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Analysis of AC Power System for JT-60SA Superconducting Magnets

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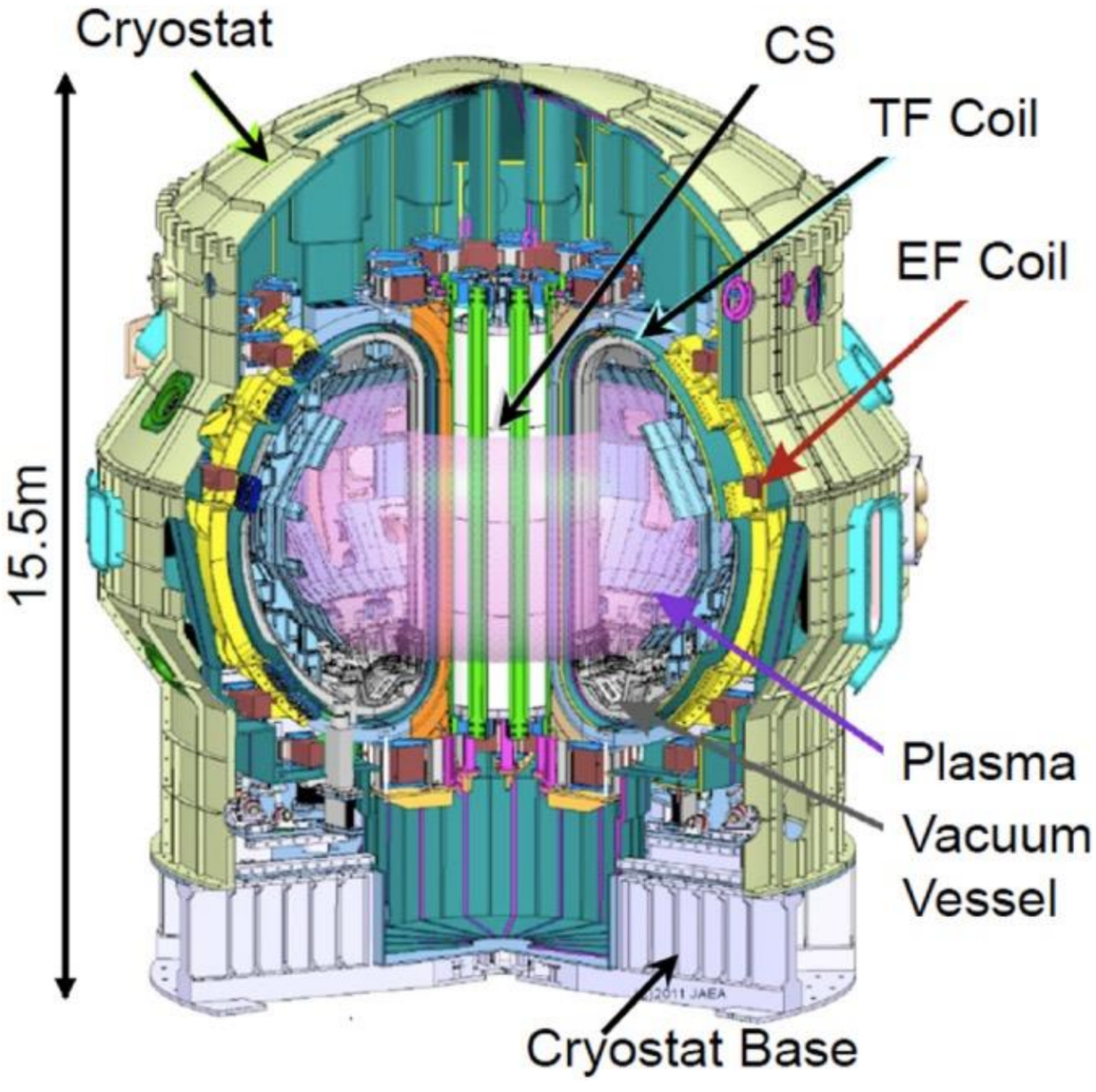
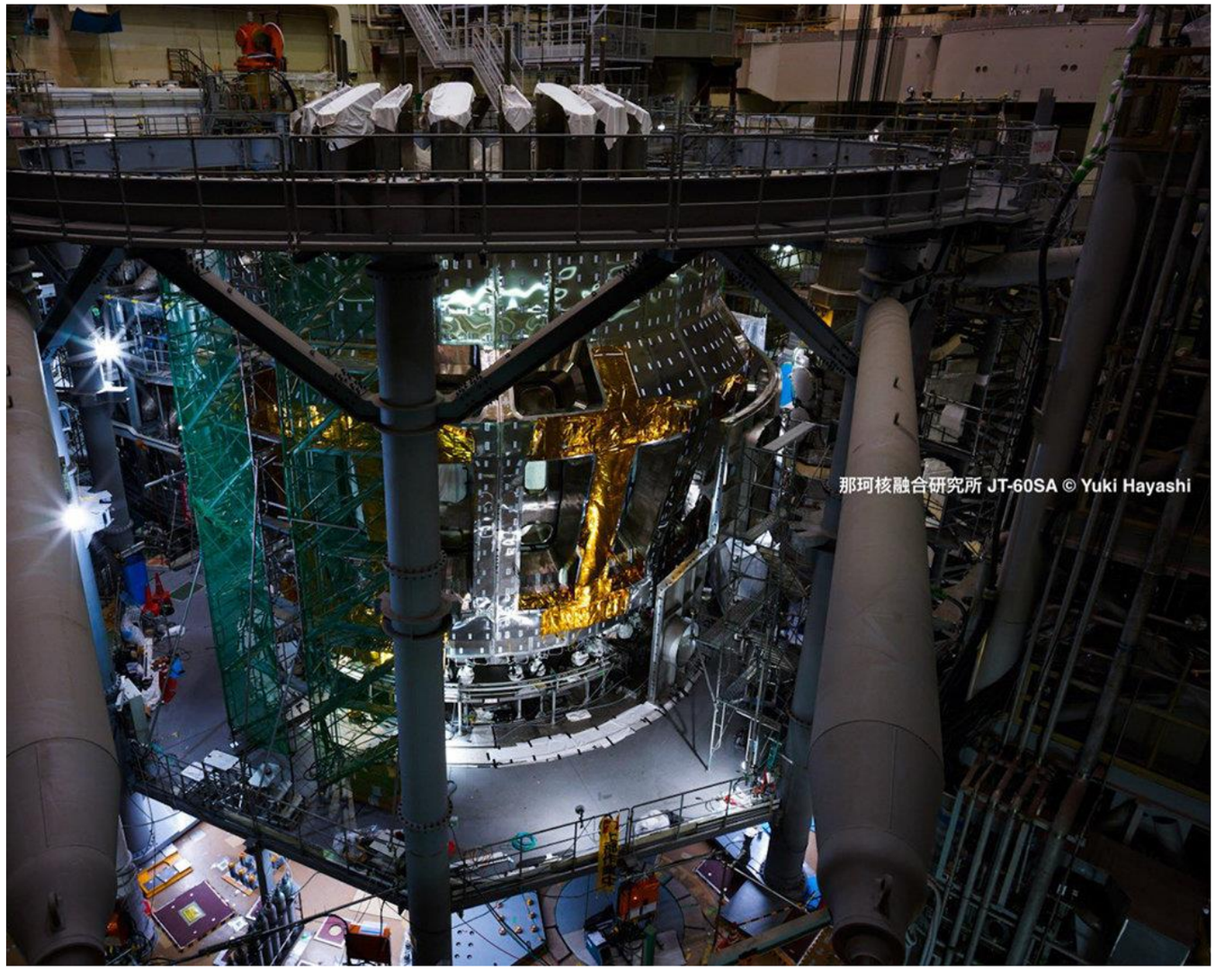
One of the largest tokamak JT-60SA

Assembly and commissioning ongoing aiming operation in Sep. 2020.



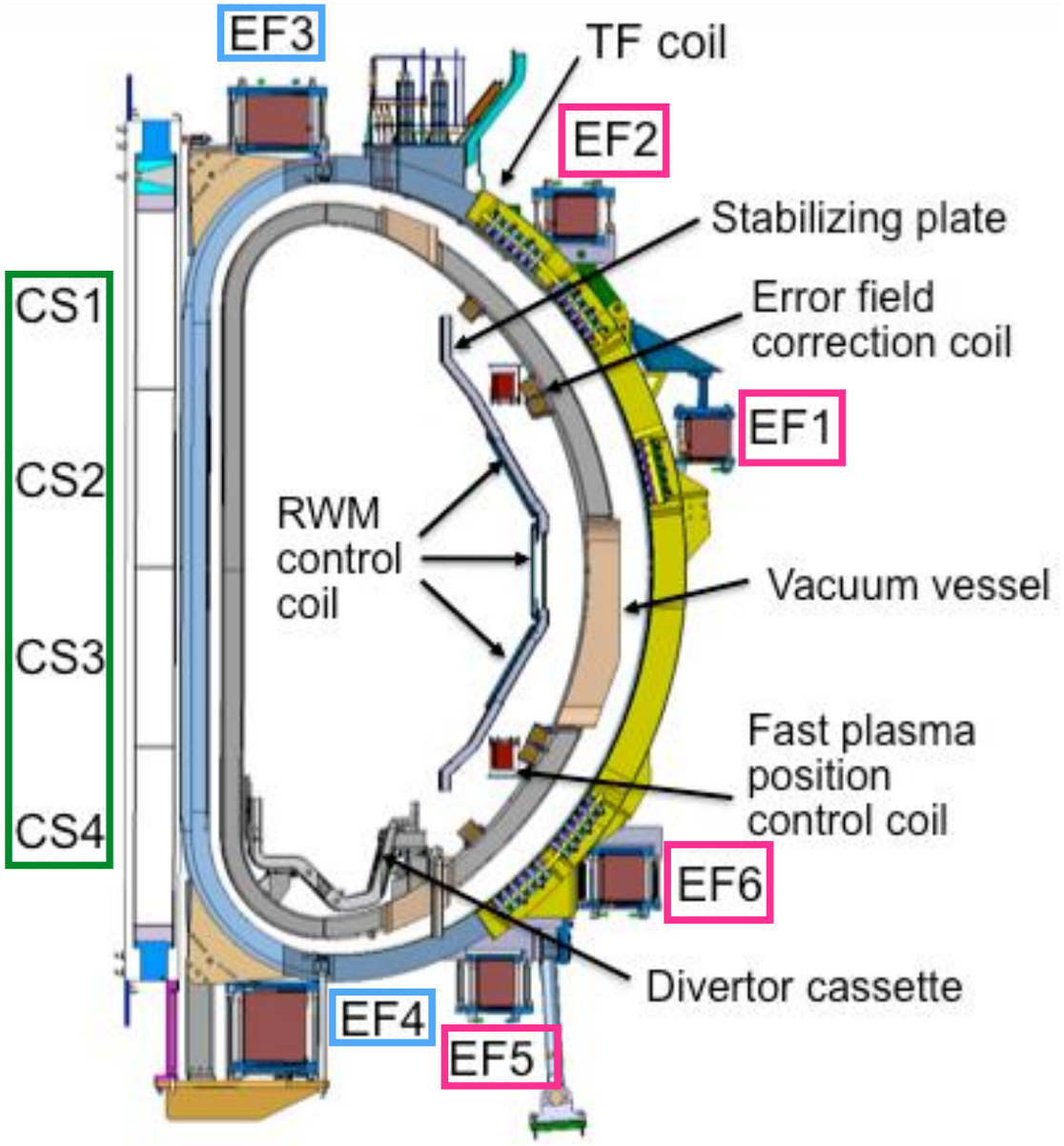


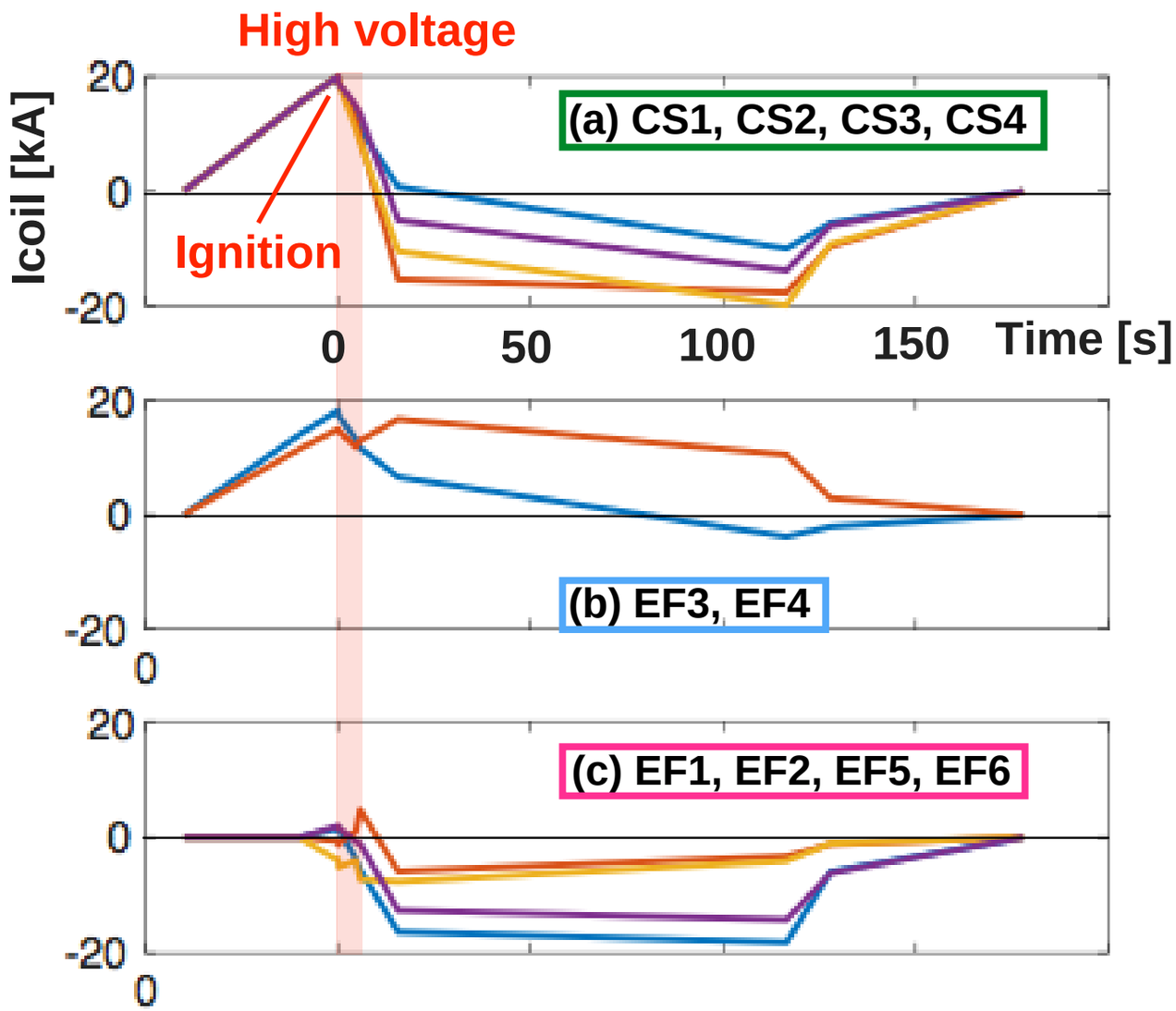
Y. Kamada. et al., Nucl. Fusion, 55, No.10

- Main magnets are super conducting for long operation (~ 180 s)
- 10 Poloidal filed coils (4 CS, 6 EF coils)
- 18 Toroidal field coils (2.25 T@center of plasma, stored energy 1 GJ)

Current waveforms in the operation

Drastic current change around plasma ignition and ramp-up





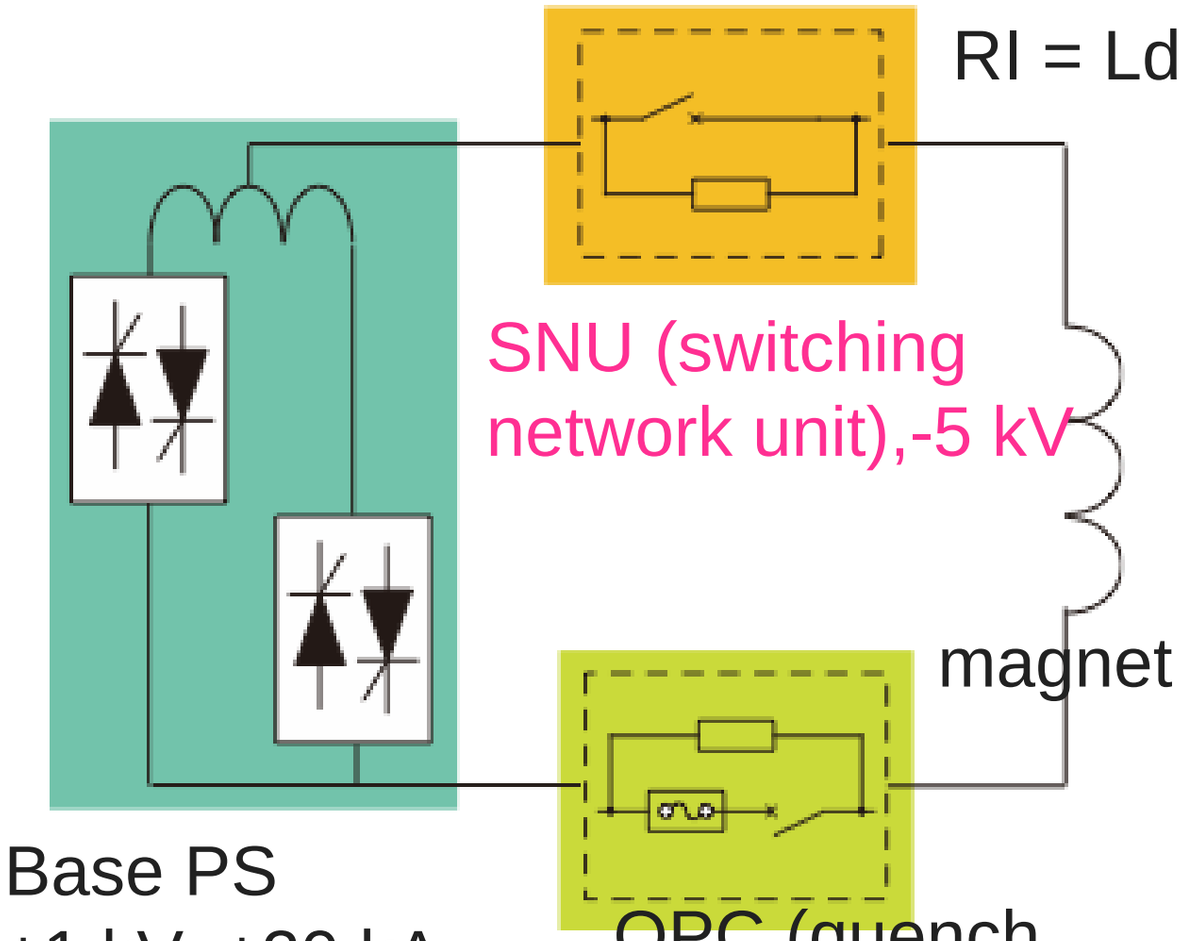
PID (v3.8) Scenario #1. Full current, Inductive, DN, 41 MW

- CSs induce current in plasma for heating and confinement
- EF coils control shape and postion of plasma
- High voltage (< 5 kV) is necessary only at ignition and ramp-up phase.

Circuit Configuration for PF magnets

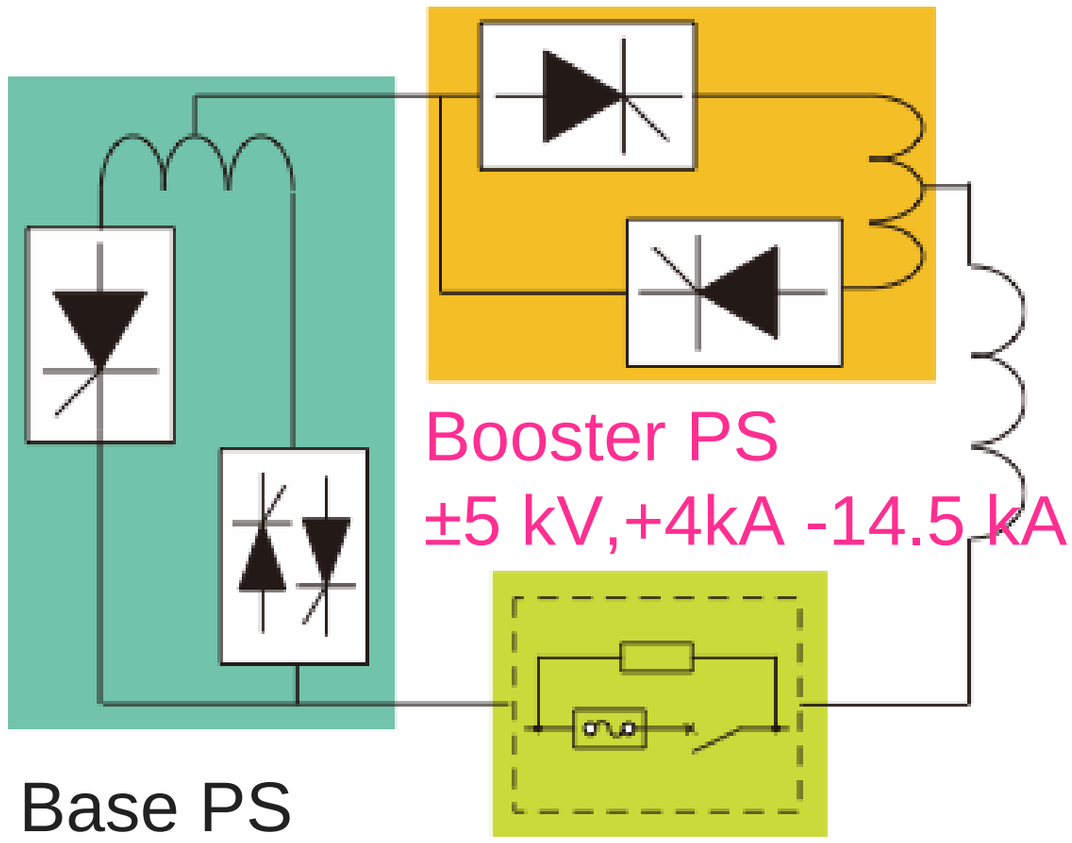
High voltage converter needs large reactive power

for CS,EF3,4



- Resister is inserted for induction and initiation of plasma
- The resistor is bypassed at 5 s after the ignition

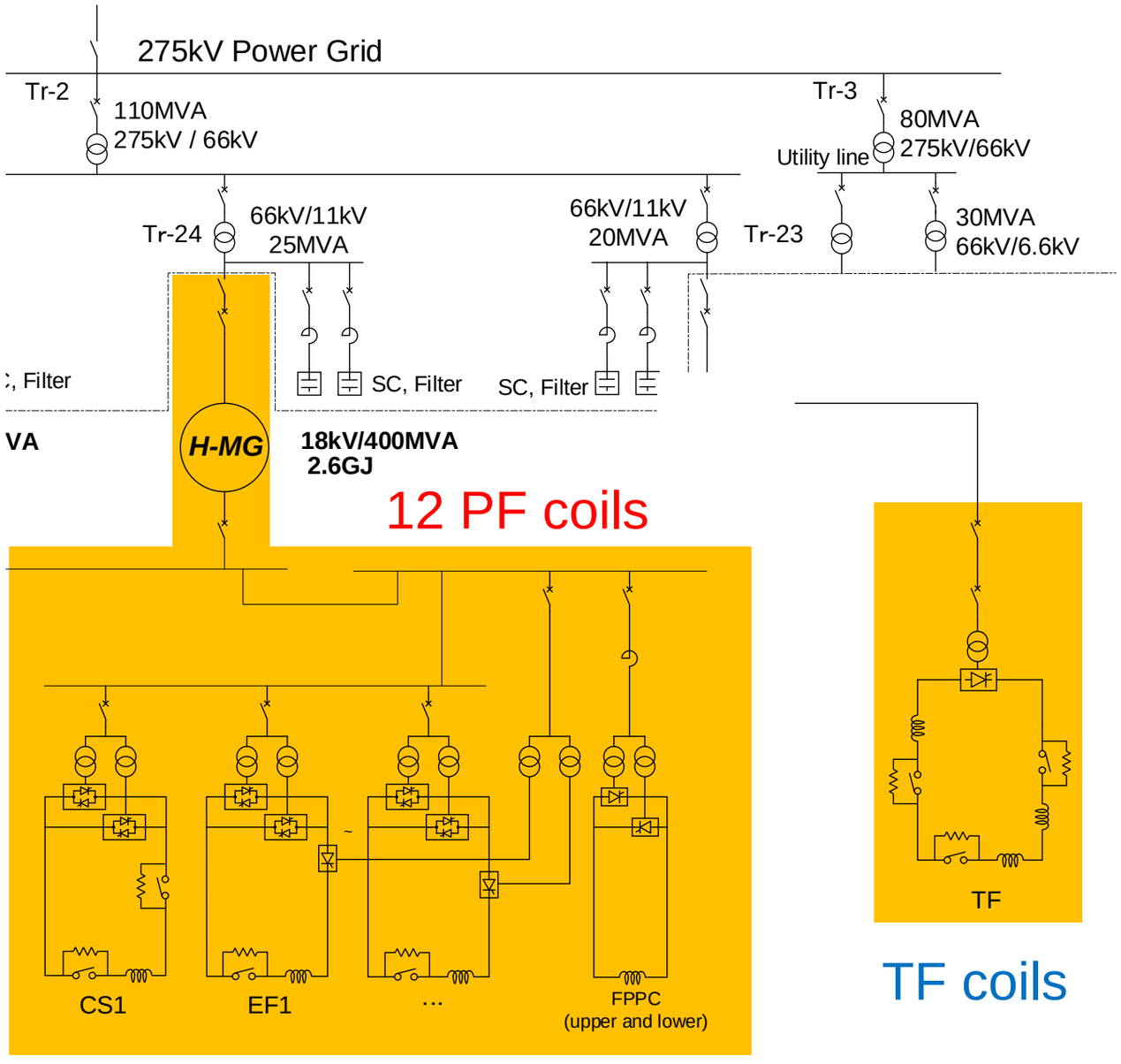
for EF1,2,5,6



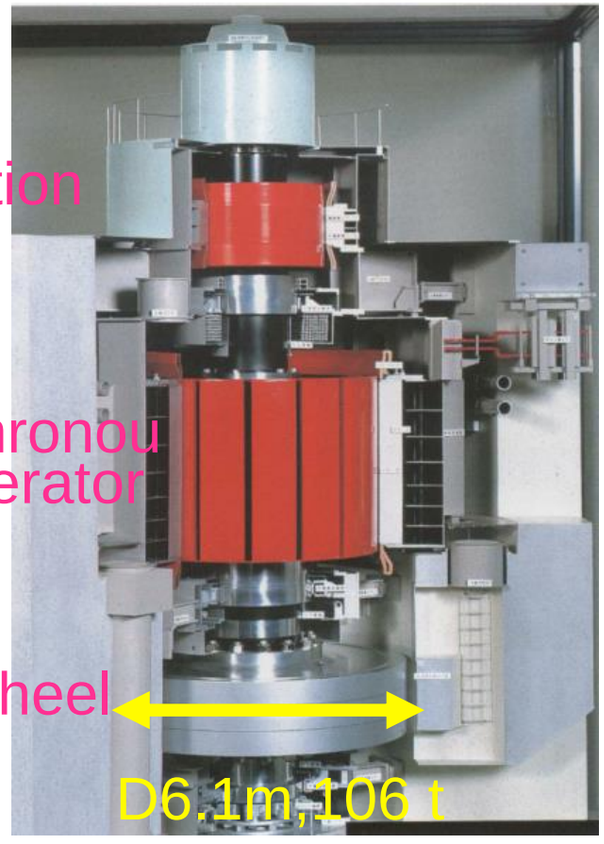
- Booster PS is used for highspeed control of plasma shaping
- Low voltage operation of Booster PS cause large reactive power

Dedicated motor-generator for PF Magnets

250 MVA is required for PF magnets power supplies in total



H-MG



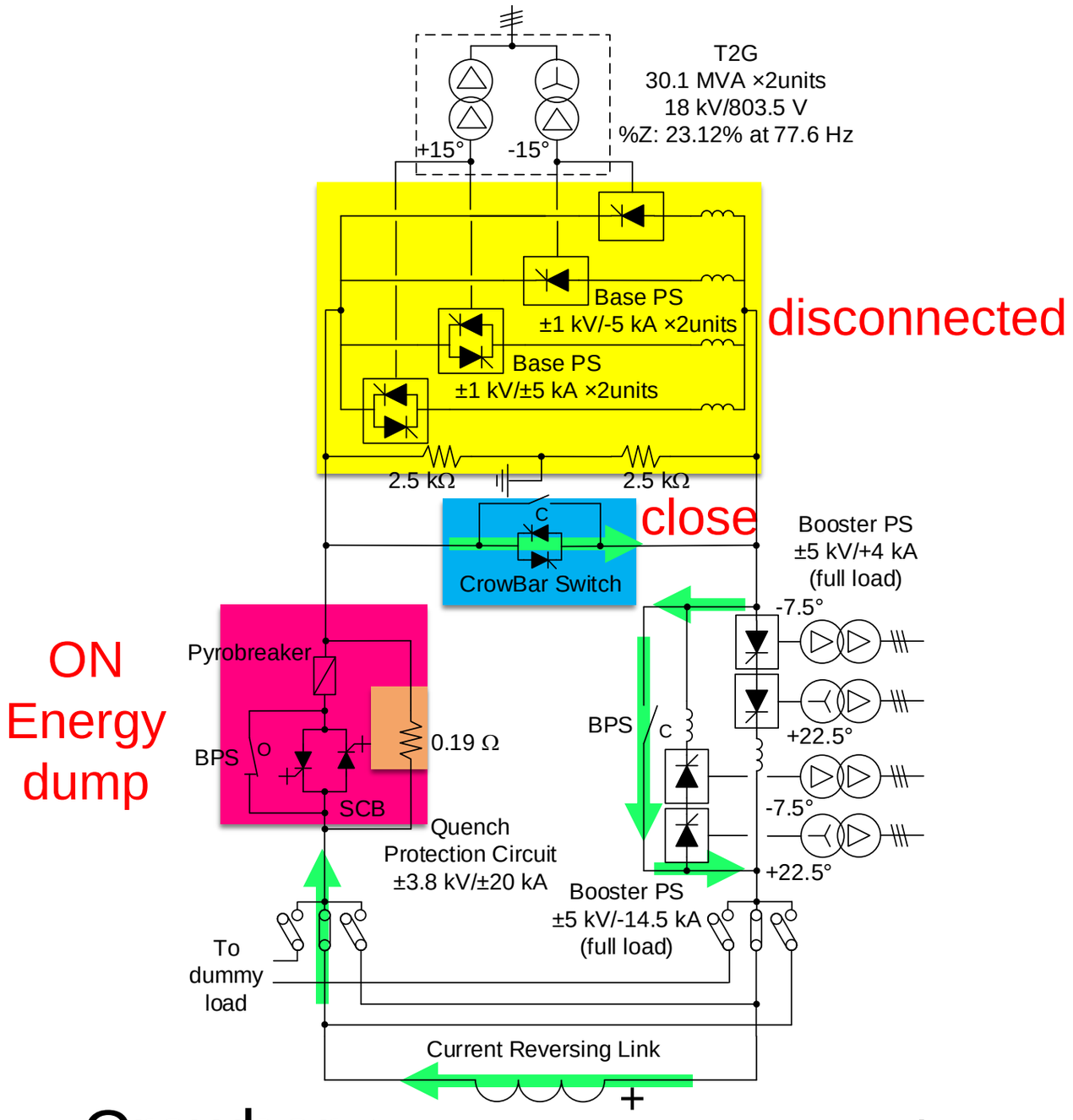
Output Power	400 MVA
Voltage	18,000 V
Current	12,830 A
Power Factor	0.62
Rotation	582～406.5 rpm
Frequency	77.6～54.2 Hz
Discharge Energy	2.650 GJ

Issues

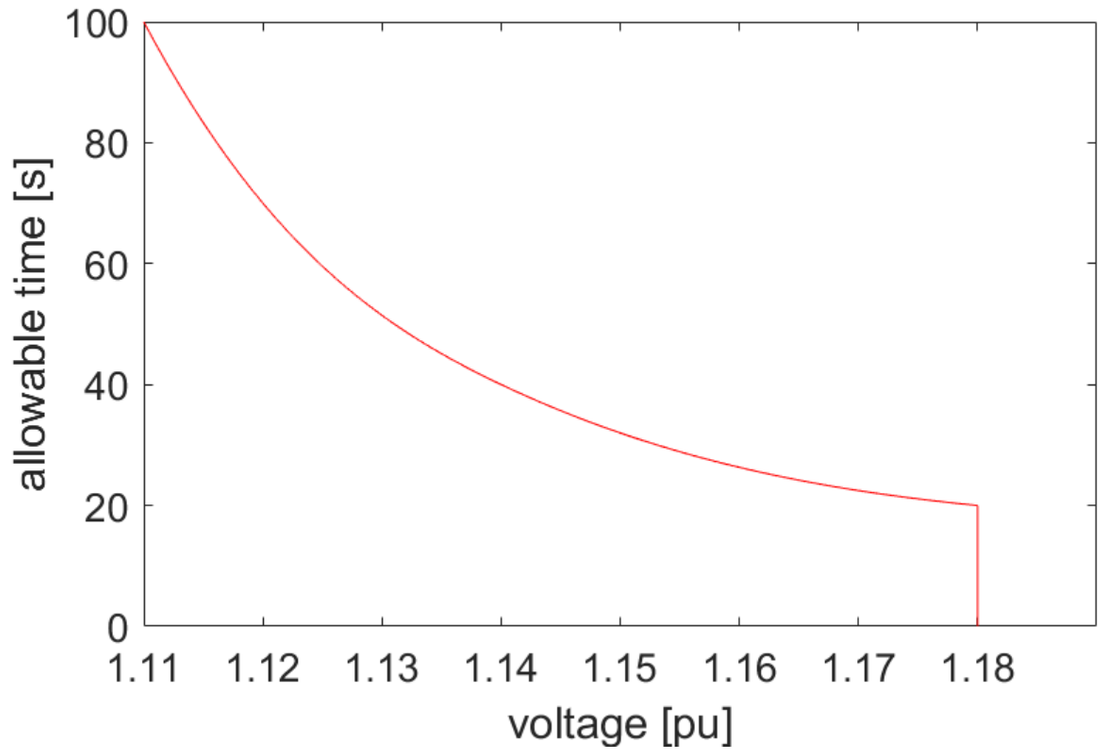
- Over voltage due to breaking large power
- Harmonic current (heating in damper winding)

Issue1. Over voltage due to magnet quench

All PF circuits start fast discharge even when only one magnet quench



Criteria



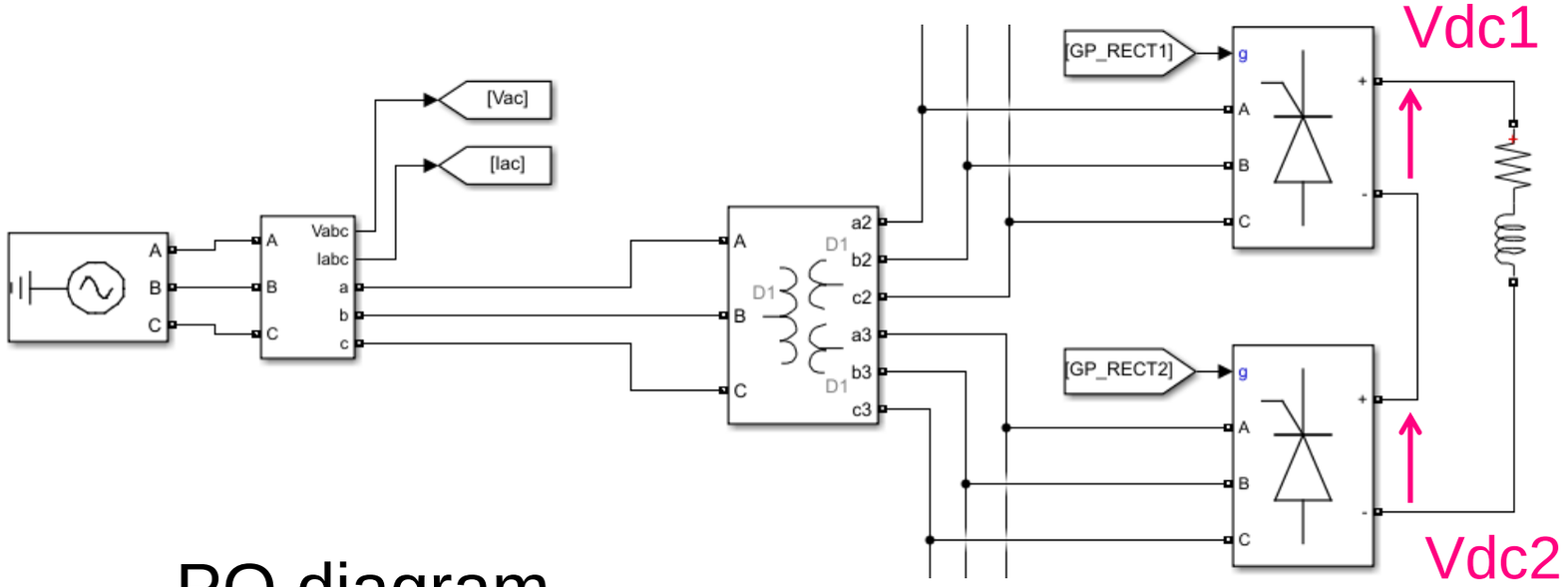
- inverse time characteristics
- definite time characteristics

- Crowbar (thyristor and mechanical hybrid) breaks load in a moment (~ ms)
- Voltage controller of H-MG can not suppress the rapid change
- Power reduction is only way to reduce the over voltage

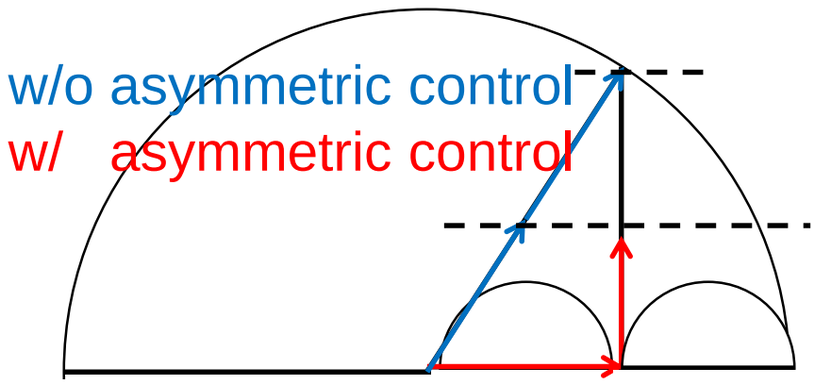
Issue 2. Harmonics due to reactive power reduction

“Asymmetric control” reduces reactive power of series converters

How to split Vdc



PQ diagram



Output voltage

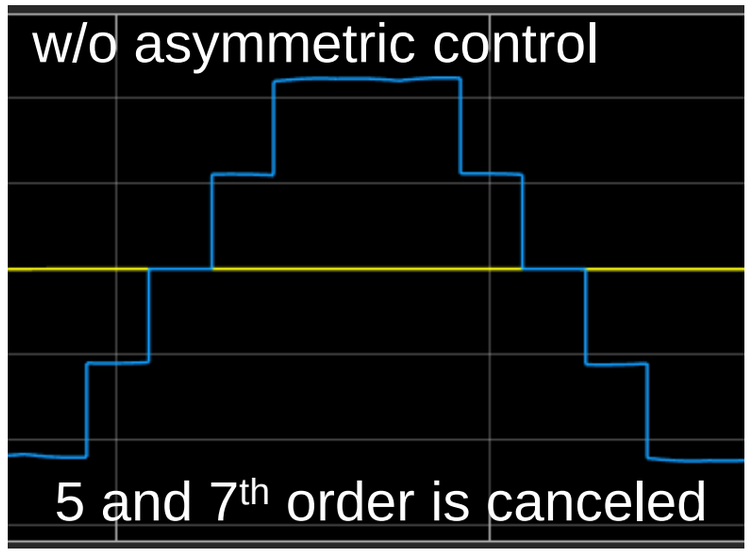
$V_{DC} = 1.35 \times V_{ac} \times \cos(\alpha)$

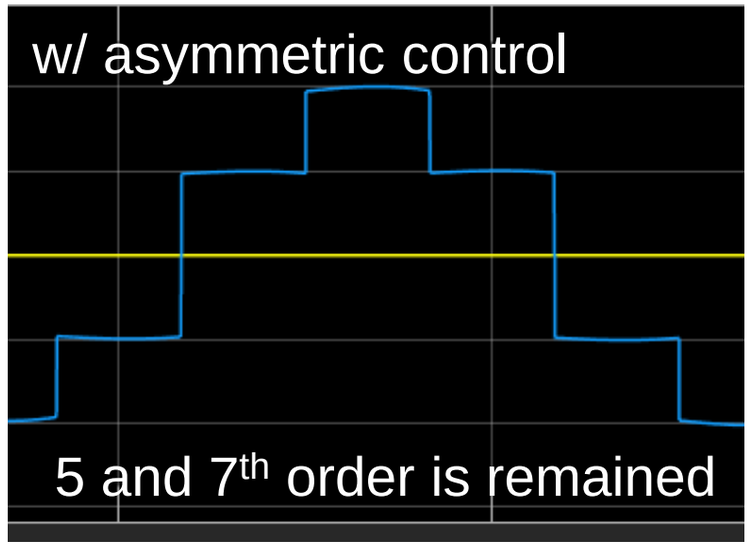
Active and reactive power

$P = 1.35 \times V_{ac} \times I_{DC} \cos(\alpha)$

$Q = 1.35 \times V_{ac} \times I_{DC} \sin(\alpha)$

Current in primary side

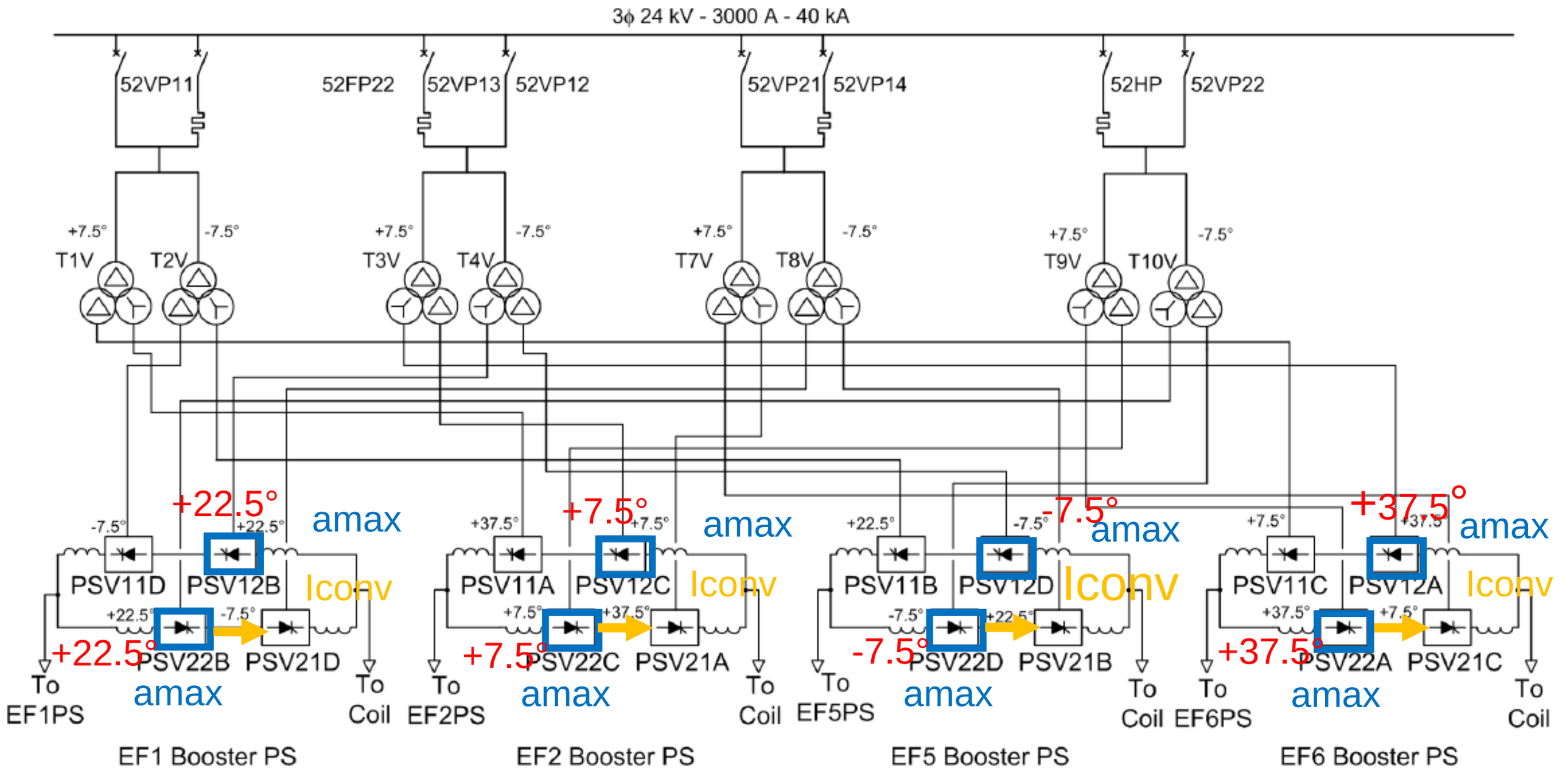




- Vdc is proportional to active power P and reactive power Q
- Reactive power can be reduced by changing distribution of Vdc
- Criteria of harmonics is $I_{eq2} = \sqrt{\sum \frac{N}{2} \times I_N^2}$ **< 15 % of nominal current**

How to reduce harmonic current

Difference power supplies cancel harmonics together

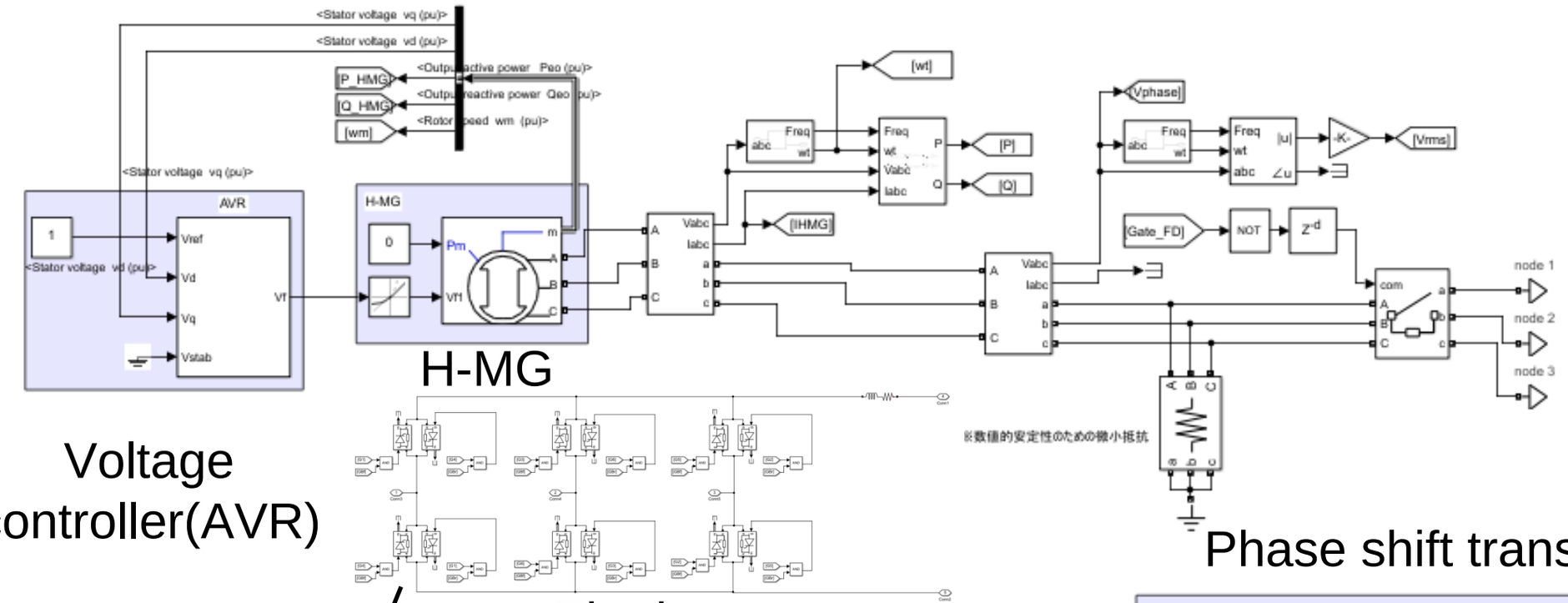


- This assumption depends on command phase angles and amplitude of current for each converters during discharge
- The effect should be confirmed by integrated model of PS system

Integration model

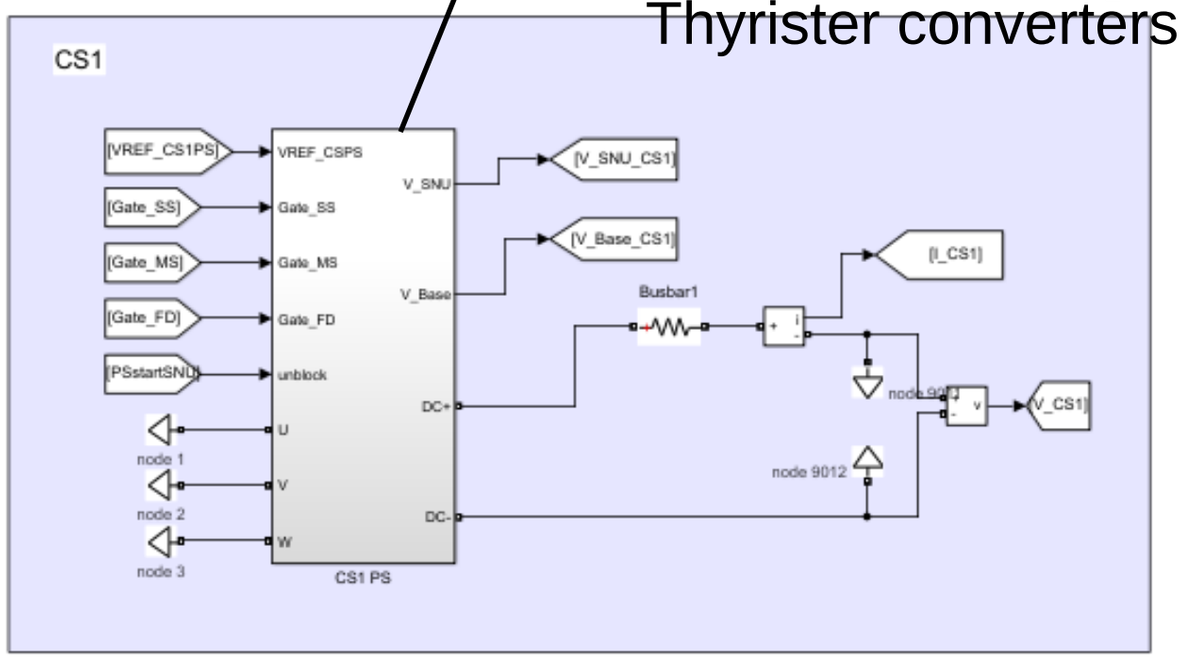
All components are inplemented without simplification in simulink

Voltage controller(AVR)



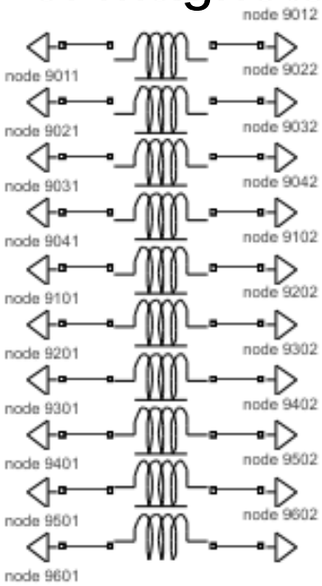
H-MG

Thyrister converters

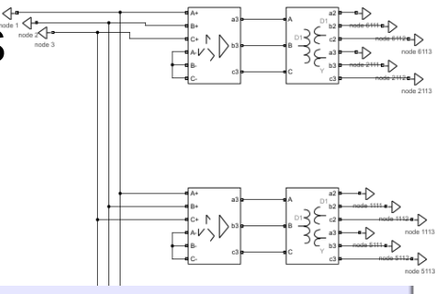


Booster PS type × 4 (EF1-4)

Mutual coupling of magnets



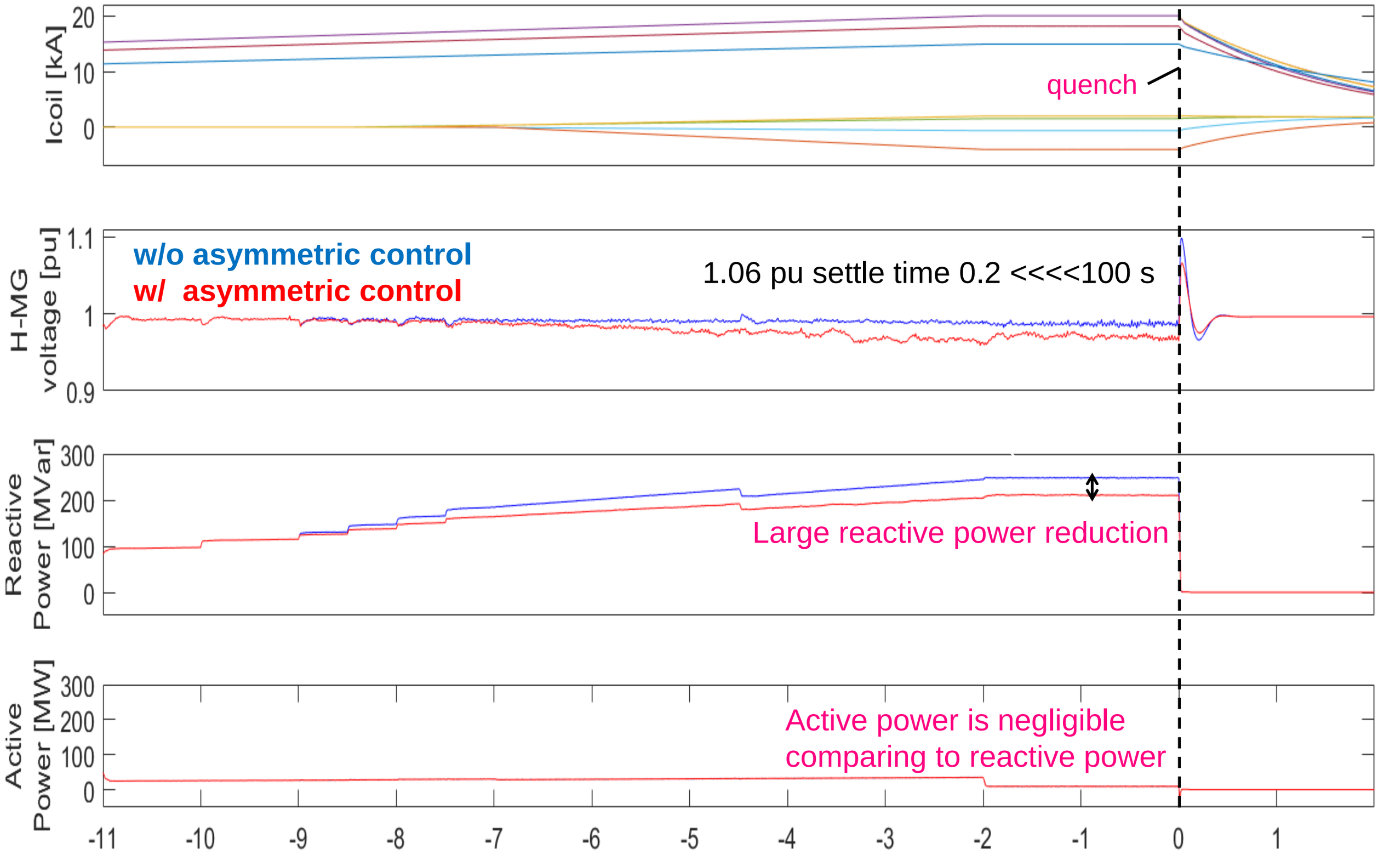
Phase shift transformers



Booster PS type × 4 (EF1-4)

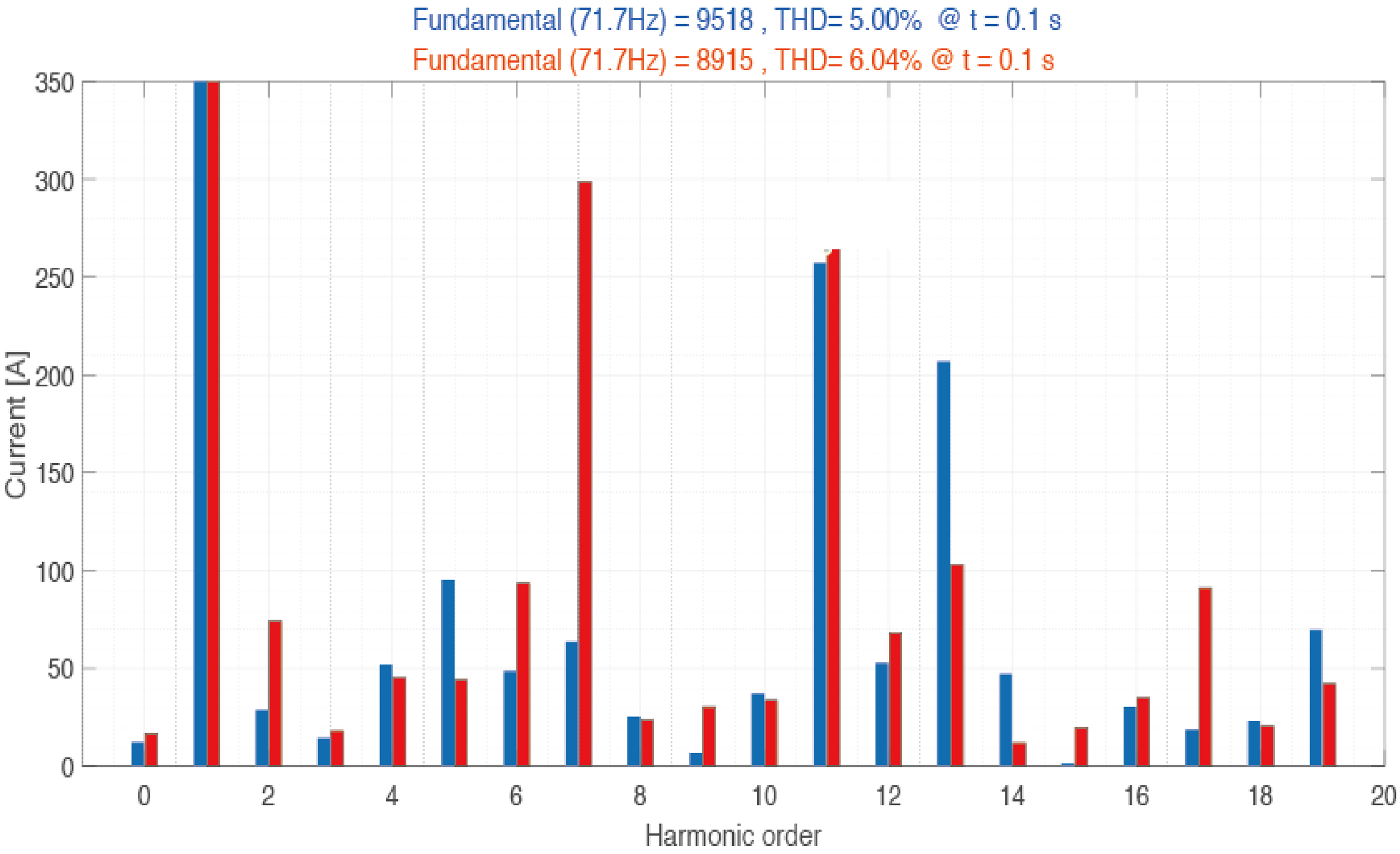
Overvoltage estimation at quench

Pass criteria +6 % < +18 % (definite time)



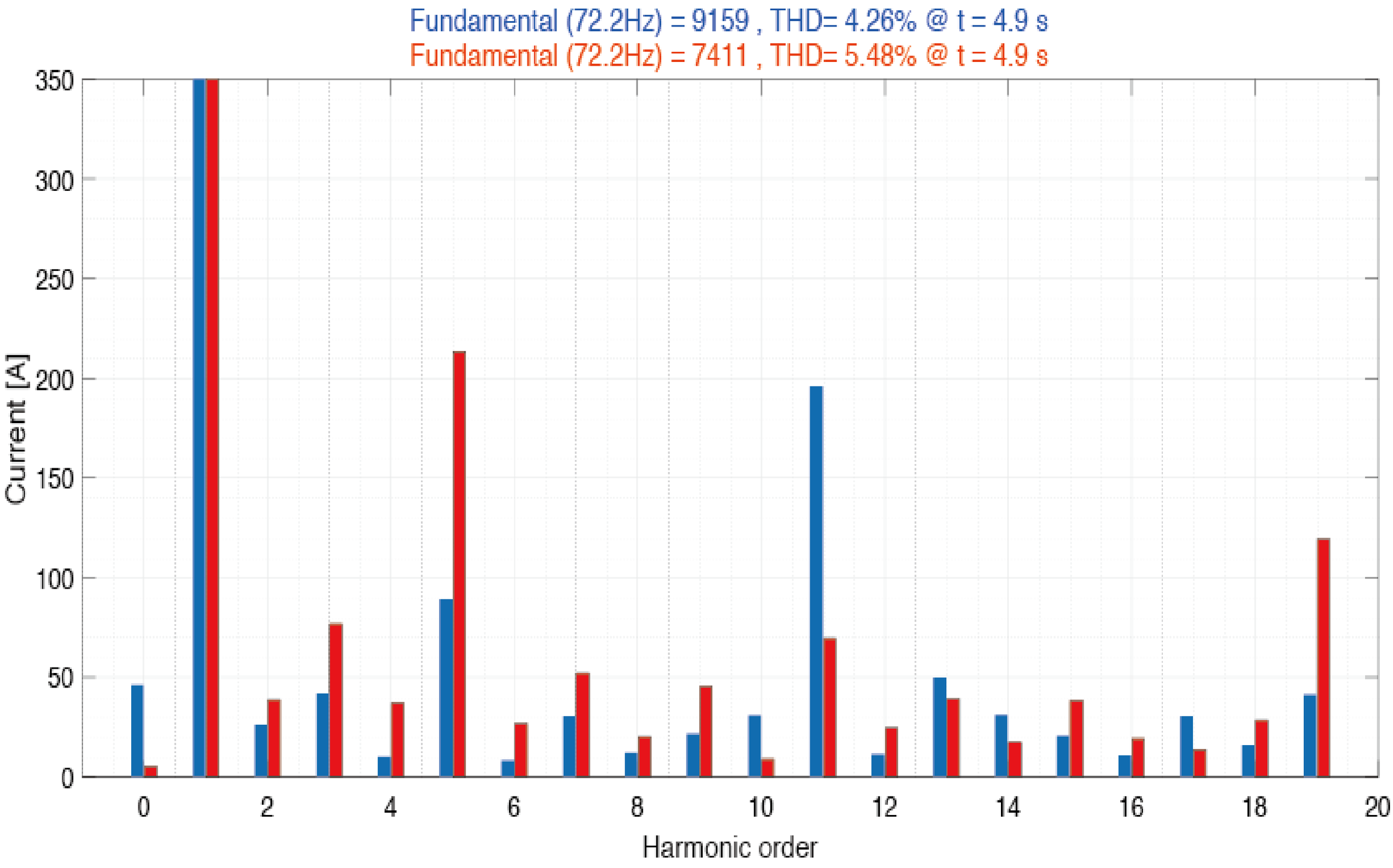
Harmonic current estimation

I2eq = 5.96 % <<<< 15% @ t = 0.1 s (around ignition)



Harmonic current estimation

I2eq = 3.51 % <<<< 15% @ t = 4.9 s (just before Booster PS stop)



Conclusion

- Large reactive power is required for PF magnet system in JT-60SA
- At magnet quench, over voltage of H-MG is happened due to load breaking
- Asymmetric control can reduce reactive power
- However, asymmetric control causes harmonic current
- In JT-60SA, phase shift transformer is optimized for reduction of harmonics
- Series connected converters for each magnet can reduce the harmonics together
- Over voltage and harmonic current is estimated using integration model of PS system
- Over voltage is suppressed less than 6 % (criteria < 18 %)
- Harmonic current is also suppressed less than 6 % (criteria < 15 %)