : No Harmonic filter and Induction motor suitable

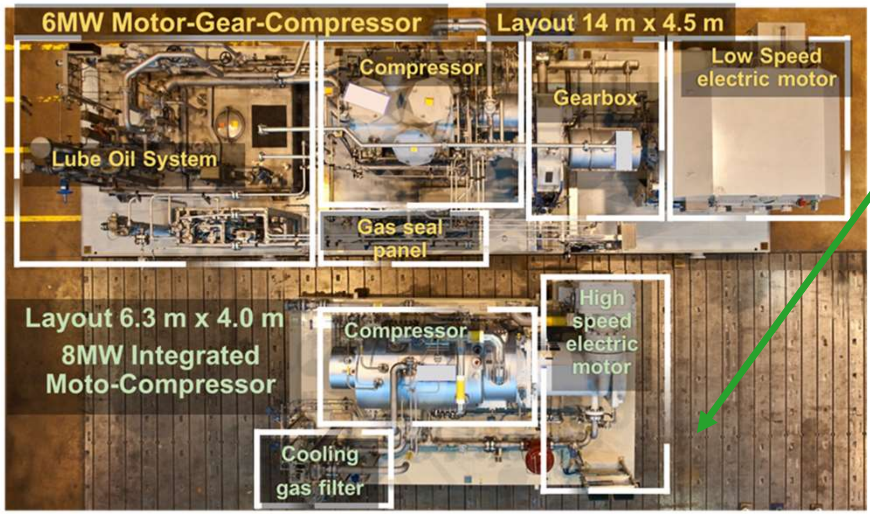
System Arrangements and Layouts

Air cooled Standalone Gearbox Drive

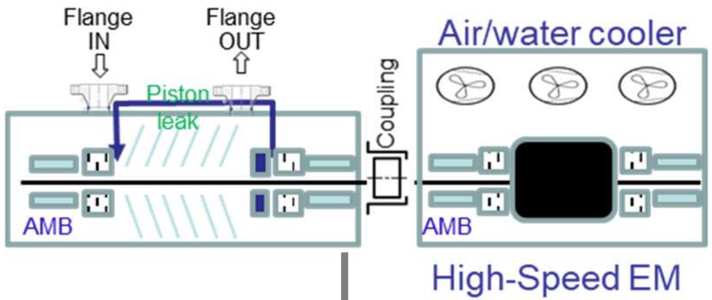


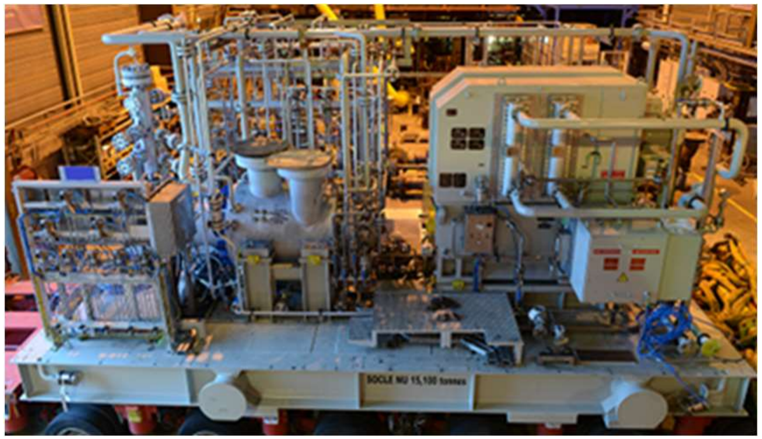
Gas cooled Integrated Direct Drive





Air cooled Standalone Direct Drive



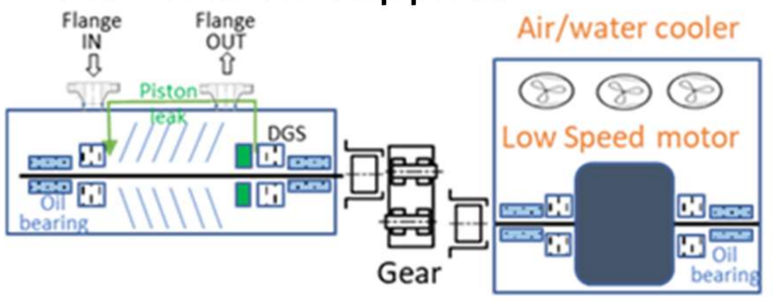


6.9 MW Direct-Drive Off-shore Export Gas Compression Service

Direct Drive Solutions are better in layout – Integrated Solution removes Dry Gas Seals

Standalone Electric Systems with Gearbox

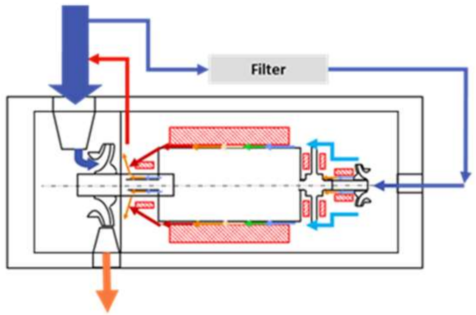
- Large and heavy conventional speed Electrical Motor fed by a VSD
- Requirement lubricated gear, coupling, lubricating oil system and acoustic enclosure
- Compressor with dry gas Seals DGS, weakness point of reliability, complex and expensive seal gas conditioning system (DGS failure is the first cause of compressor trouble shooting)
- Atmospheric oil drainage for offshore floating installation
- Many auxiliary and connections for air, nitrogen, cooling water and air supplies
- Continuous gas leakage to the flare
- Long commission time
- Large integrated CAPEX and high OPEX



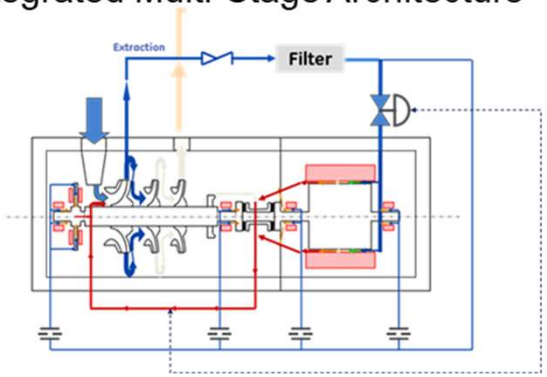
End User List of Limitations and Issues …

Integrated Electric Motor-compressor

Integrated Single-Stage Architecture



Integrated Multi-Stage Architecture



Export Integrated Compression
4.7MW – 2.8 kV – 11500 rpm
7.5 MSm3/day

Ethylene Integrated Compression
2.8MW - 2.4kV - 11000 rpm
13 to 97 bars - 0.77 MSm^3/day

Mix-Refrigerant Small-Scale LNG
integrated Compression
8MW – 5.6kV – 9400rpm
1.75 MSm^3/day

Pipeline Natural Gas Station
8.6MW - 6kV - 11000 rpm

Turbine Replacement for Pipeline
19MW – 7.5kV - 6500 rpm

90+ References up to 19MW in operation with cumulated hours over 5,000,000 hours

Integrated Electric Moto-compressor

- Strong reduction of weight, footprint & Noise
- No more gear box, no more lube oil system, no more dry gas seal systems
- No cooling water, no lubricating oil, no instrument air, no nitrogen,
- Only few remaining instruments,
- No direct emission (no gas leakage to the flare, no oil vapor),
- Reduced maintenance (no Dry Gas Seal),
- Drastically simplified the packages transportation and the construction,
- Reduction of commissioning time and start-up operations,
- Reduction of integrated CAPEX and low OPEX,
- Minimization of the number of compression stages and intercoolers.
- Remote control of the compressor.

The integrated motor is designed for the following conditions

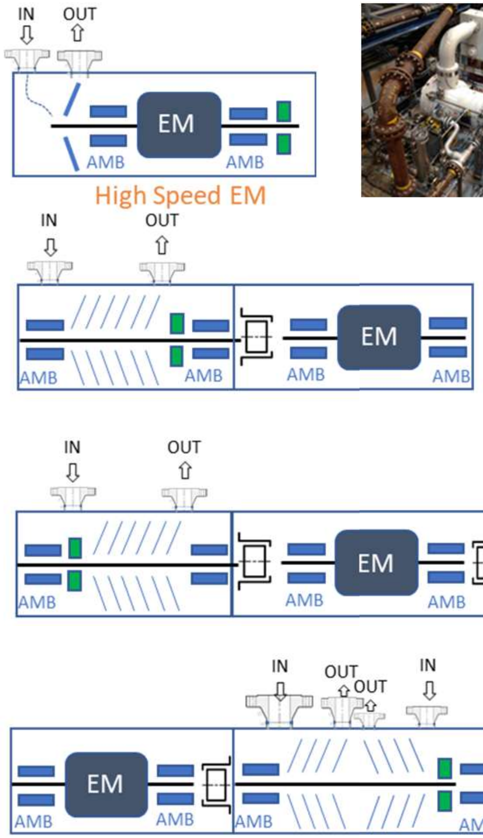
- Up to 15 bar partial pressure CO2
- Up to 15 mbar partial pressure of Wet H2S
- Up to 150 mbar partial pressure of Dry H2S
- Up to 200 bar Settle-Out Pressure (SOP)
- Up to 100% relative humidity at suction
- Rapid Gas Decompression (RGD) < 30 bars/min

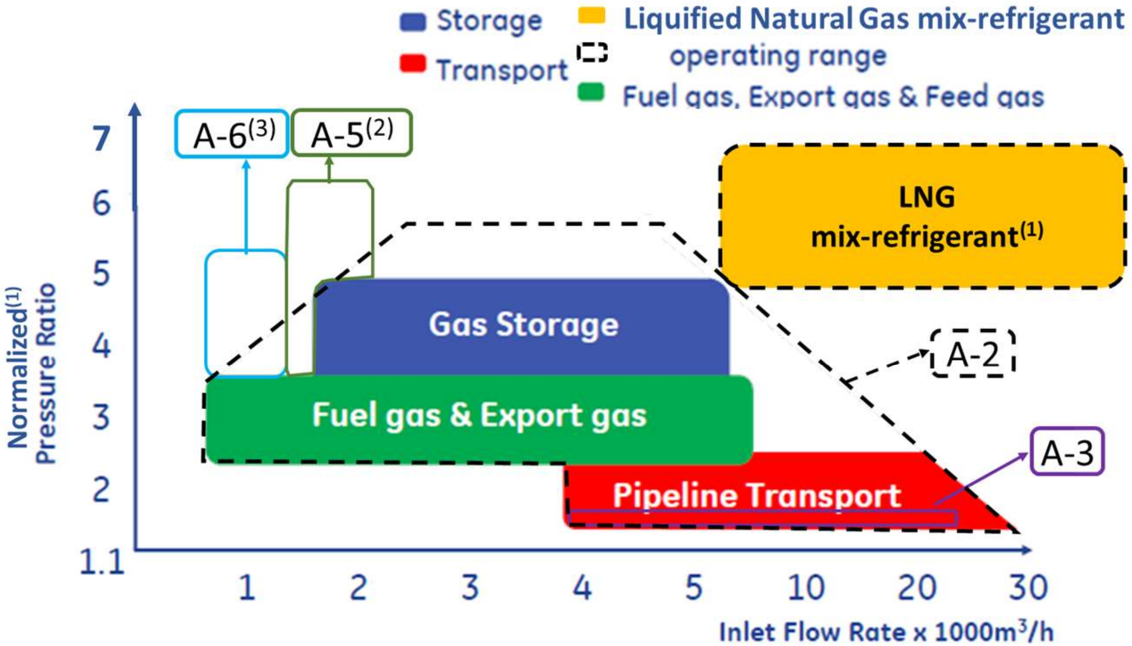
- Mid & Upstream: Natural Gas and Associated gas,
- LNG: Mix-refrigerant, Boil of Gas,
- Downstream: Ethylene, Propane, Butene, H2 …

Integrated compression is qualified for most of the Upstream, Mid & Downstream

Except for high H_2S and Ammoniac contents, cracked gas, and pressure > 300 bars

Integrated Systems Arrangements

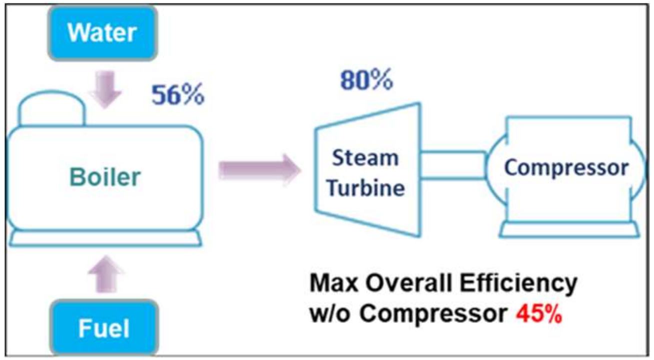


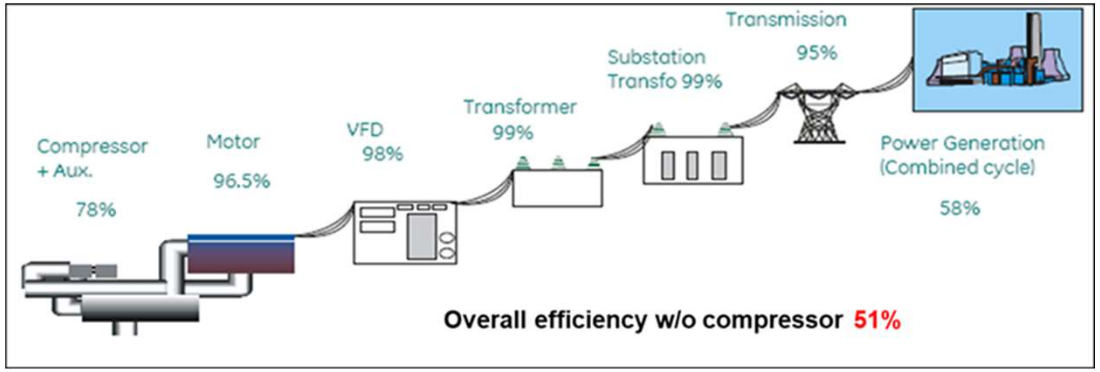


(1): Pressure ratio map is normalized for a Natural Gas with a Mol. Weight ranging from 20 to 24 gr/mol
(2): gas storage applications with extended pressure ratio for low inlet pressure
(3): gas storage applications with extended pressure ratio for high inlet pressure

Integrated System Arrangements with Flexible Coupling cover most of the compression needs

Why replace Turbines?

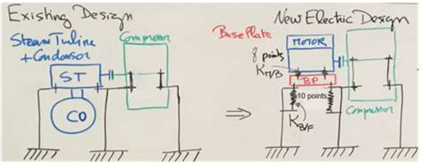




- **High flexibility**
- **Global efficiency** ➔ Turbine 45% vs Electric 51%
- **Environment, health & security**
  - ➔ NL Klimaatakkoord law reduces Industrial GHG emissions by 60% by 2010
  - ➔ France wants to reduces from 400 Millions Tons of CO_2 to 262 Millions Tons in 2030
  - ➔ Electrical solution reduces by around 30% CO_2 emissions
- **Operation cost**
  - ➔ Major overhauls: Turbine 10 years vs Electric Motor 15 years
  - ➔ High consumption of treated water for condensing steam turbine
  - ➔ Gas Monetization
  - ➔ CO_2 Emission Taxes : 40€/tCO_2 @ 2024 ➔ 60€/tCO_2 @ 2030 in EU
- **Key enabler of the electrical solution**
  - ➔ Compatible size with the existing environment : High-Speed Direct-Drive Motor

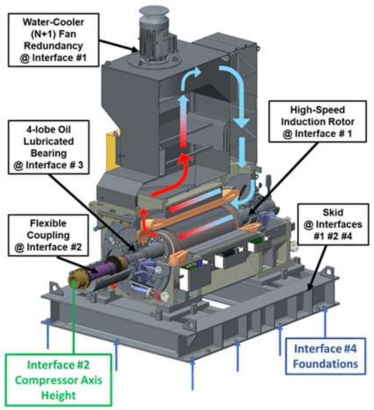
Turbine replacement ➔ Main Challenges

Interface Compatibility



- ***Interface #1:*** Maximum available volume
- ***Interface #2:*** Axis height & Rotor of the compressor
- ***Interface #3:*** Re-use of the oil system for the bearings
- ***Interface #4:*** Existing 10-point of fixation by tie-rods in the foundation

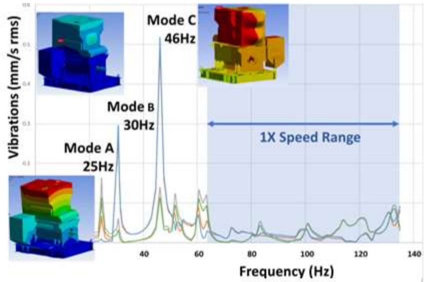
Motor-fans for compressor baring at low speed



Mechanical Integration

Design Rules for Mechanical Integration:

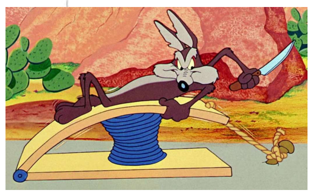
- No rotor bending mode in 1X speed range
- No end-shield axial mode in 1X & 2X speed range
- No system « Reed » bending mode (horizontal or axial) in ½X, 1X and 2X speed range
- Skid vibration near the motor feet < 30% of bearings vibration



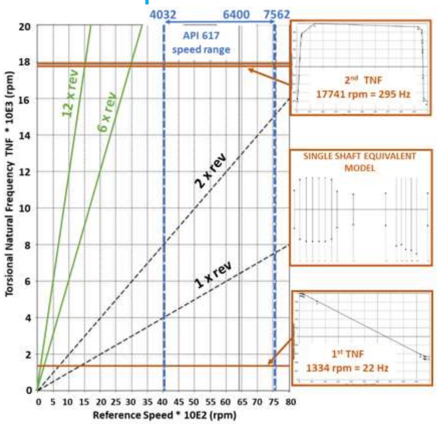
Skid optimization

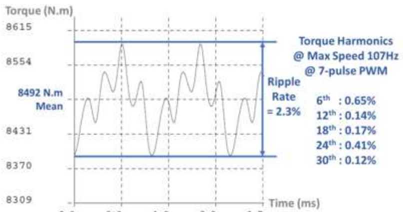
&

Requested Stiffness of foundation > 10^{+9} N/m



Torque Pulsation





High-Speed Direct-Drive Motor-Compressor Train fed by VSI:

- Simple train arrangement
- Less torsional modes
- Less torque harmonics and amplitudes

Compared to Gearbox-Motor-Compressor Train fed by LCI

Turbine-Motor Swap

35 days from compressor shutdown to commissioning of the new motor

1. Extensive demolition
Removal of steam piping and the old steam turbine

2. Key challenge ➔ turbine separation from its tabletop foundations without damaging the concrete and skid installation

3. Skid Baseplate grouting

4. Electric motor installation and alignment to compressor

5. Mechanical, electrical and instrumentation connections

In addition to Site Electrification, the Motor Integration is the main challenge

Exemples of High-Speed Motors for Steam & Gas Turbines Replacement

2.4 MW @ 10 700rpm
on Oil bearings

8.4 MW@ 6 200 rpm
On Oil bearings

3.2 MW @ 14 200 rpm
on Active Magnetic bearings

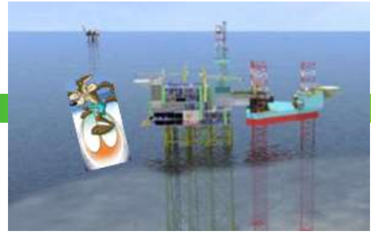
11.9 MW @ 5 100 rpm
On Oil bearings

5.7 MW @ 6 400 rpm on Oil bearings
On Site after steam turbine replacement

4.9 MW @ 4 900 – 7 500rpm on Oil bearings
FAT – Load tests

More and more references during the last 5 years …

Off-shore Gas Turbine Replacement



Off-shore Export Gas Service
2-pole Induction Motor on Active Magnetic Bearings

16MW @ 8000rpm rated / 9000 rpm MCS

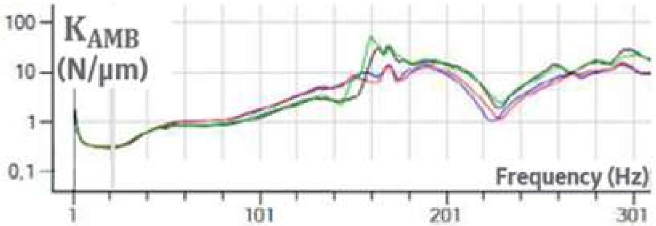


Fig.31. AMB stiffness vs Frequency.

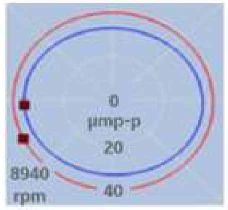


Fig.30. Shaft orbits @ 8940rpm.

High-speed induction motor on AMB(s) brings substantial reduction in weight and footprint reducing the size of the topside structure of the offshore platform

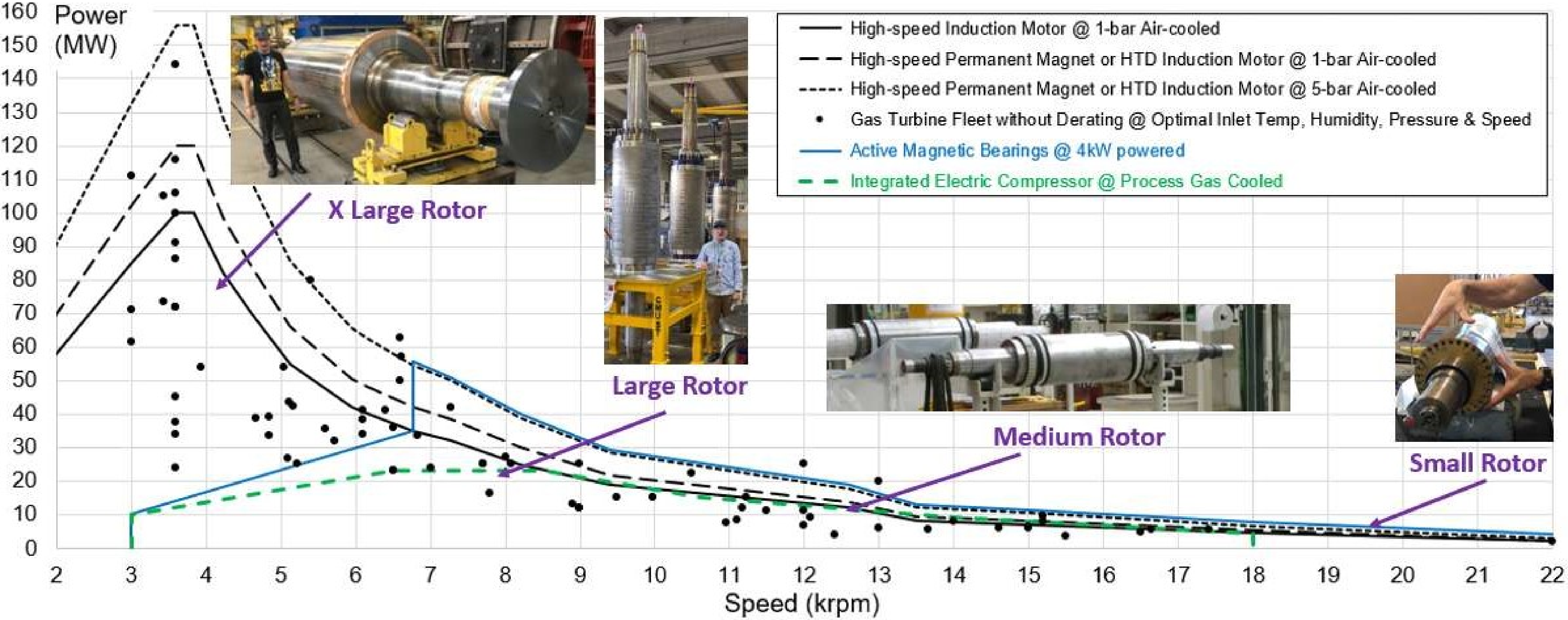
Typical cost ratio of 10 to 20 k$ per ton of installed base is the usual assumption for offshore structure

Replacement by the End-user of existing turbines, and compressors on oil bearings by a standalone arrangement on active magnetic bearings for an off-shore platform

ELECTRIC COMPRESSION COVERAGE

CONCLUSION & PERSPECTIVES

Power vs Speed Coverage of High Variable Speed Electric Motors



Reference High-speed Induction Laminated Motor @ 1-bar Air-cooled ➔

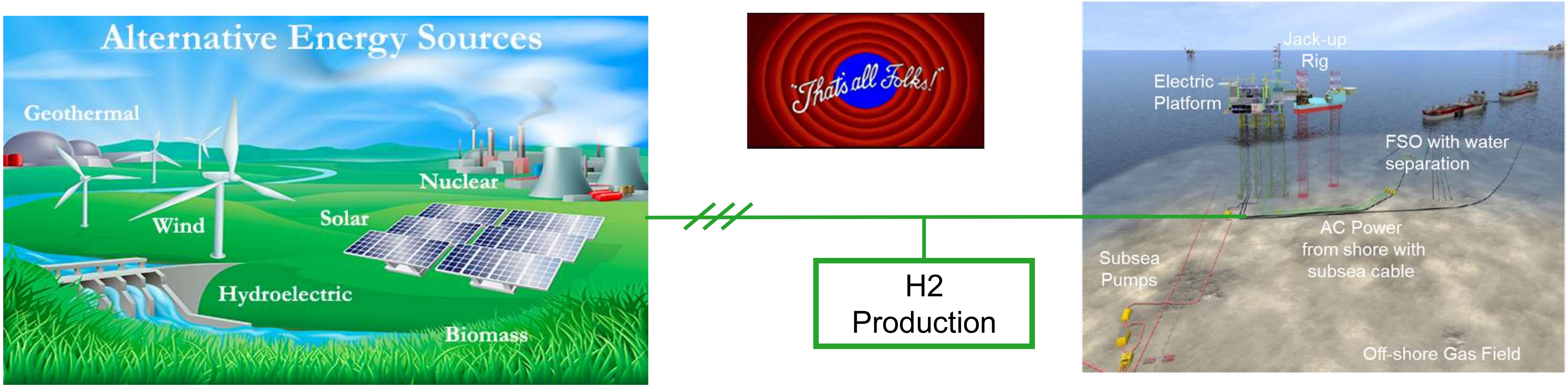
- 5-bar Air-cooled Pressurization	**Δ Torque Density = +30%**	**Δ Motor Efficiency = -1%**
- 2-pole HTD Induction Rotor	**Δ Torque Density = +10% to 15%**	**Δ Motor Efficiency = - 0.1%**
- 4-pole HTD Induction Rotor	**Δ Torque Density = +20% to 25%**	**Δ Motor Efficiency = - 0.3%**
- 2-pole Permanent Magnet	**Δ Torque Density = +10% to 15%**	**Δ Motor Efficiency = + 0.3%**
- 4-pole Permanent Magnet	**Δ Torque Density = +20% to 25%**	**Δ Motor Efficiency = + 0.2%**

More than 95% of the existing mechanical drive turbine ratings can be replaced by VSI-fed Direct Drive High-speed Motors

Conclusions & Perspectives

Variable Speed Electric Systems (VSI + Induction) provide flexibility of compression services over the time without derating constraints (Temperature, Speed …) compared to Thermal Machines (Steam & Gas turbines)

Electric Compression (Standalone & Integrated) is attractive in term of CAPEX & OPEX compatible to the evolution of news technologies of Electrification (microgrids, storage & power generation, H_2 …) reducing natural gases emissions (Global warming, Taxes, No Flaring in 2030 in Europe) and wastes (Monetization)



The best Investment of the XXI Century is the Electrification of our planet !

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Thanks for your attention!

There are no foolish questions,
and no man becomes a fool until he has stopped asking questions.
Charles Steinmetz

Tribute to the Genius Chuck Jones,
The Expert about High-Speed Processes!
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Q & A!