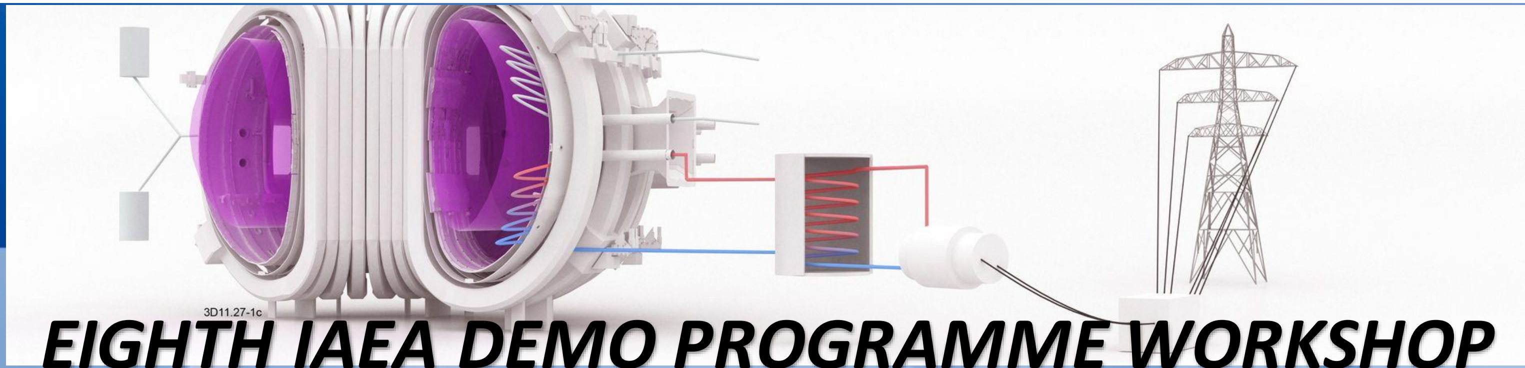

EIGHTH IAEA DEMO PROGRAMME WORKSHOP

EUROfusion

Topic 3, Efficiency: coolant selection, cost, and delivering time

Electrical Power Management, the path toward efficient energy production

E. Gaio and the EU DEMO WPPES team

CONSORZIO RFX
Ricerca Formazione Innovazione

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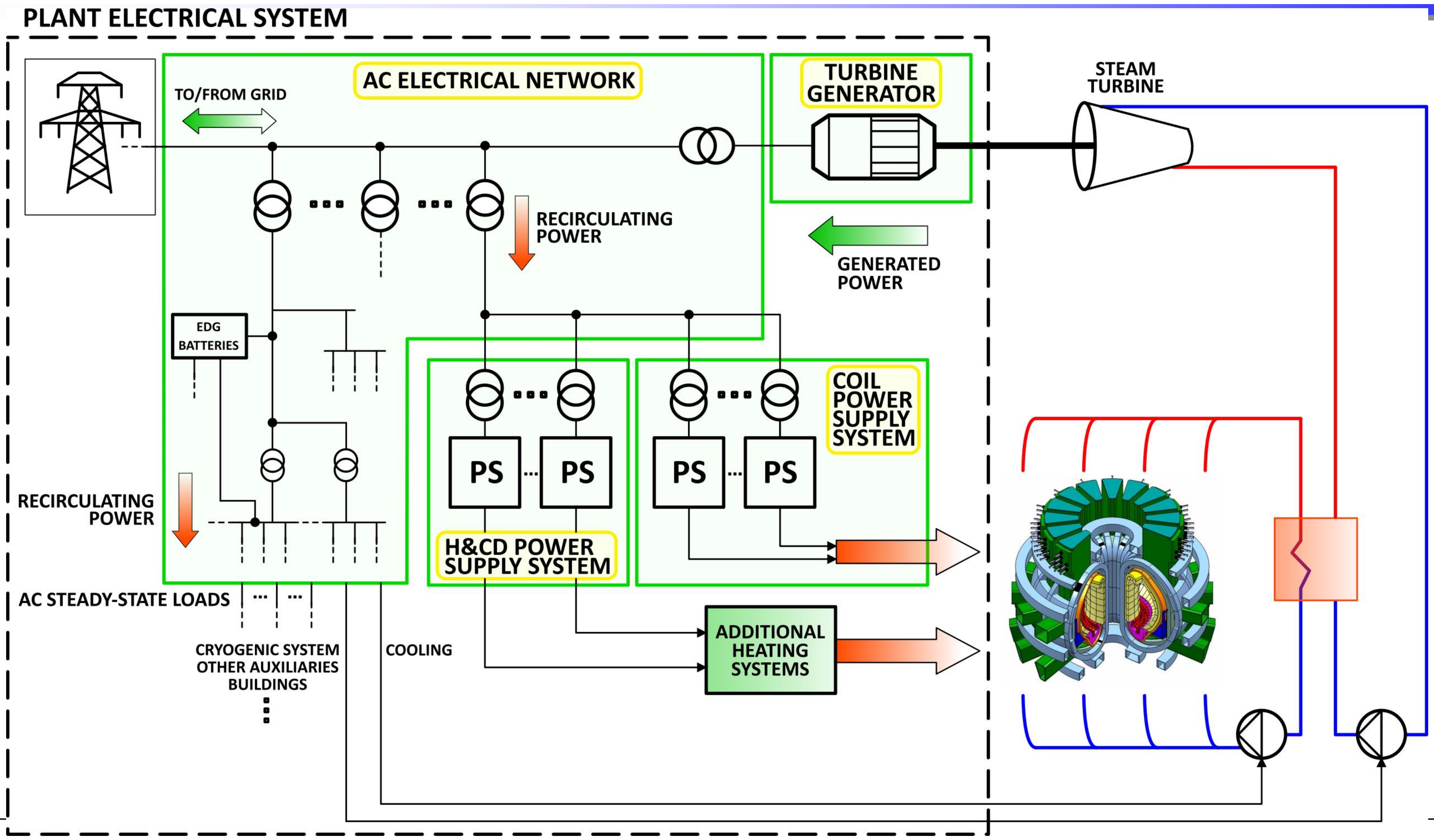
Outline

- *The plant electrical systems*
- *What deals with the plant efficiency*
- *The recirculating power*
- *Other fundamental requirements*
- *The electrical power management: issues and areas of studies and R&D*
- *Understanding and discussing the issues*
- *R&D priorities*
- *First outcomes from the studies and R&D for the EU DEMO*

Simplified block scheme of a fusion plant electrical system



"Electrical gain" of the fusion power plant

P_{HCD_el} = gross HCD power

P_{HCD_pl} = net HCD power input

η_{aux} = efficiency of HCD power

P_F = Fusion Power

P_α = power associated to α particles

$P_{neutrons}$ = power associated to neutrons

Q = fusion gain

P_{TH} = thermal power

M = neutron energy multiplication factor in the blanket

η_{TH} = thermal to electrical conversion efficiency

P_{EG} = gross electrical output

P_R = recirculating power

ε = fraction of recirculating power

P_{EN} = net electrical output

Q_{el} = "Electrical gain" of the fusion power plant

around 10 in traditional Power Plants
around 1 for the DEMOs

$$\boldsymbol{Q_{el} = \frac{P_{EN}}{P_R} = \frac{(1-\epsilon)}{\epsilon}}$$

$$\eta_{aux} = \frac{P_{HCD\_pl}}{P_{HCD\_el}}$$

$$P_F = P_\alpha + P_{neutrons}$$

$$Q = \frac{P_F}{P_{HCD\_pl}}$$

$$P_{TH} = P_F * (0.2 + 0.8 * M + \frac{1}{Q})$$

$$\eta_{TH} = \frac{P_{EG}}{P_{TH}}$$

$$\boldsymbol{\epsilon = \frac{P_R}{P_{EG}}}$$

$$P_{EN} = P_{EG} * (1-\epsilon)$$

P_R is much higher than in NPPs

Overall electrical efficiency challenged by:

- ***The pulsed operation***
- ***The need of long shutdown to replace in-vessel components which qualified life is shorter than the life of the reactor (EU-DEMO goal is 30%, against >90% of NPP)***
- ***The low overall RAMI of DEMO due to its huge complexity***

Note: electrical systems components are characterized by high efficiency, so the impact is low on the recirculating power, which is mainly an input for the electrical systems design

Recirculating Power

Wide range of values in the estimations of the recirculating power fraction versus P_{EN}

DEMO Reactor	Recirculating power estimation	Reference
DEMO CREST	0.5 (NBI only accounted)	R. Hiwatari, NF 47 (2007)
EU PP	Based on process code, CD and helium pumping only first, later other components added: 0.27-0.57 (from 2014 to 2019)	D. Maisonnier, NF 47 (2007) process runs
CFETR	0.5 with a more detailed estimation	X. Liu, NF 57 (2017)
K-DEMO	0.85 and 0.65 for two design options, but without justifications of the numbers	J.H. Yeom, FED 88, (2013)
ARC	0.3 with the estimation commented	B.N. Sorbom, FED 100 (2015)
Spherical Tokamak PP	0.35 as average between values from 0.06 to 0.64 found in the literature	F. Schoofs, FED 176 (2022)

Recirculating Power

"The fraction of electrical power re-circulated is shown to be of crucial importance in assessing the credibility of fusion systems as commercial reactors"[1]

What is?

- the gross electrical input power necessary for the plasma heating and current drive
- the power necessary to run ALL the plant systems

- **impacting on the plant efficiency**
- careful estimations needed without neglecting any components
- difficult to be estimated at the present level of development of the DEMOs designs and relevant electrical systems

The preparation and update of the electrical load list for the EU DEMO is in progress

1. Davenport, Nuclear Fusion 18, 1978

Minucci, Energies 13, 2020

Other fundamental requirements

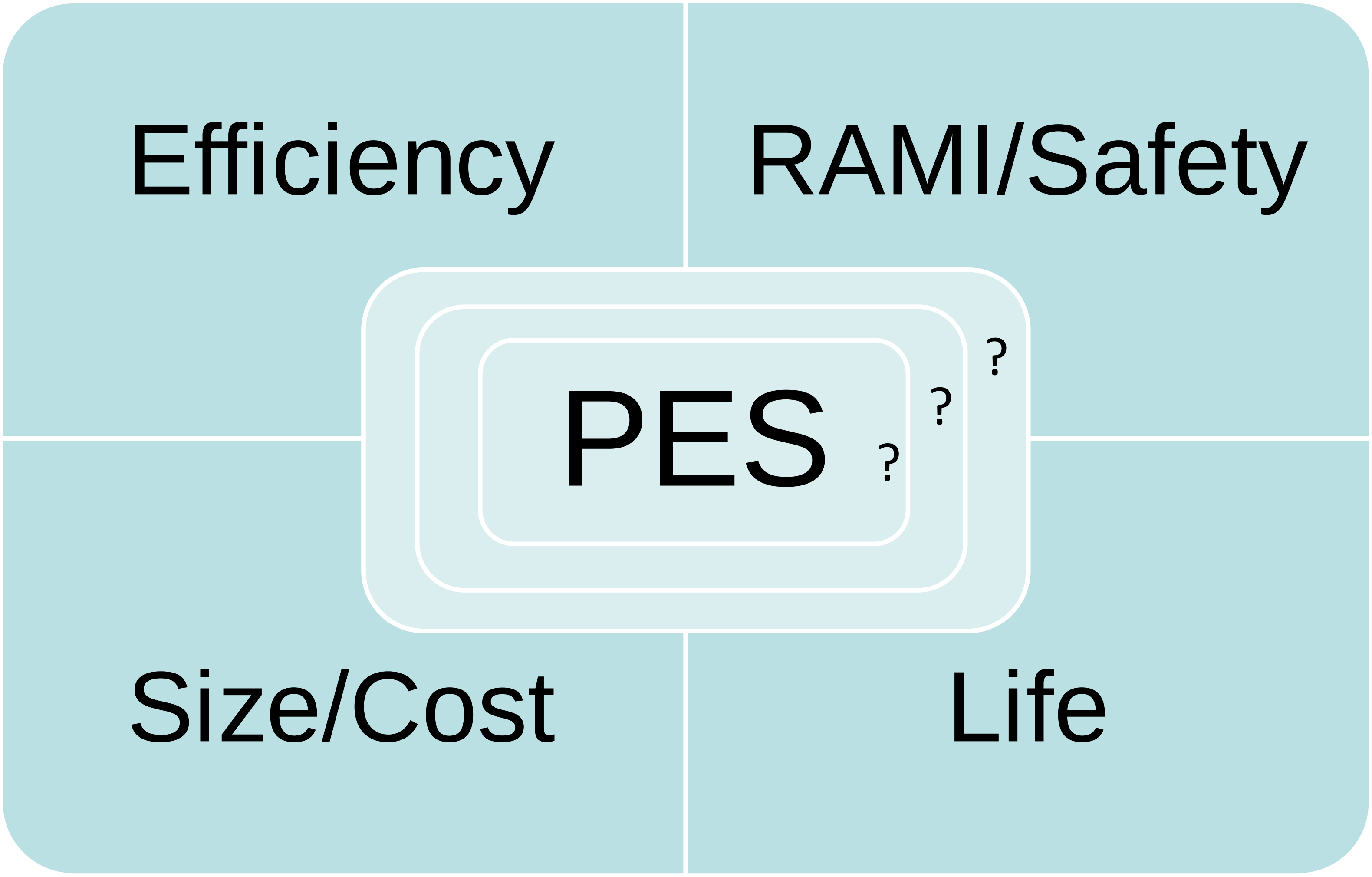
Other fundamental requirements for a commercial fusion power reactor; to be:

- **SAFE**
- Licensable (in all the phases of construction, operation, maintenance and decommissioning)
- Environmentally friendly
- With high RAMI level
- With sufficient lifetime
- With minimized capital and operational cost

In EU, system studies aimed to satisfy the listed requirements have been included since 2000[1], and later, in the fusion roadmap and workprograms for the EU DEMO design development[2]

1. S. Paidassi, FED, 49-59, 2000
2. EU fusion Roadmap, https://www.euro-fusion.org/eurofusion/roadmap/
3. G. Federici et al., NF 59, 2019; FED 178, 2022
4. Morris et al, Plasma Phys. Control. Fusion 64 064002

Impact on plant efficiency, safety, RAMI, size, cost..?



Are we ready to say how much the plant electrical systems affect the plant efficiency, the level of RAMI (reliability and availability in particular), the safety, the size and the cost of the plant?

Are the related technical aspects already quite well assessed and tested in the existing experiments to provide replies in those regards?

Are we ready to reply?

NO

- it is questionable whether some known technologies well tested in existing experiments are still adequate when scaled to the DEMOs
- there is the need for R&D to identify and verify the feasibility of suitable alternative solutions
- not negligible part of the plant electrical subsystems/components of the DEMOs are not Commercial Off The Shelf (COTS); some of them are First Of A Kind (FOAK)
- the moderate level of maturity of the design of the majority of the DEMO components make the requirements for the electrical systems, and consequently, the related design solutions, **not well defined**

Issues and the areas of study and R&D

Issues and areas requiring studies and R&D identified for the EU DEMO, but relevant for any pulsed DEMOs

- **the assessment of the pulsed operation of the turbine generator** from the electrical point of view
- **the capability to supply the necessary active power waveforms** mainly required for the plasma formation, vertical stabilization and control and without impacting on the Power Transmission Grid (PTG)
- **the huge reactive power demand** if the classical thyristor converter technology is adopted
- **the risk of instabilities** in the Power Transmission Grid (PTG) if **too large static var compensator systems** are installed
- **the assessment of the level of active power steps and derivatives and voltage perturbations compatible with the stable operation of the PTG**
- **the connection to the PTG and the assurance of reliability and continuity of service**
- **the increase of the power utilization factor** for coil power supply, which is extremely low
- **the quantification of the recirculating power**
- **the assessment of the impact of the harsh environment (nuclear radiation, magnetic field, temperature, humidity, floor response spectra, pressure in normal and accidental conditions)** on electrical components inside the reactor building
- **the layout optimization**, considering radiation and magnetic field map, fire zonings and trains separation for the systems performing nuclear safety functions
- **the need to satisfy the strict nuclear rules for design, fabrication, qualification, maintenance, inspection and test for safety classified emergency electric power**

Note: The last six issues are valid for steady state DEMOs, too

Understanding and discussing some issues

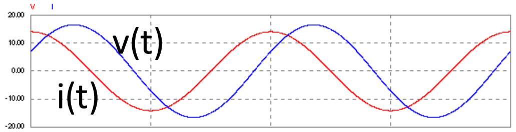
DEFINITIONS

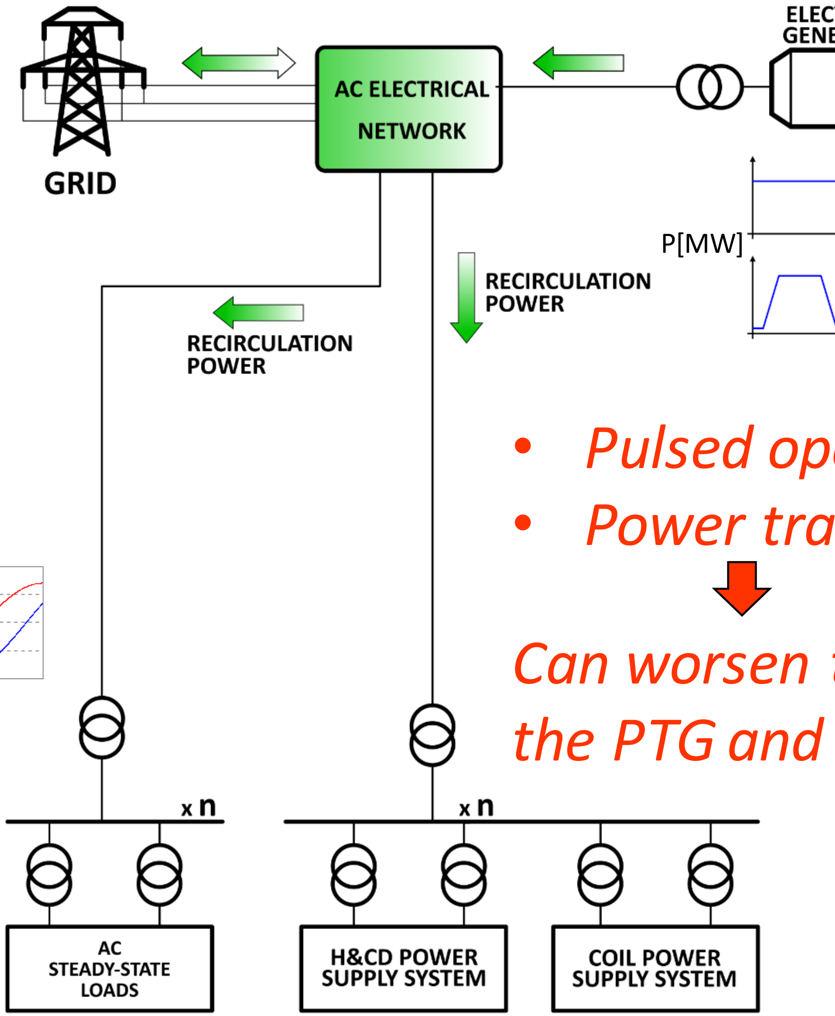
- **P, Active Power: real part of the complex power that is really utilized for the useful work of the electrical loads**
- **Q, Reactive Power: imaginary part of complex power corresponding to energy exchanged between the supply source and the load without producing useful work**
- **S, Apparent Power**

$$P = V * I * \cos\varphi \ [W]$$

$$Q = V * I * \sin\varphi \ [\mathrm{VAr}]$$

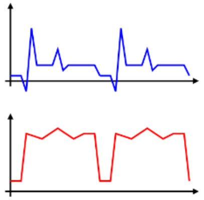
$$S = V * I = \sqrt{P^2 + Q^2} \ [VA]$$





- *Pulsed operation*
- *Power transients*

Can worsen the power quality of the PTG and internal network



high peaks during plasma formation and plasma control

highe value of reactive power during almost all the plasma pulse

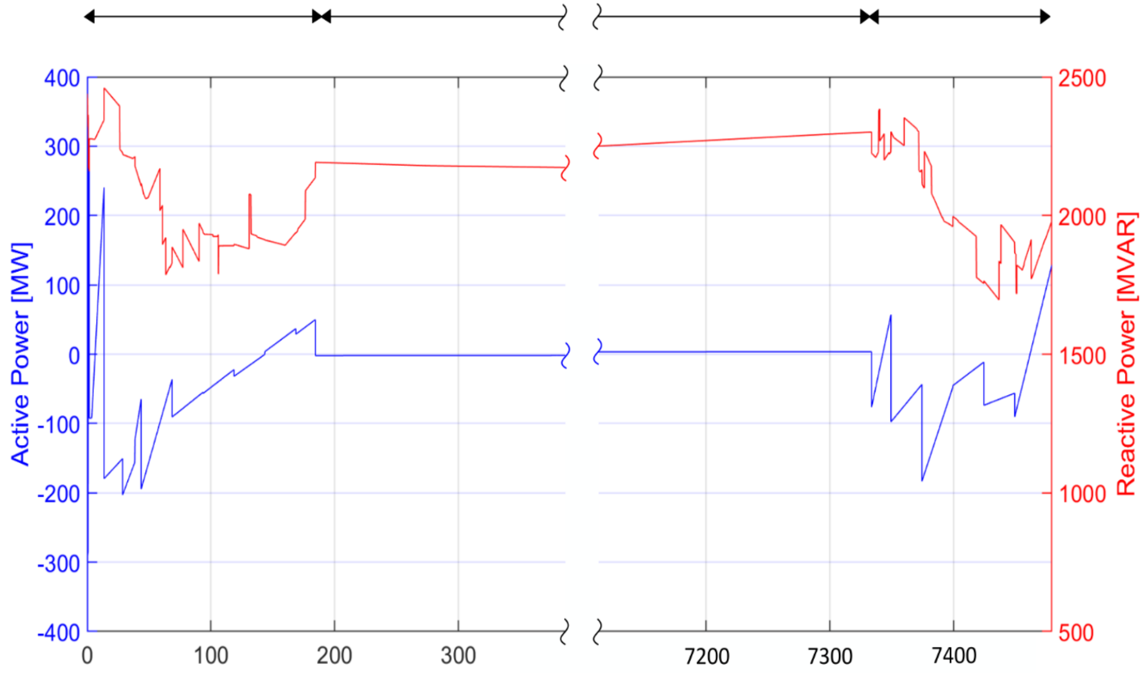
almost constant profiles of active and reactive power

- f: frequency of the sinusoidal waveforms
- V, I: rms values of voltage and current
- Φ: phase shift angle between V and I
- THD: total harmonic distortion
- PTG: Power Transmission Grid
- Ncc: short circuit power of the PTG node

Power quality: degree to which the voltage supply conforms to ideal steady sine wave

Understanding and discussing some issues

Active power peaks and reactive power demand, mainly caused by pulsed PS



Example of P and Q profiles calculated for an EU DEMO scenario under study and assuming to use thyristor converters technology to supply SC coils

ACTIVE POWER steps and derivatives: *WHY AN ISSUE?*

$$\Delta f = \frac{\Delta P}{N_{CC}}$$

frequency variation

⇩

stress on the PTG synchronous generators

⇩

risk of loss of synchronism

REACTIVE POWER demand and variations: *WHY AN ISSUE?*

$$\frac{\Delta V}{V} = \frac{\Delta Q}{N_{CC}}$$

Voltage perturbations of the PTG ⟹ flickers

Voltage perturbations in the internal network

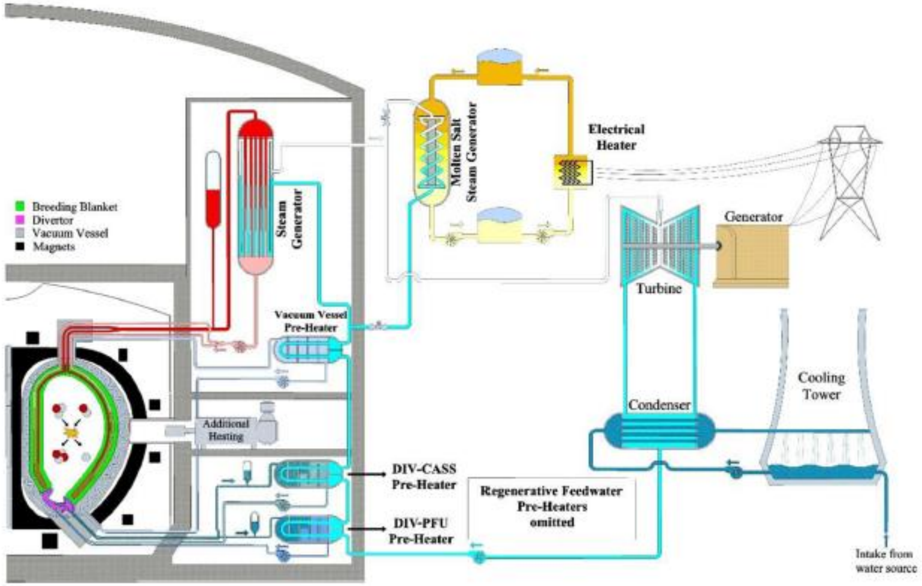
Tentative assumptions of limits for the EU DEMO

Characteristic	Values
Reactive power	250 MVAR
Active power peak	600 MW
Active power steps	150 MW
Active power derivative	500 MW/s
Fault Level	15 GVA

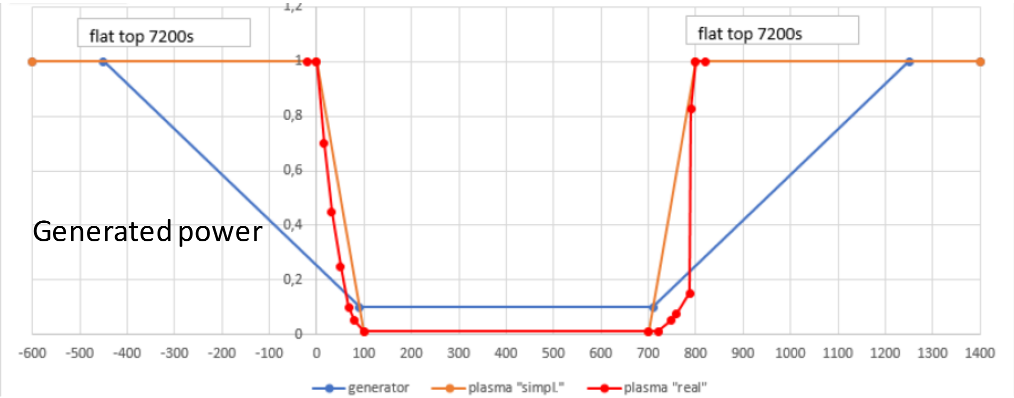
Understanding and discussing some issues

Variable Power Generation in case of pulsed operation of the plant turbine generator

Water Cooled Lithium Lead (WCLL) Direct Coupling between the Primary Heat Transfer System (PHTS) & Power Conversion System (PCS)



Example of waveforms under study of the EU DEMO turbine generator in case of PHTS&PCS Direct Coupling



L. Barucca, et al., Fusion Eng. Des. 169 (112504) (2021)

Technical aspect

- **Fastest ramps close to steps**
- **Stress and risk of loss of synchronism for the turbine generator and the PTG synchronous generators**
- **Limit of derivative to be assessed from the electrical point of view**

Regulatory aspect

- **Operation NOT acceptable for the European Regulation (ENTSO-E) for the connection of the synchronous generators to the EU PTG**
- **Variable generation, more comparable to that of renewable plants, to be assessed from the technical and economical point of views with Transmission System Operators**

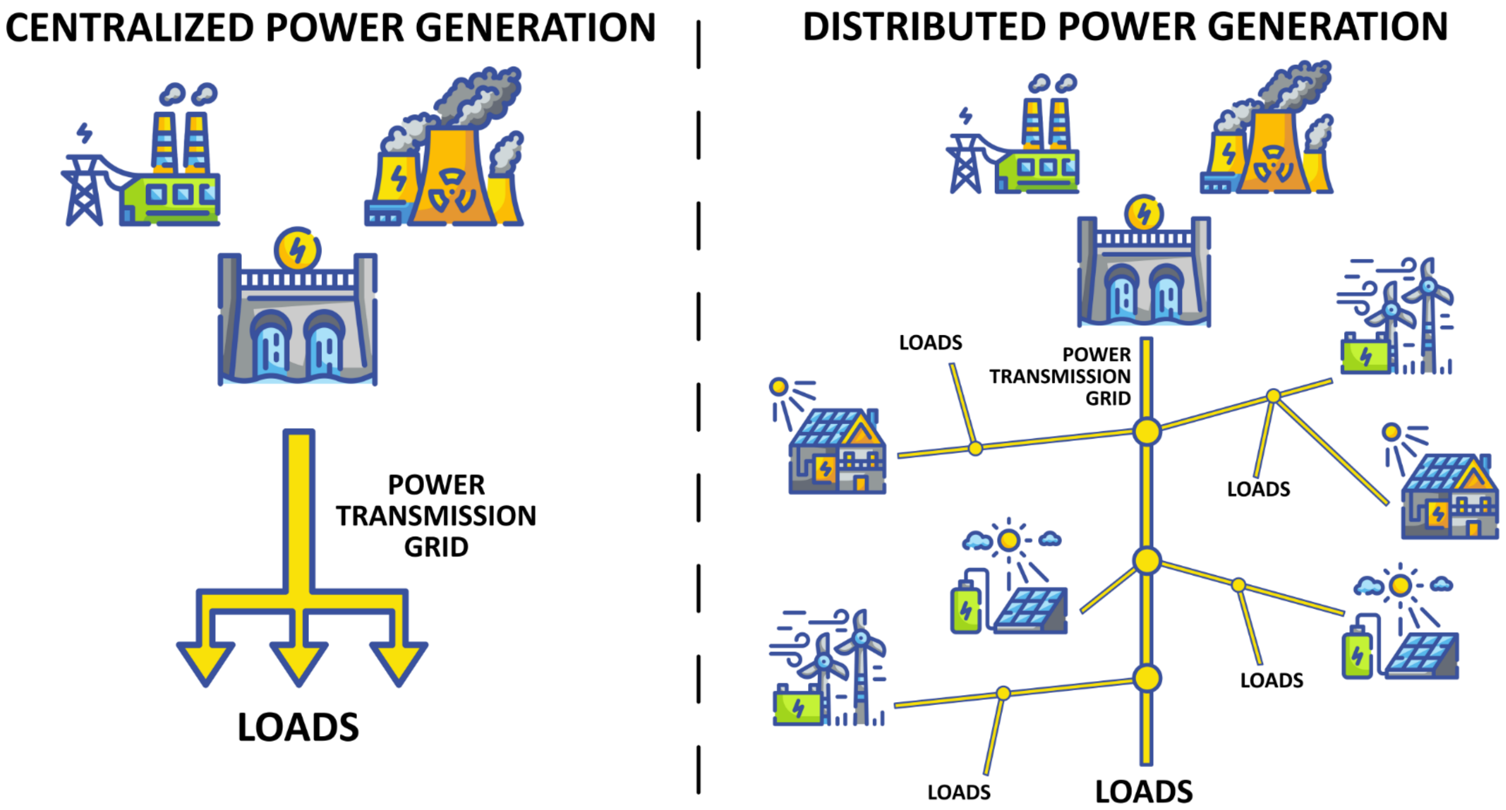
Understanding and discussing some issues

Connection to the Power Transmission Grid

The PTG has to assure the highest reliability and continuity of service for nuclear safety

The generated and absorbed power by the plant has to assure the required quality

- ***The challenge has the potential to be even higher in future energy scenarios characterized by much larger number of renewable sources, which cannot assure the kinetic energy storage supporting the network stability***
- ***Any credible assessment requires the involvement of Transmission System Operators***



Understanding and discussing some issues

Power Utilization Factor for SC coils PS

- defined as the ratio between the maximum active power required on the SC coils and the rated power of the converters
- **very low**, due to the large difference between the level of voltage/power needed for plasma formation and instabilities control and that one needed in quiet phases of the flat-top.
- unavoidable to some extent
- affecting very much **the investment cost** of the coil PS
- room for improvement should be explored

Discussing studies and R&D priorities

- Acceptable Power Quality
- Pulsed generation
- Connection to the PTG
- Nuclear radiation on electrical components in the tokamak building

→ Feasibility

- Provisions for licensing and nuclear safety (reliability of emergency PS, redundancies, fire zonings, trains separation / segregation, layout optimization…..)

→ Feasibility
The most important, but to start an assessment a first selection of technologies and design of key electrical plant components are needed

- Quantification of recirculating power → Efficiency

- Power utilization factor → Investment cost

R&D addressed to improve the Electrical Power Quality

The use of only thyristor converters, robust and cost effective technology largely used in all fusion experiments, seem not so suitable for supplying highest power SC coils when scaled to the DEMO level

R&D approach

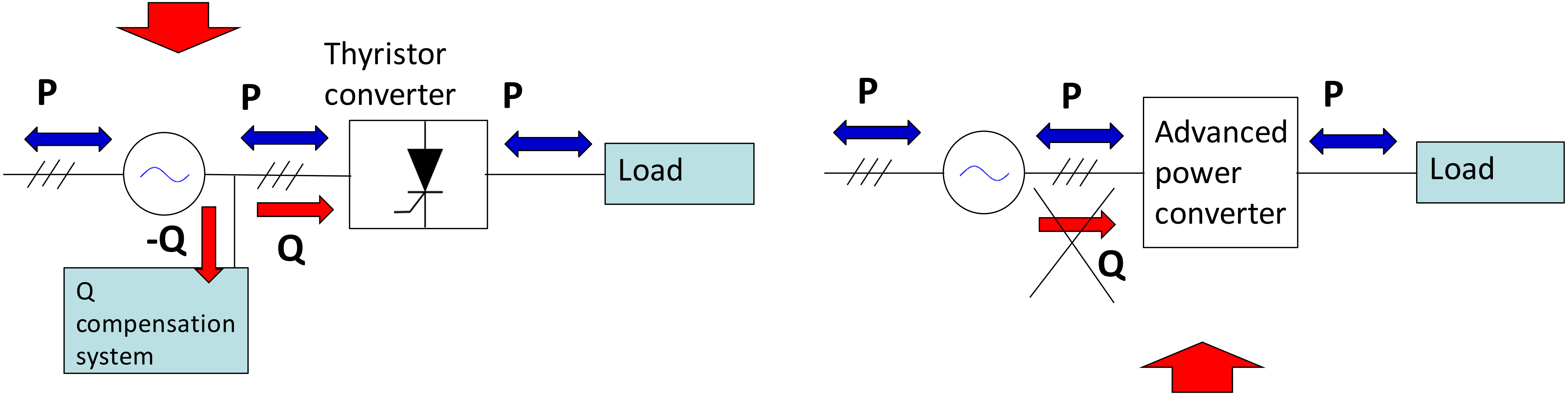
ACTIVE POWER TRANSIENTS

Conceiving smart electrical energy storage schemes embedded in power converters supplying pulsed loads, to provide all necessary control actions, while limiting active power transients

E. Gaio et al, FED 177 (2022)

REACTIVE POWER DEMAND

- **The reactive power demand is strictly linked with the thyristor converter technology traditionally used**
- **Traditional approach is to respect the limits by compensating the reactive power in excess**
- **Too high level of compensated power can lead to instabilities**

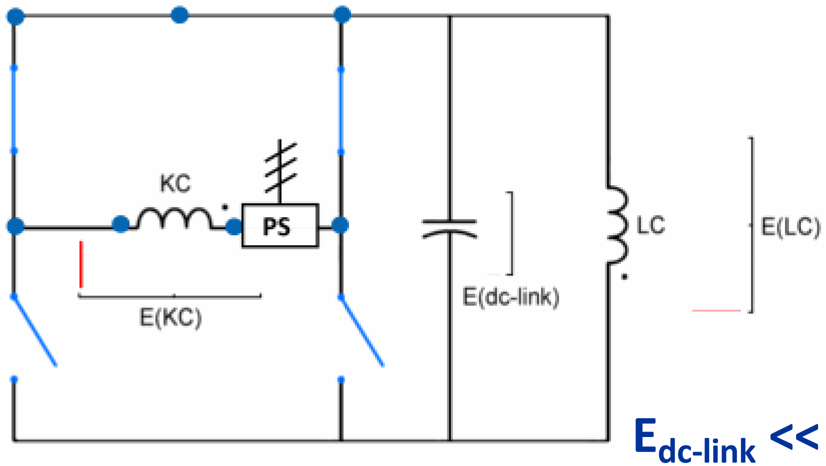


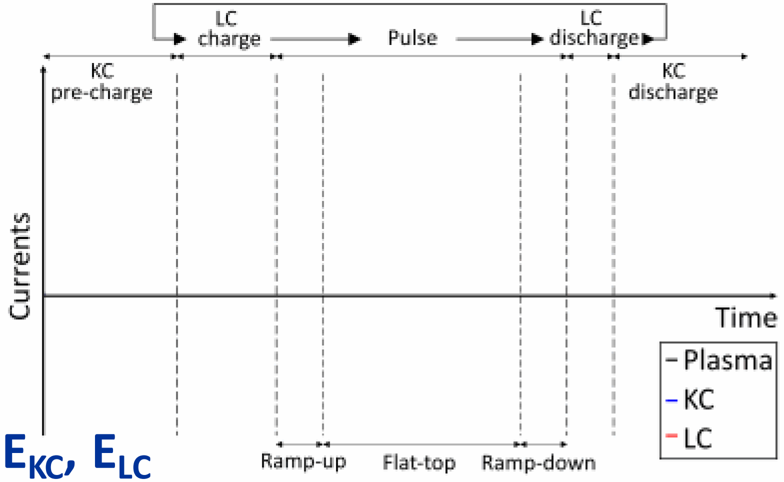
Conceiving solutions to avoid the reactive power absorption instead of compensating for it

First outcomes from the R&D for the EU DEMO

THE MEST: Magnetic Energy Storage and Transfer system

- new concept for the supply of CS and PF coils
- based on SMES (Superconducting Magnetic Energy Storage)





$E_{dc\text{-}link} \ll E_{KC}, E_{LC}$

~350kJ << ~ 4GJ

BASIC PRINCIPLE

- **to provide an additional SC sink coil (KC) for each load coil (LC)**
- **to store in KC at least all the needed energy during the plasma pulse**
- **to transfer the energy from the KC to the LC and vice versa via switched capacitor (C)**

- **internal energy exchange** between the load and sink coils
- **nearly unitary efficiency** for energy storing / transfer being coils superconducting

F. Lunardon, et al., Fusion Eng. Des., 157, 2020

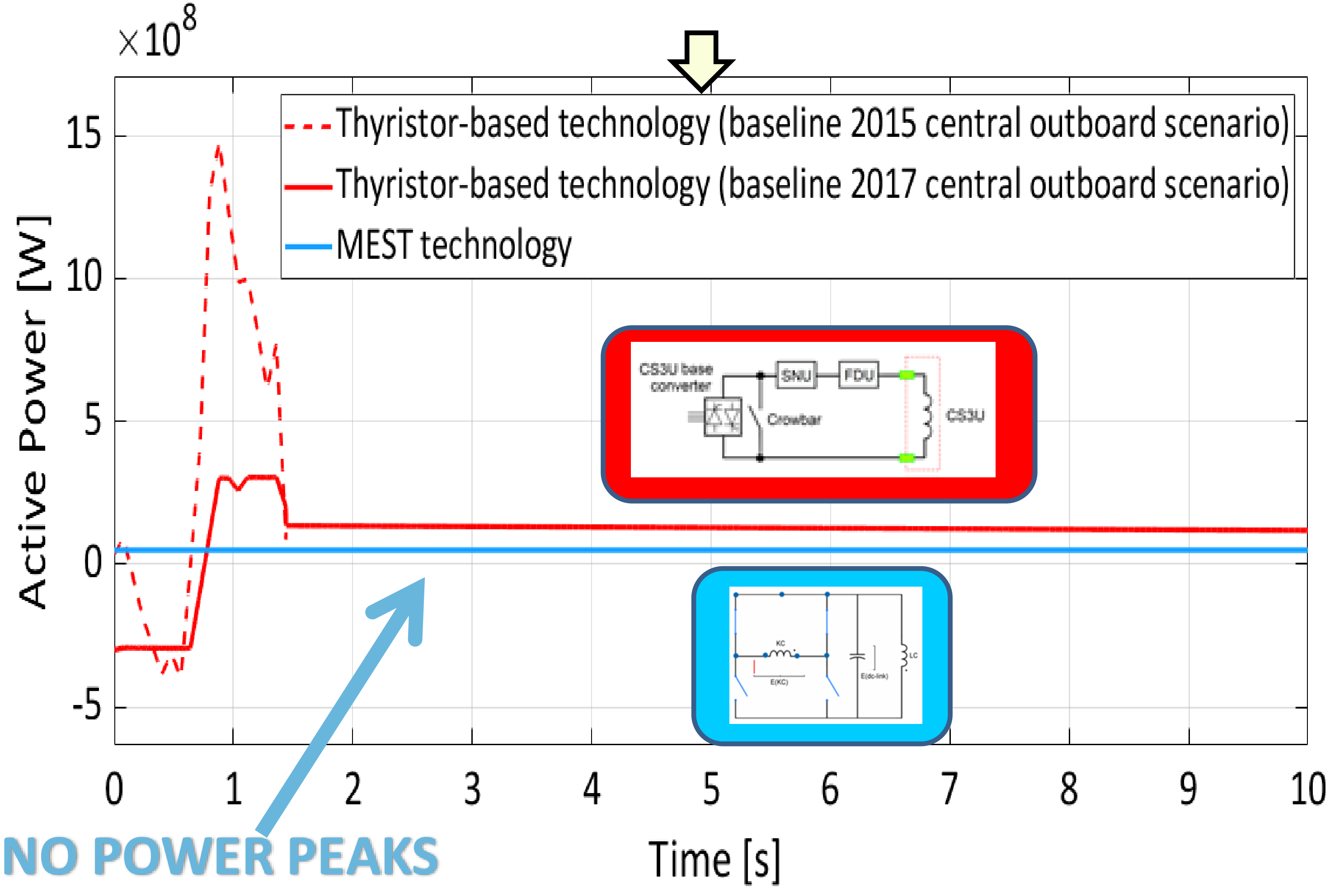
First outcomes on the R&D for the EU DEMO

Expected effectiveness of the MEST in reducing the power peaks at the plasma breakdown – application study to the DEMO CS and PF coils

FULLY NEW
No application exist

The reactive power is nullified as well

Average active power only to form and sustain the plasma and to compensate for the circuit losses has to be provided from the ac side → **NO POWER PEAKS**



ASPECTS TO BE EXPLORED

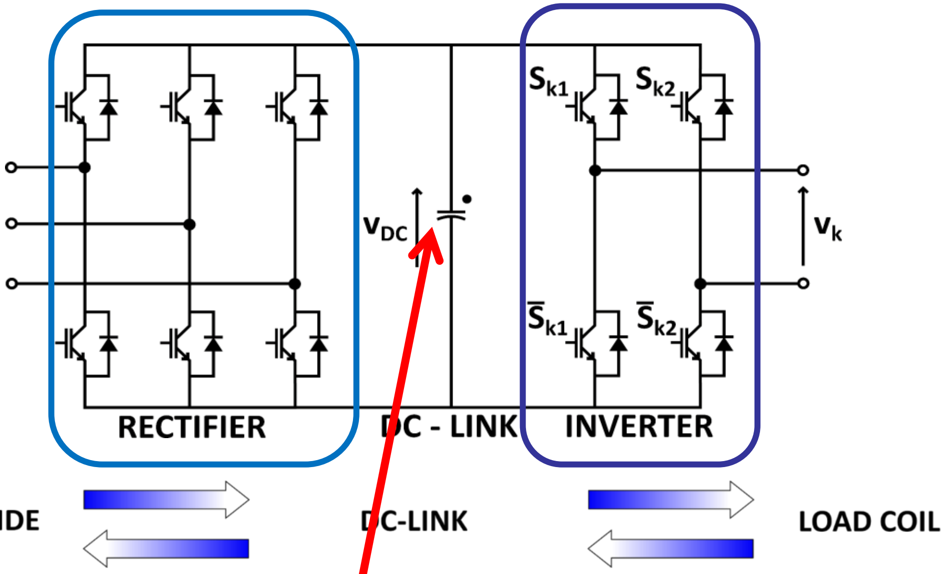
- ***Size / cost of sink coil and relevant protection, cryogenic power***
- ***Applicability, integration in the circuit, fault analysis***

OTHER ALTERNATIVES TO THYRISTOR CONVERTERS?

Industrial applications exist BUT at much lower power level

BASIC CONCEPTUAL SCHEME of Voltage Source Converters with Active Front End technology

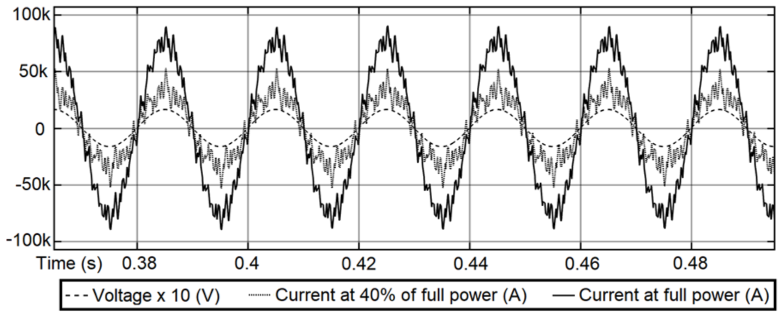
AFE: Line-side converter



Capability to almost nullify the REACTIVE POWER demand

BUT NOT to significantly reduce so high ACTIVE POWER peaks

Example of waveforms on the ac side
Currents and voltages almost **sinusoidal** and **in phase**
NO REACTIVE POWER



Results of numerical simulations of a model of one EU DEMO PF circuit with VSC+AFE technology

- **Different topologies to be explored**
- **Key aspect: evolution of technologies for dc link energy storage**

A. Ferro, et al., Fusion Eng. Des., 146, 2019

Summary of hints for discussion

- Recirculating power
  - definition
  - estimation
  - importance of minimization for the overall efficiency
  - mainly an input for the electrical systems design

- Electrical power management: not ready to give replies in terms of reliability, lifetime, safety, cost….
- Need of studies and R&D before
- R&D priorities
- Importance of requirements to perform studies and R&D

Summary of hints for discussion

The path

- Awareness of the issues related to the electrical power management in fusion power plant
- Contribution to the assessment of good requirements
- Taking full benefit from lessons learnt from ITER for the design development
- Understanding the limits of applicability of known and mature technologies and design solutions when scaled to the DEMOs level
- Studies and R&D to identify suitable solutions and verify their applicability also with the involvement of the industry (*expected interest of the companies in this business cannot be taken for granted*)

Thanks for your attention