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Klystron modulators for ESS

Development status by Oct. 2015

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www.europeanspallationsource.se

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Summary

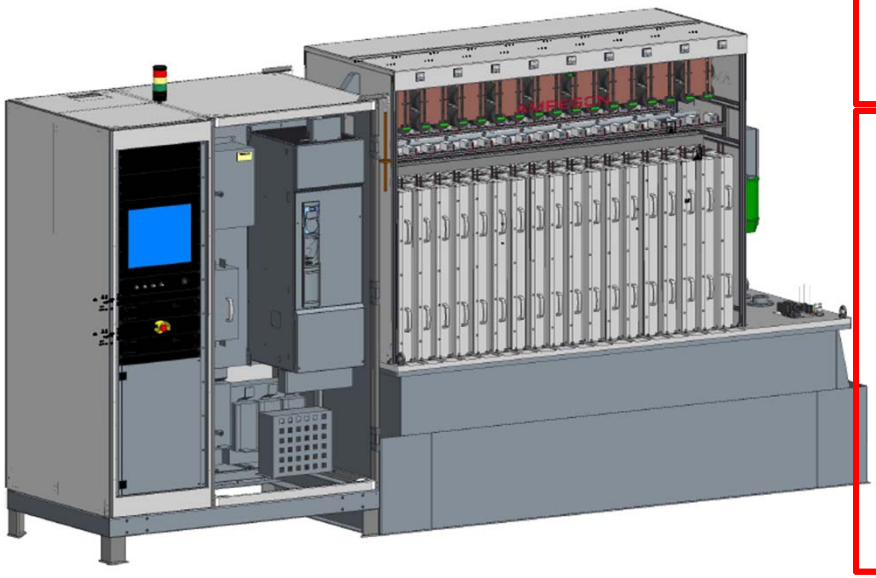
1. The Modulator development and procurement strategy: Recall;
2. Situation of the commercial 330kVA modulator prototype development – Ampegon contract;
3. Situation of the commercial 330kVA modulator prototype development – CEA DTI/SigmaPhi contract;
4. Situation of the Reduced Scale prototype development (SML Modulator) - ESS;
5. Comparison of the three topologies (prototypes) in terms of:
   a) Modularity versus monolithic;
   b) Scalability to higher power levels (i.e. more klystrons per modulator);
   c) Reliability;
   d) Cost;
   e) Volume/footprint and quantity of oil required;
   f) Pulse quality (rise time, flat-top accuracy, efficiency);
   g) AC grid power quality (flicker, harmonic distortion, power factor);

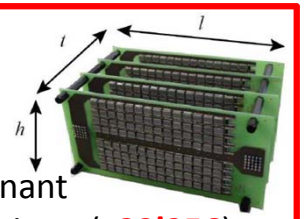
1. Development and procurement strategy for ESS modulators (RFQ, DTL and Medium Beta)

Strategy	Rated power	Ready/Delivery of prototype	Validated	Decision point	Outcome
A – SML (ESS internal development)	660 kVA (4 klystrons 704MHz in parallel)	Dec 2015	Jan 2016	If A: SML fully validated, Q1 2016 If B: Sept 2016	Strategy A: Launch call for tender for 660kVA modulators: - 3 units for RFQ + DTL; - 9 units for medium beta; - Total cost: **~ 12 M€**
B:1- Ampegon (ESS contract)	330 kVA (2 klystrons 704MHz in parallel)	May 2016	Fall 2016		
B:2 – DTI/SigmaPhi (CEA contract)	330 kVA (2 klystrons 704MHz in parallel)	Jan 2016	Mid 2016		Strategy B: Launch call for tender for 330kVA modulators: - 6 units for RFQ + DTL; - 18 units for medium beta; - Total cost: **~ 18 M€**

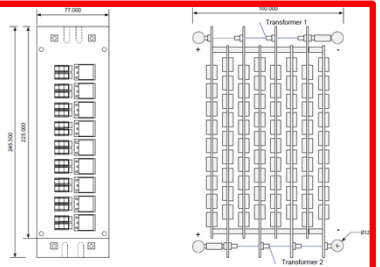
2. Situation of the commercial 330kVA modulator prototype development – Ampegon

AMPEGON AG

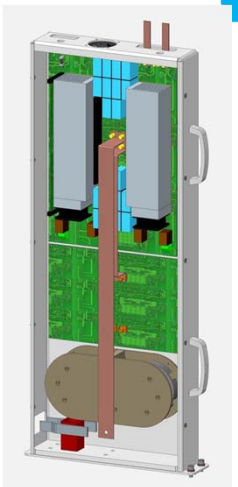




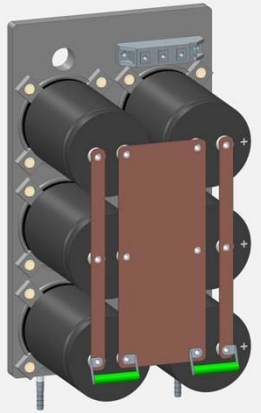
Resonant capacitors (**x32’256**)



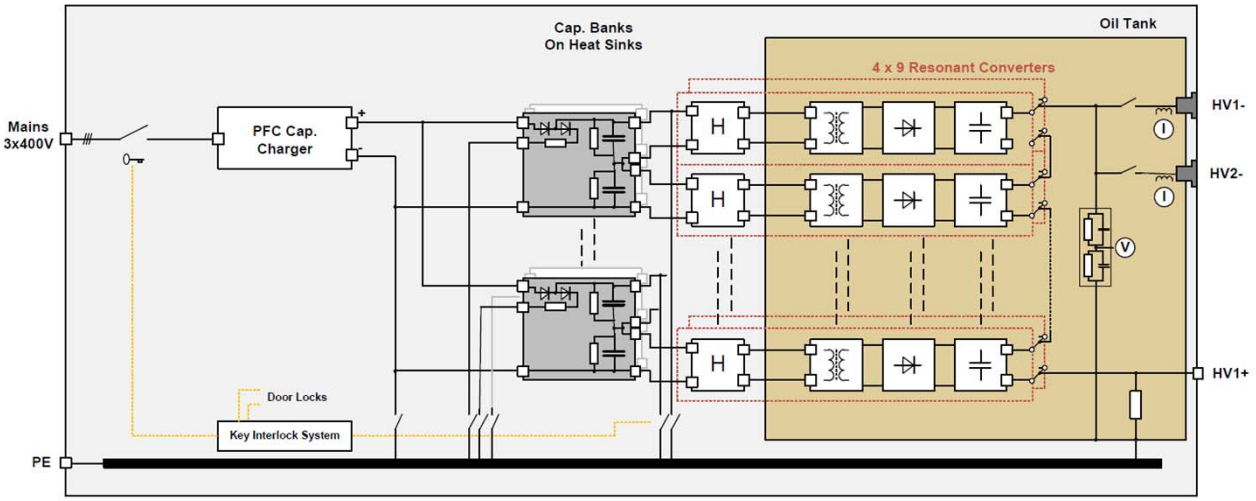
HV rectifier bridges based on Diodes (**x 5’184**) and resonant capacitors (**x 31’104**)

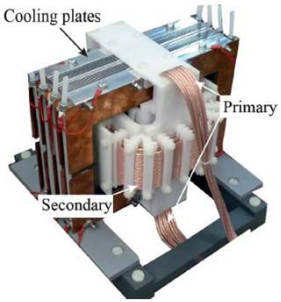


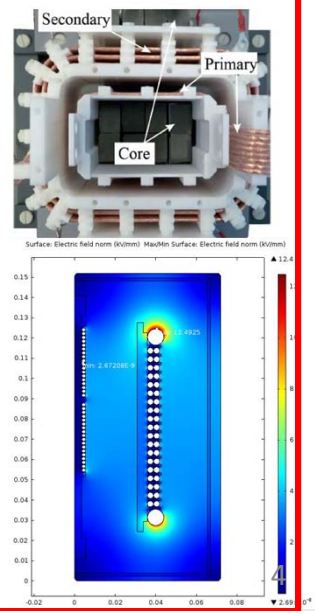
H-bridge inverters based on MOSFET’s (**x 720**)



Electrolytic capacitors (**x 108**)







HVHF transformers (**x 36**)

2. Situation of the commercial 330kVA modulator prototype development – Ampegon contract

Main observations:

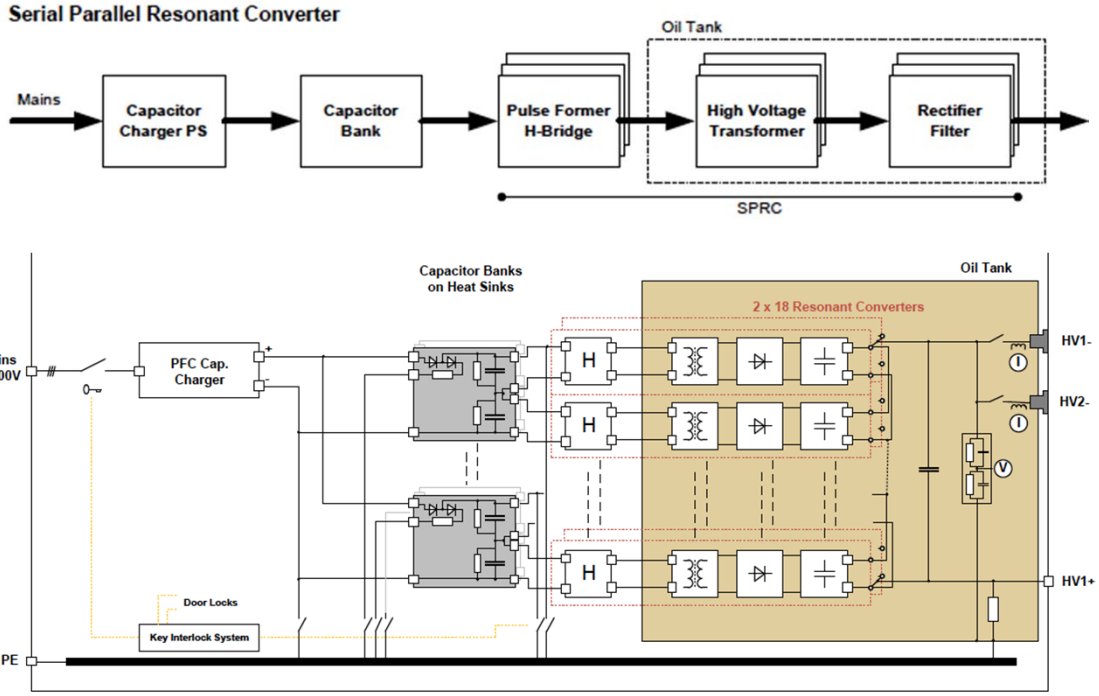
- **TDR V1 was not approved**. Main reasons were:
  - 1)- **HVHF transformer design could not work** (2 cm clearance in oil not enough; creapage distance not enough, no anti-corona rings). **Corrected in V2** (3 cm clearance, 8mm anti-corona rings added, creapage distance improved;
  - 2)- **Type of main capacitors used (electrolytic) not compliant with the specifications** (polypropylene film). **Not changed in V2**;
  - 3)- **Reliability analysis has shown a typical MTBF of ~5'000h, therefore not compliant** with the specifications (70'000h). **Changed to >50'000h in V2 without any justification** (no design changes could justify this increase);
  - 4)- **Tolerance of the components (SMD capacitors) would generate prohibitive ripple** in the pulse flat-top. **Changed to a better circuit implementation in V2**;
- Topology is complex and requires too many components and interconnections (750 MOSFETS with drivers, 60'000 SMD capacitors, 5'000 diodes, 108 electrolytic capacitors, 72 fans, 72 fuses, 32 HVHF transformers, …);





- Choice of topology, design of components and control algorithms done up-to ~80% extent by University of Zurich. Photos and schematics from existing publications in the TDR (authors from Univ. Zurich only);
- Delays in the construction :
  - HVHF transformer could not withstand the High Voltage, due to corona discharges on the insulators (3D printed !!!). Redesign with a different type of insulator material in progress.

2. Reliability Analysis (RAMI) by Enric Bargalló, using MIL-HDBK-217

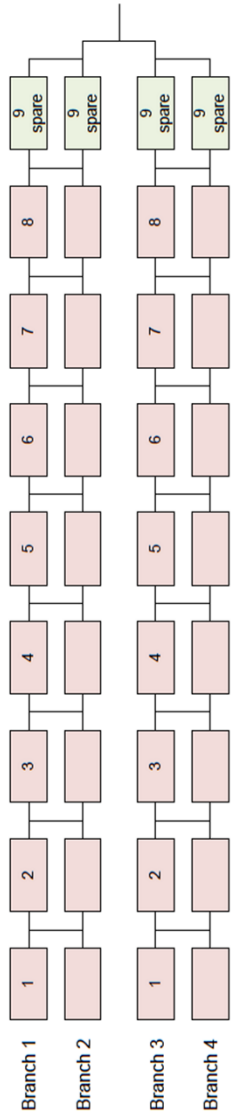


Redundancy scheme taken into account (still needs to be demonstrated in practice)

- 36 modules (4 branches of 9 modules each)

– 4 redundant modules have been added;

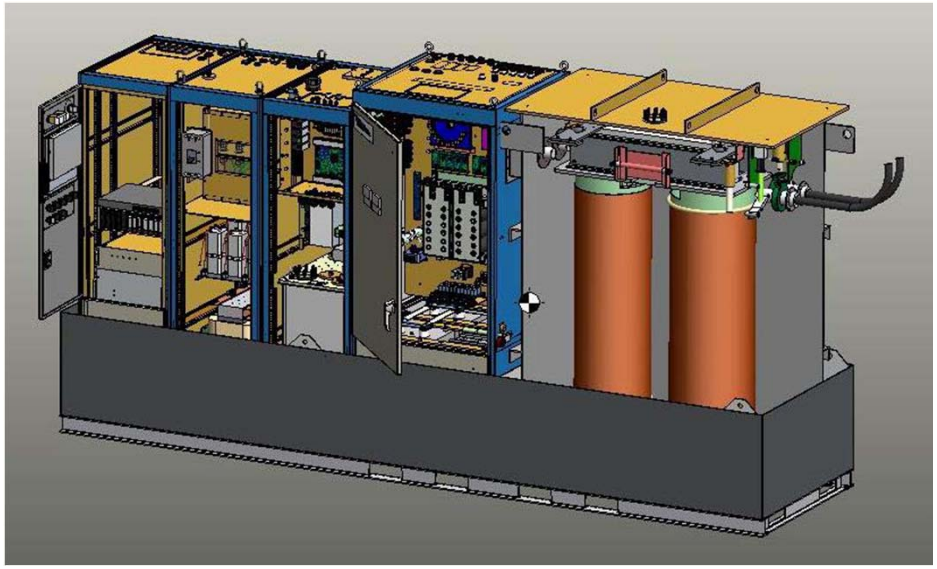
– modules go by pairs: if one module fails, another from another branch has to be deactivated (actually, redundant modules are only 2)



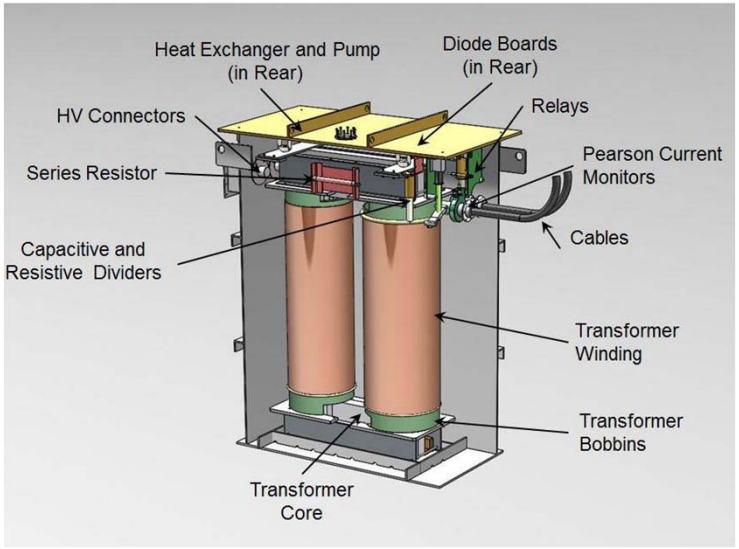
PM is in all faulty modulators	~ MTBF (1 modulator)	Annual # of failures (1 modulator)	Annual # of failures (66 modulators)
No Preventive Maintenance (PM)	3'180h (specified was 70'000h)	1.52	100.0
PM every year	3'455h	1.27	83.8
PM every half year	4'484h	1.02	67.3
PM every 288h	19'101h	0.26	17.16

3. Situation of the commercial 330kVA modulator prototype development – DTI/SigmaPhi contract

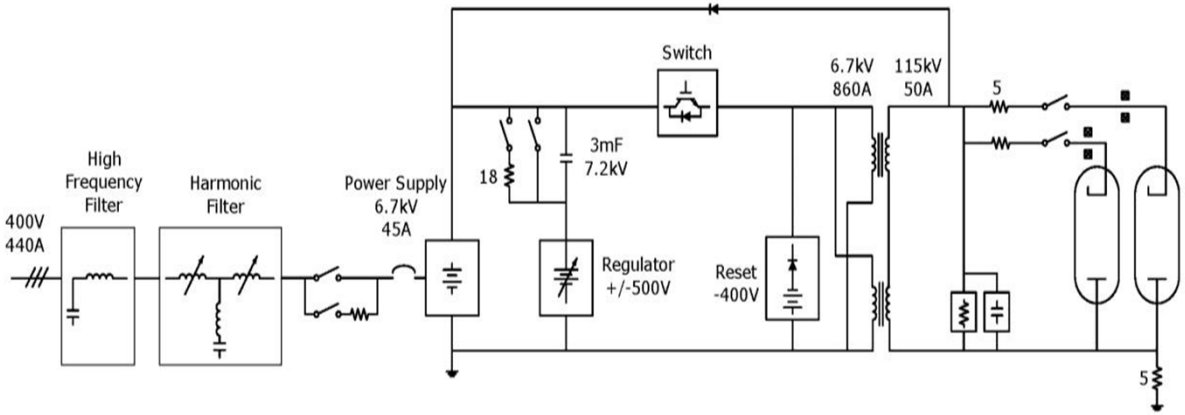
Diversified Technologies Incorporated, DTI

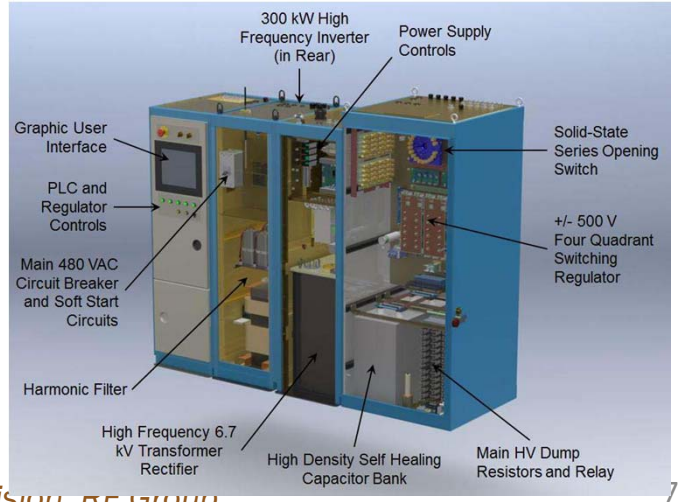


Pulse Transformer (7.4tons; 1’850 liters of oil)



Primary pulse generator (weigth = 5 tons)





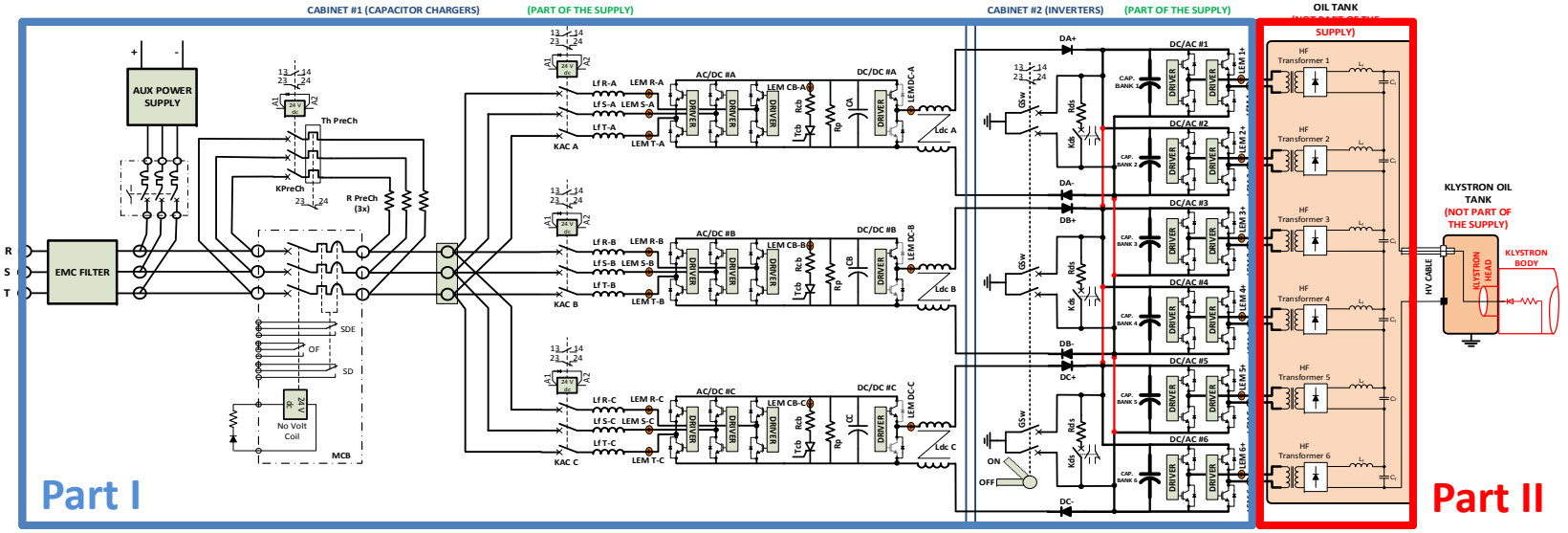
3. Situation of the commercial 330kVA modulator prototype development – DTI/SigmaPhi contract

Main observations:

- Topology is very simple, and therefore very reliable (good MTBF);
- However, due to the usage of single/large components (pulse transformer, etc.) the time to repair is considerably high (MTTR), keeping the Availability just reasonable;
- The power quality on the AC grid is not compliant with the relevant international standards (not acceptable for ESS);
- The pulse quality (rise time = 120µs, flat-top accuracy = 0.1%) is good;
- All components (HV switches, pulse transformer, power stacks) are custom made and proprietary (i.e. single source);
- Two oil tanks (1 for capacitor charger, 1 for pulse transformer) instead of one;

4. Situation of the Reduced Scale prototype development (SML Modulator) - ESS

Initial plans (up-to Feb 2015)



Part I – Call for tender on a "built-to-print" basis:

- Contract awarded to AQ Elautomatik AB (Sweden);
- Successfully delivered on time;
- Successfully tested on resistive loads (@1kV) by Jan 2015;

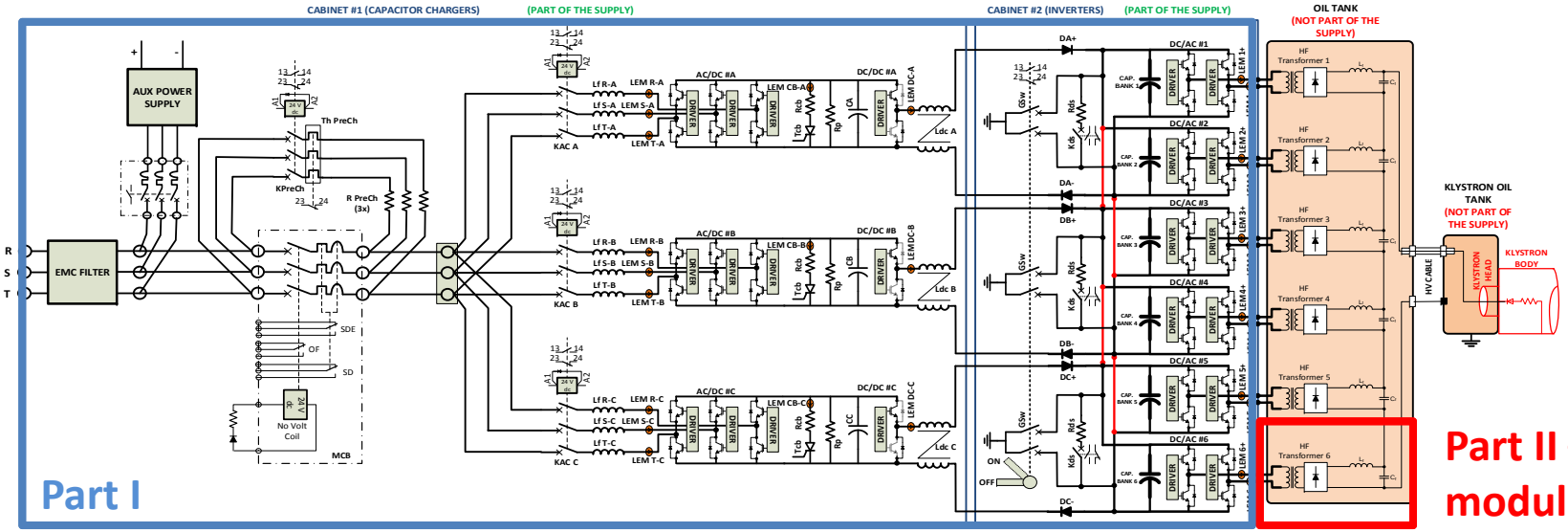
Part II – Call for tender on a "turn key" basis (design + construction) :

- Contract awarded to Ampegon – PPT (Germany) in June 2014 (delivery foreseen for Feb 2015);
- TDR submitted Nov. 2014;
- Company changed administration (CEO) and project main engineer in Dec. 2014;
- Construction started Feb 2015 (delayed);
- Design has changed to 3 times bigger in volume;
- Cost increase claimed to 50% higher;
- Deadline extension claimed to additional 8 months;
- Conflict of interest with Ampegon – Switzerland ?;

Contract cancelled in May 2015
Plan B launched in Feb 2015

4. Situation of the Reduced Scale prototype development (SML Modulator) - ESS

Plan B (after Feb 2015)



Part II – ESS/LTH design followed by a "build-to-print" contract:

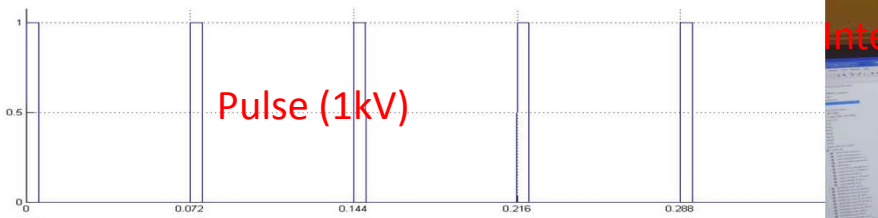
- Detailed design of HV module #1; — Feb 2015
- Construction of HV module #1 prototype at Lund Technical University;
- Testing of HV module #1 prototype on a resistive dummy load at nominal ratings;
- Detailed 3D CAD model of the entire HV oil tank assembly;

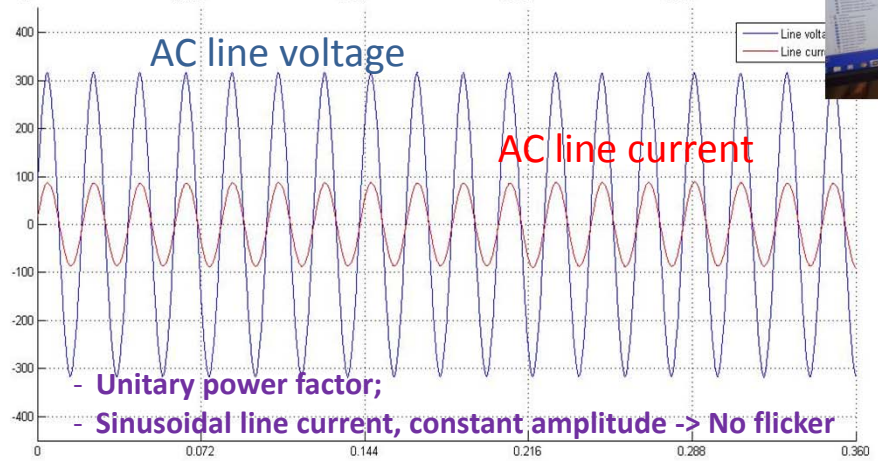
~ 4 months

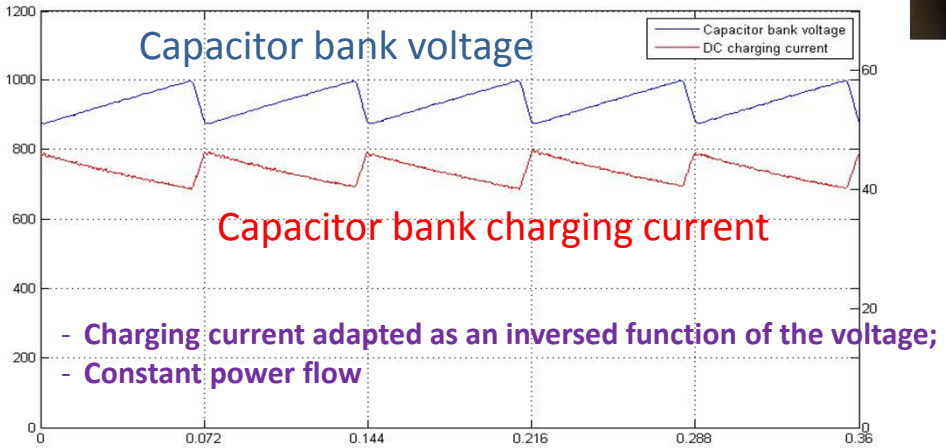
- Write up of technical specifications, Bill Of Materials (BOM) and assembling instructions; — Mid June 2015
- Launching Invitation To Tender; — 2nd July 2015
- Return of offers; — 16th Sept 2015
- Selection of company; — 24th Sept 2015
- Award of contract — ?

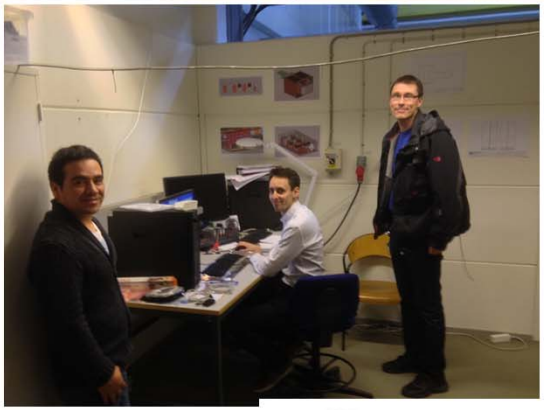
~ 3.5 months

4. SML Modulator – Testing of Part I on resistive dummy loads (Feb. 2015)

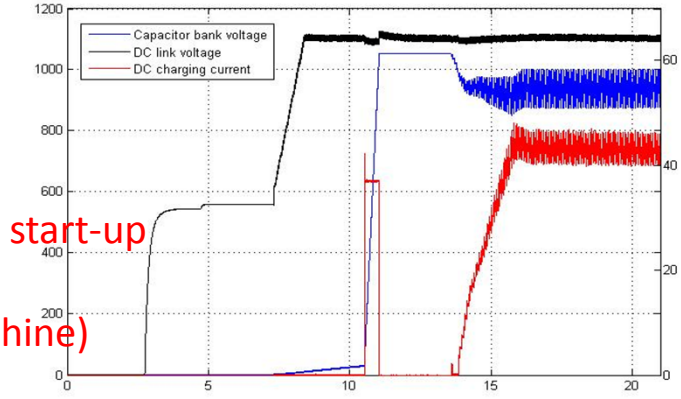








Part I - Low voltage power converter stage



Automatic start-up sequence (state machine)

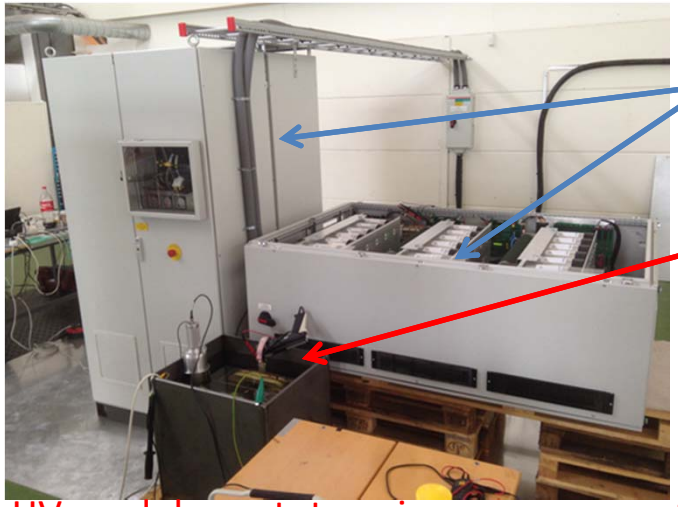
4. Modulator test stand at Lund Technical University

Small room (30m²), for low power testing

Moving, Feb 2015

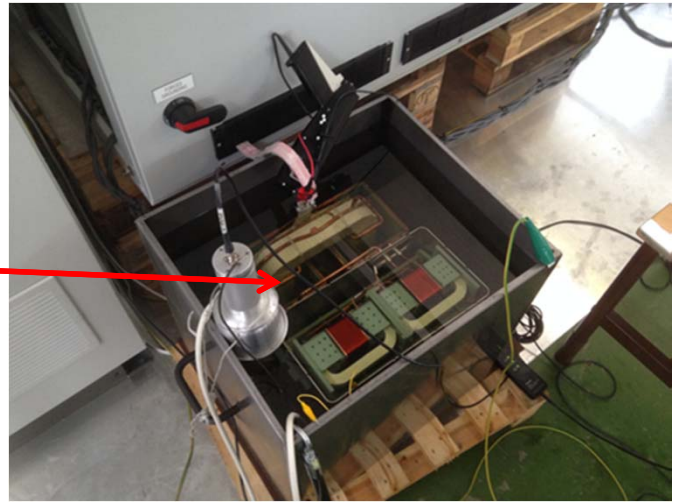
Larger test stand (130m²), for high power testing (160 kVA)

4. SML Modulator – Testing of the HV module #1 on a resistive dummy load, driven by a LV power converter module



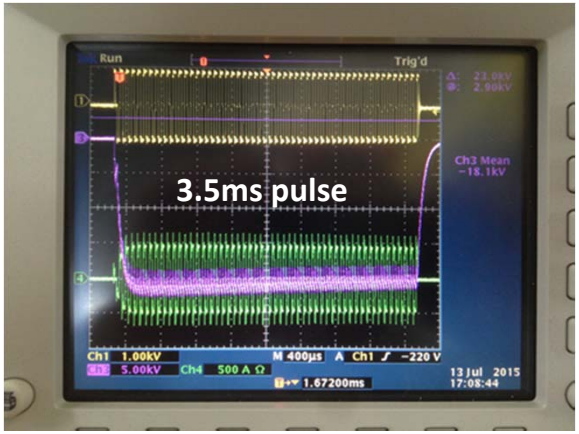
Part I – Low voltage power converter

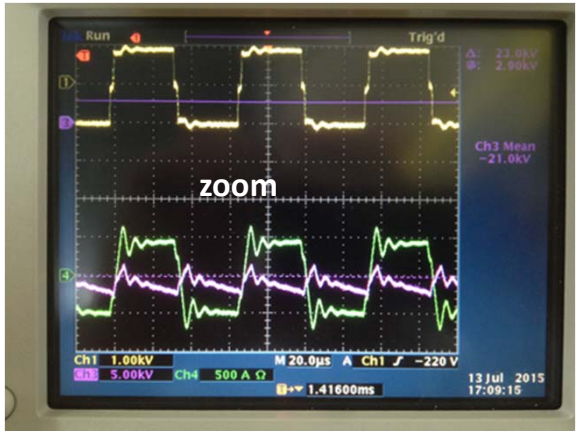
Part II – HV module #1 prototype in oil tank



HV module prototype in assembly workshop at LTH

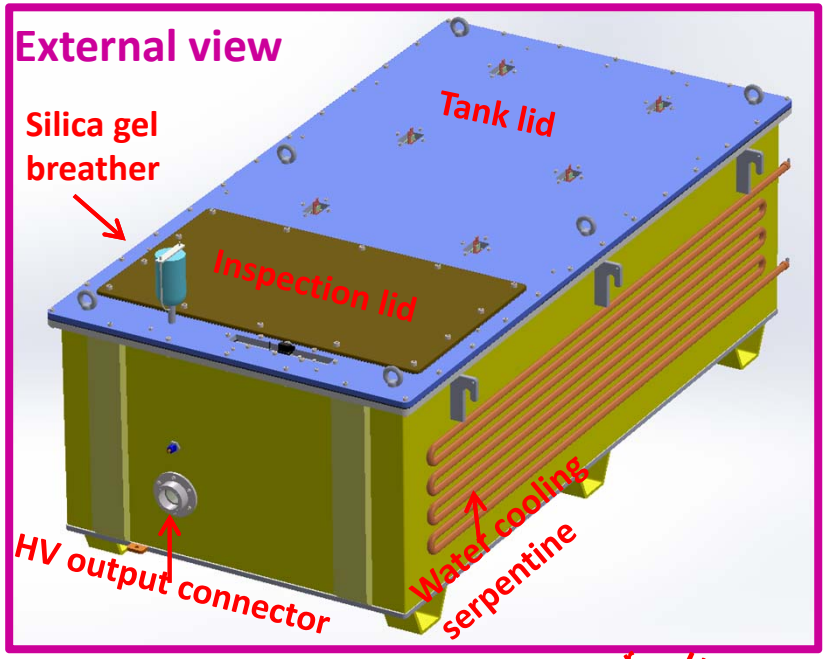
Experimental results at full power: Pulsed at 20kV/20A, 3.5ms/14Hz
(*Note: no output filter present; waveforms are as expected*)

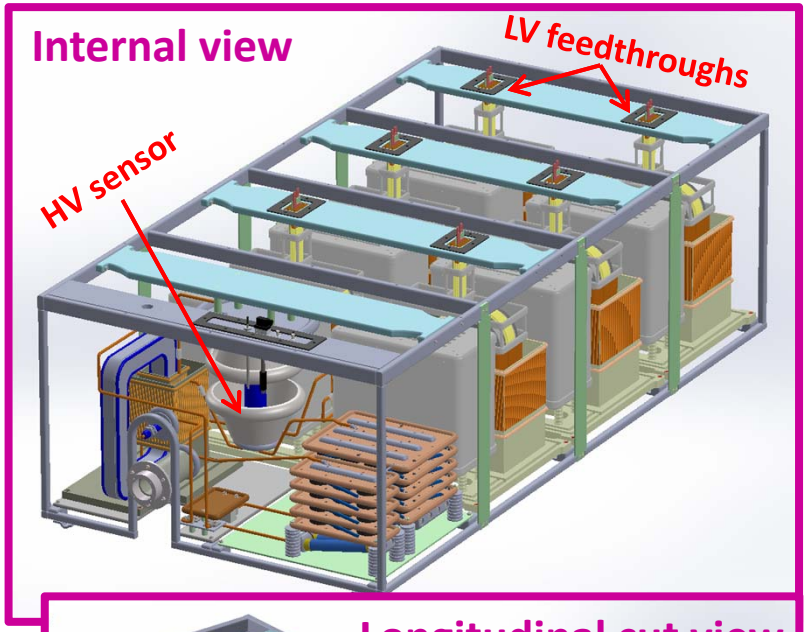


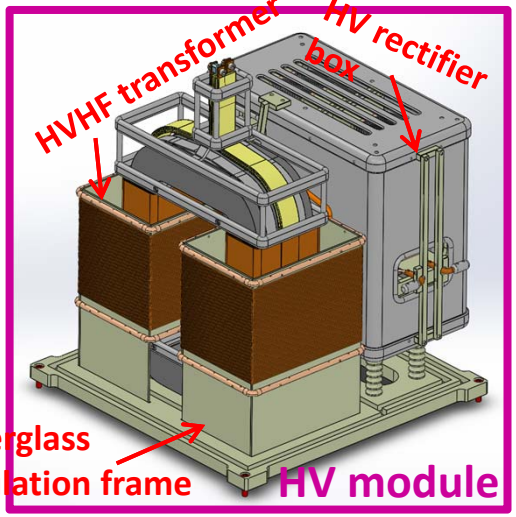


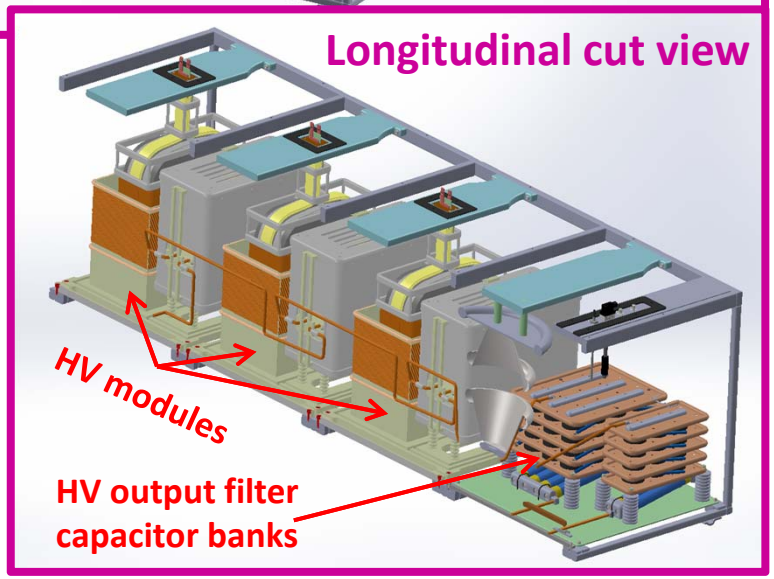
Magenta: HV output pulse; Yellow: LV input voltage; Green: LV input current

4. SML Modulator – Part II, complete 3D model of HV tank assembly

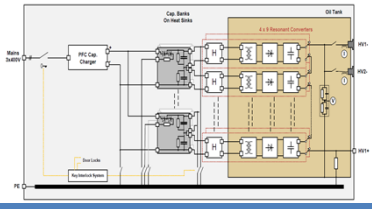
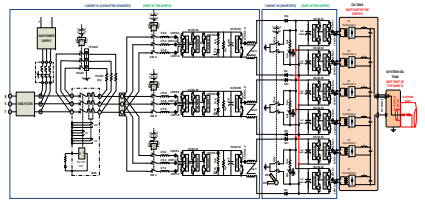
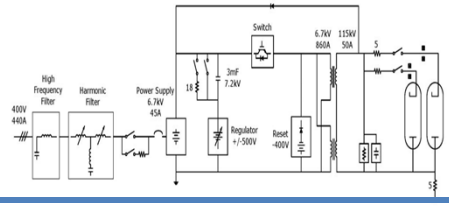








5. Comparison of the 3 modulator topologies

	Ampegon	ESS	DTI/SigmaPhi
			
Modularity versus monolithic	Too much modular (36 for 330kVA, ~~72 for 660kVA~~)	Good modularity level (6 for 330kVA, 6 for 660kVA)	Not Modular / monolithic (1 for 330kVA, ~~1 for 660kVA~~)
Scalability to higher power levels (i.e. more klystrons per modulator);	Very poor / impossible (too many small components)	Up-to 660kVA possible (6 modules, reasonable size of modules, larger components)	Very poor / impossible (size of pulse transformer, poor AC power quality)
Reliability / Availability	Extremely poor (too many small components)	Good (reasonable number of components, modular)	Good (lower number of components, however too large)
Total cost for ESS Linac	~ 56 M€	~ 35 M€	~ 50 M€
Weight/footprint and quantity of oil required	Good, if rated for 330kVA	Very good, even when rated for 660kVA	Poor, already when rated for 330kVA (7 tons pulse transformer)
Pulse quality (rise time, flat-top accuracy)	Good (70 µs, 0.2% ?)	Good (105 µs, 0.1% ?)	Good (120 µs, 0.1%)
Efficiency	89 % (theoretical)	> 92% (better if 660kVA)	> 93%
AC grid power quality (flicker, harmonic distortion, power factor);	Good (single cap. charger)	Very Good (3 interleaved cap. chargers)	Poor (6 pulse diode bridge, no active front end)

Spare slides

1. The Modulator development and procurement strategy Recall

Modulators Strategy A (baseline)

- ESS internal development of a new topology (SML – Stacked Multi-Level)
- Construction and validation of a Reduced Scale prototype rated for 120 kVA (115kV / 20A, 3.5ms / 14Hz) in collaboration with Lund University (LTH). Can power one 704MHz 1.2MWpk klystron;
- Project has started in June 2013. Completion and demonstration of technology are foreseen for Jan 2016;
- Upgrade to the full scale system 660kVA (115kV / 100A, 3.5ms / 14Hz) is a matter of thermal re-design and selection of higher current components. The full scale modulator is able to power 4x 704MHz 1.2MWpk klystrons in parallel. Straightforward approach with low risks

Modulators Strategy B

- ESS has launched an Invitation To Tender for the design and construction of one 330kVA modulator
  - Contract awarded to Ampegon on June 2014
  - Technical Design Report reviewed in April 2015 (with 6 months delay);
  - Delivery foreseen for May 2016 (with 5 months delay);
  - Soak testing in Uppsala RF test stand, from June to Sept (?) 2016;
- CEA / Saclay has launched an Invitation To Tender for the design and construction of another 330kVA modulator for their RFQ test stand. It can also serve as a technology demonstrator for ESS
  - Contract awarded to DTI on Oct 2014
  - Delivery foreseen for Jan 2016
  - Soak testing at CEA/Saclay RFQ test stand from January to April(?) 2016