A European Design Proposal on the ITER ELM-Coil Power Supply optimized for Local-Edge-Mode (ELM) Mitigation and Resistive-Wall-Mode (RWM) Stabilization

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Introduction

ITER will feature a set of internal coils for Edge Localized Mode (ELM) mitigation [1]: the ELM-coils are attached to the inner wall of the vacuum-vessel and are organized as 3 sets of nine coils, symmetrically distributed around the torus.

The ELM-coils will be energized with DC- or AC-currents with an amplitude up to 15 kA and a maximum voltage of ~150V. By phasing the coil AC-currents of one set, a rotating magnetic field is created at the outboard side of the plasma. The rotational frequency of the ELM-mitigation field is low, up to 1.25 Hz. It is foreseen, with a later power supply upgrade, to use the internal coils for the suppression of Resistive Wall Mode (RWM) [1]. The control of the RWM would require rotational frequency up to 60 Hz.

The ITER baseline includes a set of ELM-coil power supplies for ELM mitigation based on high-current back-to-back thyristor converters, ideally suited for a maximum output electrical frequency of 5 Hz (N = 4).

Under an Expert Contract from Fusion for Energy, the design of an ELM-Coil Power Supply suited for the concomitant ELM-mitigation and RWM-control was investigated in the period 2014-2017[1].

[1] J.A. Snipes et al., Prospects for the Use of Internal and External Coils on ITER, 16th Workshop on Stability Control, San Diego, CA USA, 21-22 November 2011

Power Scheme Topology

- Each ELM-Coil supplied by a H-Bridge IGBT Inverter, protected by bi-polar thyristor crowbar (plasma disruption)
- Common DC-bus (210 V_{dc}) for 9 IGBT Inverters, with IGBT-controlled Dump Resistors (O/V protection during plasma disruption)
- Two paralled thyristor converters (275 V, 12.5 kA) for 12-pulse operation

Cancellation of harmonics in input current of Inverter:

- ELM only mode: $2*f_{elm}$ cancel in 3 coils @ 120°
- ELM + RWM: $f_{rwm} + f_{elm}$ cancel in 3 coils @ 120°
- ELM + RWM: $f_{rwm} - f_{elm}$ cancel in 9 coils @ 40°

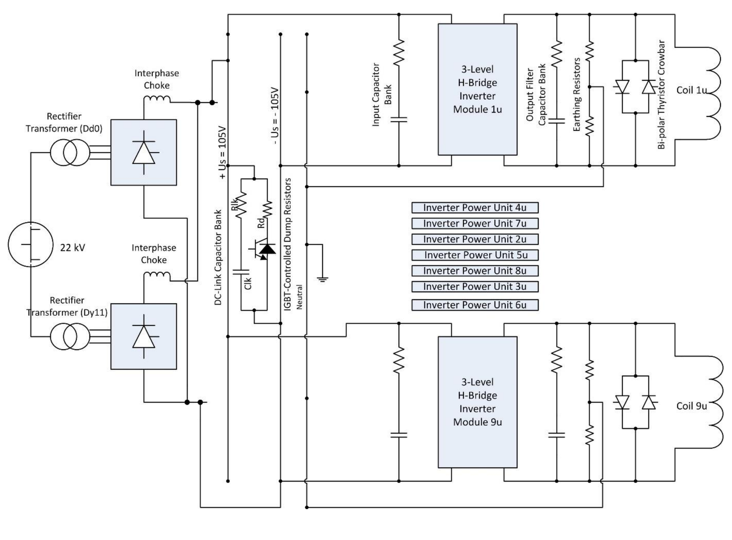

Fig. 1 – Topology of one of three Sets of ELM-Coil Power Supply

Resonance in DC-circuit

- DC-circuit featured with distributed capacitor banks (DC-link, Capacitor Banks of Inverters)
- Stray inductance of busbar/cable power connections leads to low damped LC resonance
- Resonance investigated by simulation (Fig. 2):
  - Harmonic input current of Inverter simulated by current source I1 (1 kA_{pk}, 10Hz – 1 kHz)
  - Input voltage of Inverter measured by VM1 and displayed (Fig. 3) with optimized damping
  - Resonance #1: f_1 = 73 Hz, a_1 = 23 V_{pk} (R_{sa-b})
  - Resonance #2: f_2 = 175 Hz, a_2 = 7 V_{pk} (R_{lk})

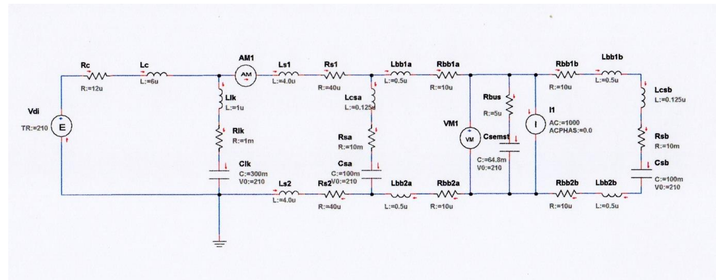

Fig.2 – Simulation Circuit for Frequency Response

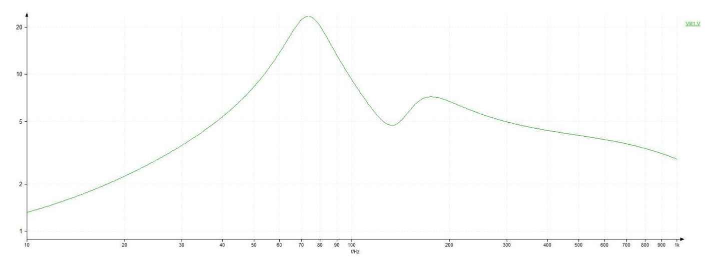

Fig. 3 – Frequency Response (optimized damping)

Inverter Power Unit - Hardware

- Compact water-cooled high power IGBT Inverter Assemblies have been developed for wind-turbines with power up to 8 MW and are readily available on the market.
- A DC-bus capacitor bank is integrated in the IGBT Inverter Assembly
- Two sets of four paralleled Inverter Assemblies provide the required output current in H-Bridge configuration with adequate de-rating.
- One Inverter Power Unit (IPU) includes the Input Capacitor Bank, the Inverter Assemblies, the LRC Output Filter and associated control

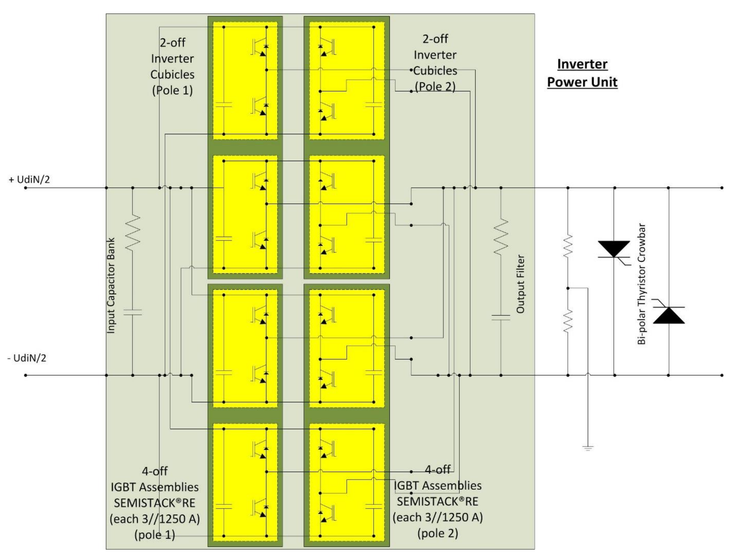

Fig. 4 – Configuration of one Inverter Power Unit

Inverter Power Unit - Control

- ELM-Coil time constant (τ = 96 ms) well above switching cycle of IGBT Inverter (t_c = 400 µs).
- Advantage of pseudo 3-level control of H-bridge:
  - Output ripple voltage reduced by half.
  - H-bridge freewheels during fraction of cycle time, proportional to output voltage. Duration of current pulse at DC-side is reduced.
  - Freewheeling of H-bridge is fast protective action to de-couple coil circuit from DC-circuit during plasma disruption
- Selected gate control features (Fig. 5):
  - Switching losses confined to one pole
  - During freewheeling, terminals of ELM-Coil clamped to the DC-bus (negative polarity)
  - Dead-band (Gp. 3) requires attention: it lies in range ±5V – ±10V (210 V_{dc}, 2.5 kHz)

Three-Levels Single-Phase Full-Bridge Inverter - Switching Transitions

Group Identification	IGBT11	IGBT12	IGBT21	IGBT22	Output Voltage	PWM State Level
Group 1	0	1	0	1	0 (-)	L
	1	0	0	1	+ 2Us	H
	0	1	0	1	0 (-)	L
Group 3	0	1	0	1	0 (-)	L
	0	1	0	1	0 (-)	H
	0	1	0	1	0 (-)	L
Group 2	0	1	0	1	0 (-)	L
	0	1	1	0	- 2Us	H
	0	1	0	1	0 (-)	L

Fig. 5 – Gate control of 3-level IGBT Inverter

Layout of Power Supply

- Compact layout of each set of ELM-Coil Power Supply, within a steel structure, drives design
- Each IPU designed as two suites of cubicles, arranged back-to-back, with central (DC- and AC-) busbar compartment (5.4*1.6*2 m (L*W*H))
- Steel structure, designed for estimated weight of equipment (150 T), has foot-print of 13.6*16.3 m.

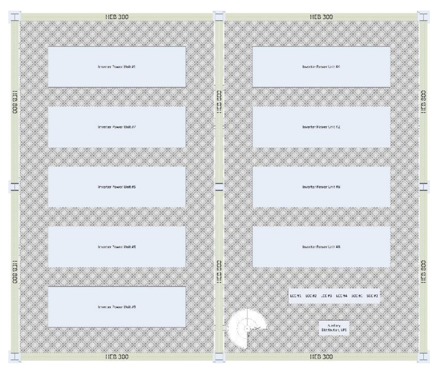

Fig. 6 – Layout of IPUs at level-1 (plan view)

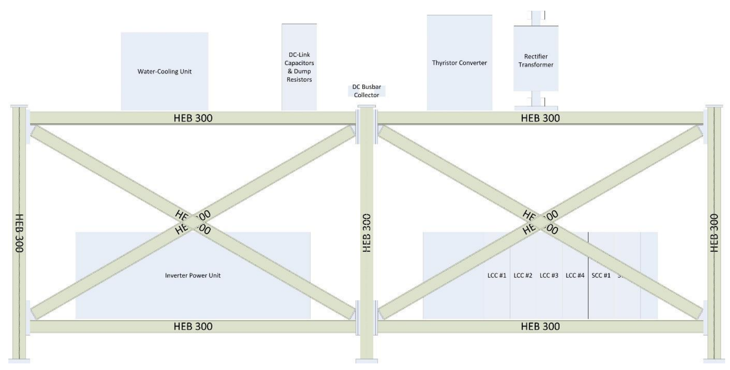

Fig. 7 – Side View of Steel Structure (elevation)

Computer Simulation

Computer Modelling

- One set of ELM-Coil Power Supply modelled with PORTUNUS® v.6.2 [2] (power and control).
- Model of ELM-Coil includes coupling to simulate induced eddy currents in nearby metallic structures (worst case: cut-off @ 25 Hz, L_{1kHz} / L_{dc} = 0.25)

ELM-Coil Current Control

- 'Direct PWM' technique [3] to dispense from the need to filter the measurement of the coil current
- Double-edge modulation with phase-opposition disposition and carrier-frequency set at 2.5 kHz.
- Computation of PWM 'target' reference improved by two correction factors:
  - Deviation of Inverter input voltage from reference value
  - Four-step quadratic extrapolation to account for delay arising from discrete control intervals
- Feedforward control signals derived from injecting ELM/RWM current references into a circuit simulating the ELM-Coil impedance at felm / frwm
- Feedback control optimized by simulating complete open-loop (controller, power circuit) in frequency domain: gain set for 45° phase-margin. Closed-loop bandwidth: 140 Hz but HG < 10 in most RWM frequency range (10 Hz – 60 Hz).

[2] Adapted Solutions http://www.adapted-solutions.com/web/adaptedsolutionsenglish/ASProductPortunus.html
[3] D.G. Holmes, T.A. Lipo, "Direct" Modulation, in: Pulse Width Modulation for Power Converters, IEEE Press, John Wiley & Sons, 2003, pp. 146-148.

Nominal ELM/RWM Operation

- Excellent results from simulations:
  - Gain- and phase-errors of ELM/RWM-currents are less than 1% / 2% and 0.2° respectively
  - Inter-modulation components of ELM-Coil currents are less than 1% of ELM current
  - Residual main harmonics at output of AC-DC converter are less than 1% of DC-value
- Simulation of nominal scenario ‚ELM (9kA, 5Hz) – RWM (1.25kA, 60Hz)' is shown in Fig. 8-9.

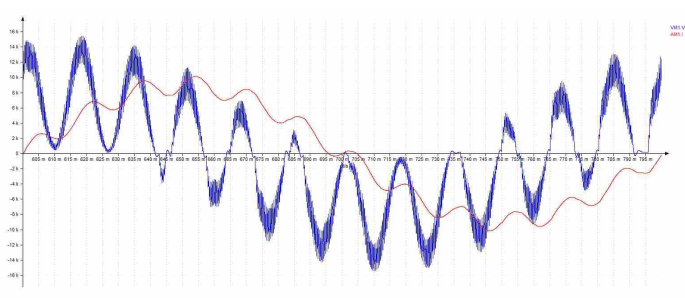

Fig.8 – Voltage and Current in ELM-Coil #1

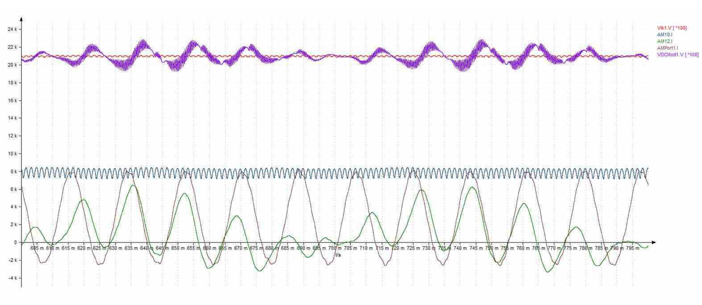

Fig. 9 – Voltage and currents in DC-circuit

Plasma Disruption

- Induced voltage during plasma disruption simulated by one cycle of sawtooth (10Vs, 100ms)
- When any ELM-Coil current exceeds 20 kA:
  - All Inverters of one set are set to freewheel
  - The bi-polar thyristor crowbars of all Inverters of one set are triggered
- DC-link voltage rise: 48V (210V => 258V)
- Rate of rise of DC-link voltage: 7.6 kV/s
- Equivalent current injected by Inverters: 20.4 kA

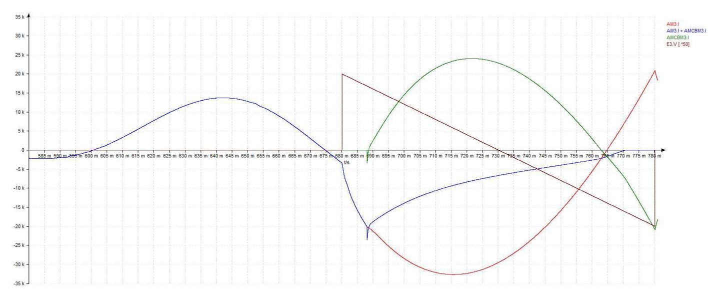

Fig.10 – Current in ELM-Coil #3, at Inverter Output and Crowbar

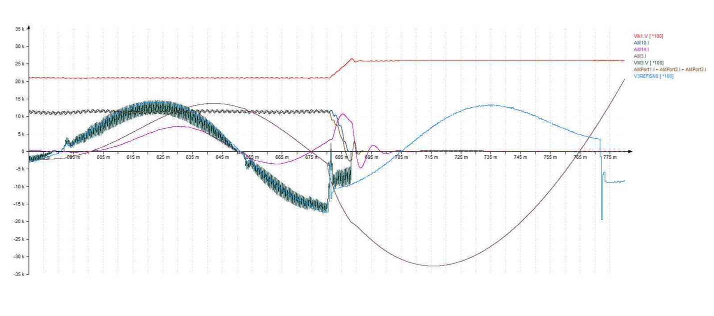

Fig. 11 – Voltage/Current in ELM-Coil #3 and in DC-circuit

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