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Comparison of ESS SML modulators to conventional pulse transformer-based modulators

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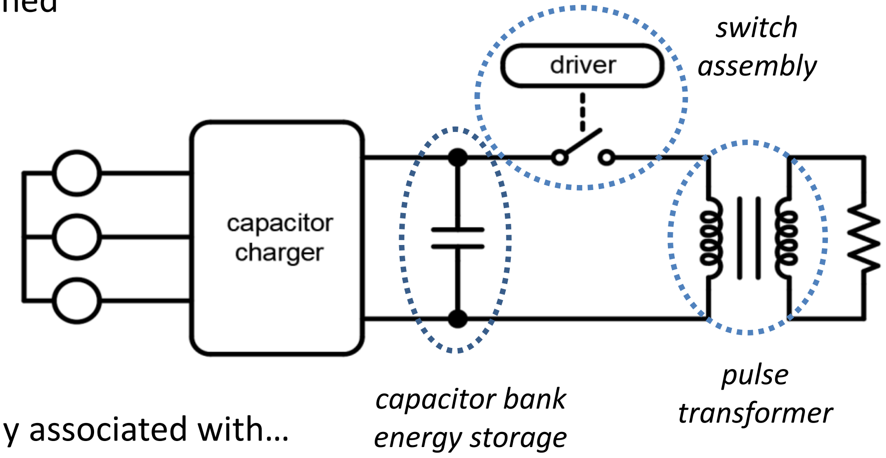
Pulse transformer-based modulators

- ❑ The pulse transformer-based modulator topology is conceptually simple

- ❑ Working principle:

  1. Input charger charges the main capacitor bank energy storage
  2. To begin pulse generation, the switch is closed- applying the capacitor bank voltage to the matching pulse transformer
  3. The transformer matches the voltage to the requirements of the klystron load
  4. To end the pulse, the switch is opened
  5. The procedure is repeated



- ❑ Used in many applications, and is typically associated with…

  - ✓ Straightforward design
  - ✓ Robustness, reliable operation
  - ✓ Good performance

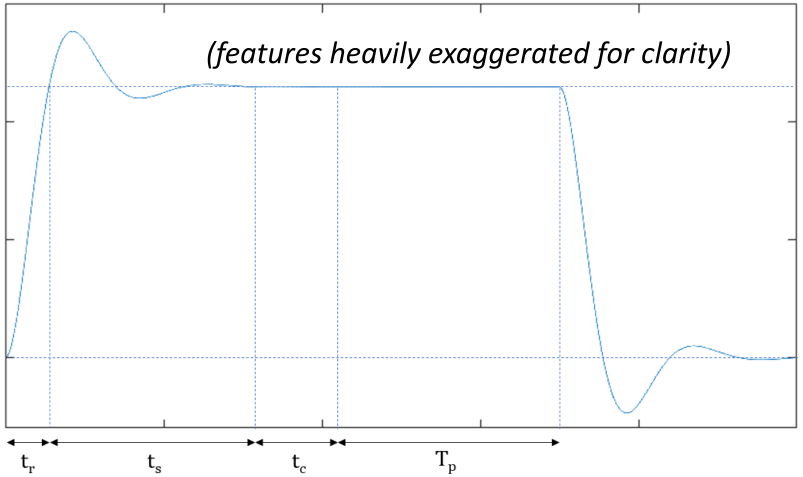
<u>this work:</u>

characterization of pulse transformer modulator subsystems considering long pulse high power applications:

- what would the corresponding pulse transformer-based modulator look like for ESS application requirements?
- what options and trade-offs exist in optimizing modulator efficiency?

Modulator efficiency

- Modulator efficiency η_m: “useful output power versus total input power”
  - Total input power: active power drawn from the electrical grid
  - Useful output power: <u>power which may be used to produce RF</u>



- Useful RF power generated only during the pulse beam time T_p…
- … But energy is also expended in going through the pulse rise time t_r, the stabilization time t_s, and the RF cavity filling time t_c
- Modulator efficiency expressed as power used to generate RF over total input power:

$$\eta_m = \eta_e \frac{T_p}{T_p + Kt_r + t_s + t_c}$$

modulator electrical efficiency

pulse efficiency

<u>ESS application</u>

$t_s = 100\ \mu s$
$t_c = 300\ \mu s$
$T_p = 2900\ \mu s$

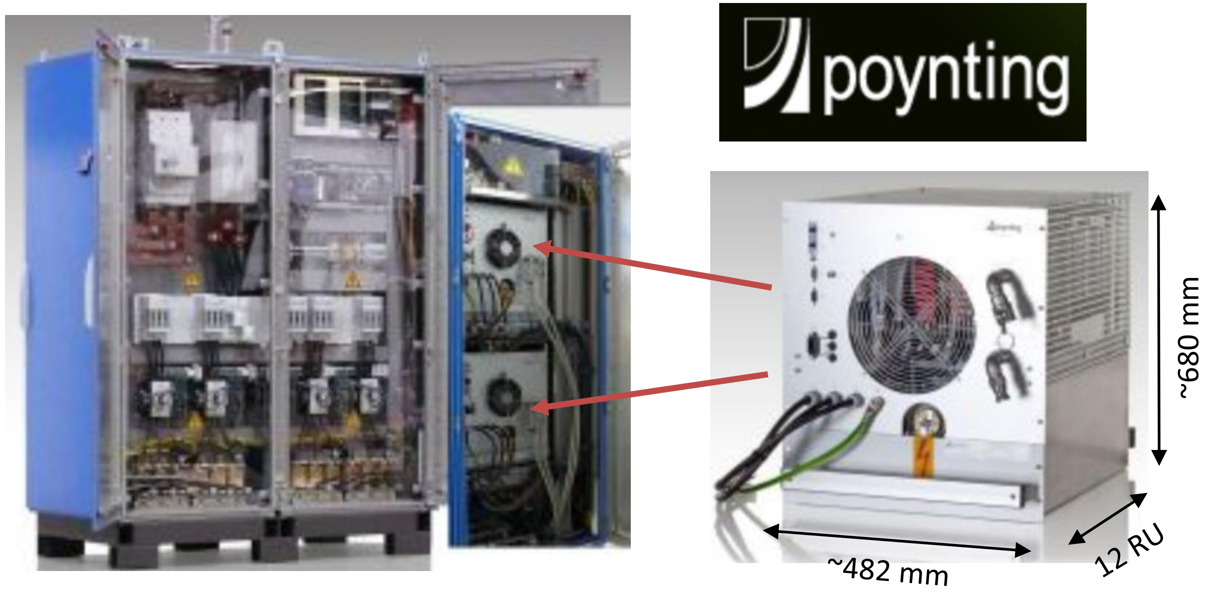
$\eta_m = f(\eta_e, K, t_r) = f(\eta_e, t_r)$

… K = 2/3 for long pulse transformers …

High power capacitor chargers (I)

- ☐ Input stage chargers re-charge the capacitor bank between pulses
- ☐ Capacitor charger are sized to deliver the system average power
- ☐ Commercial high voltage, high power capacitor chargers are based on modular rack-mount units
- ☐ In principle, any number of charger units can be operated in parallel to increase the maximum power rating

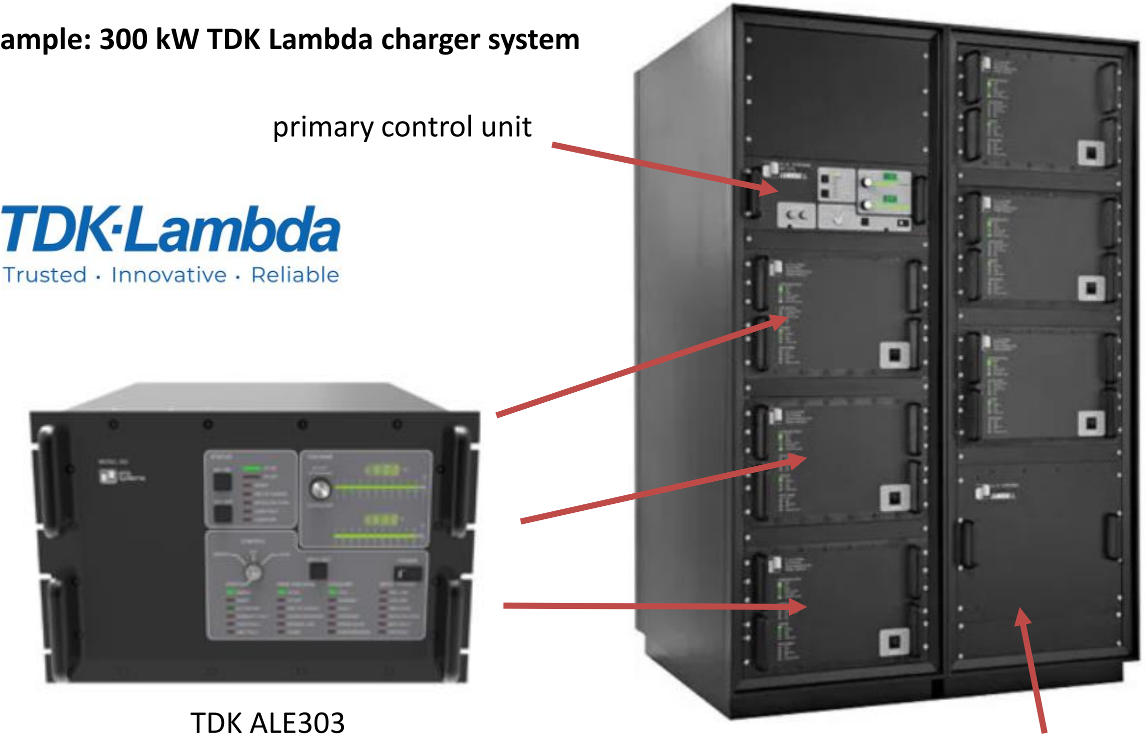
Example: 300 kW Poynting capacitor charger system



4x MOD-75 charger units = 300 kW

Poynting MOD-75
75 kW, 95% efficiency

Example: 300 kW TDK Lambda charger system



TDK ALE303
50 kW, 85% efficiency

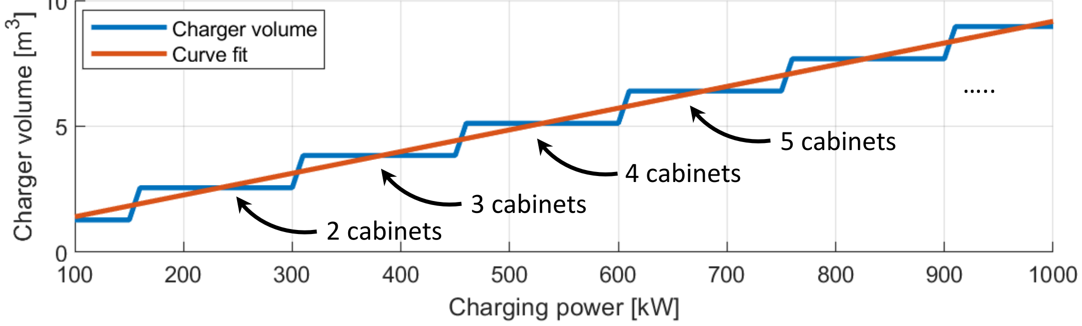
6x TDK ALE303 = 300 kW

High power capacitor chargers (II)

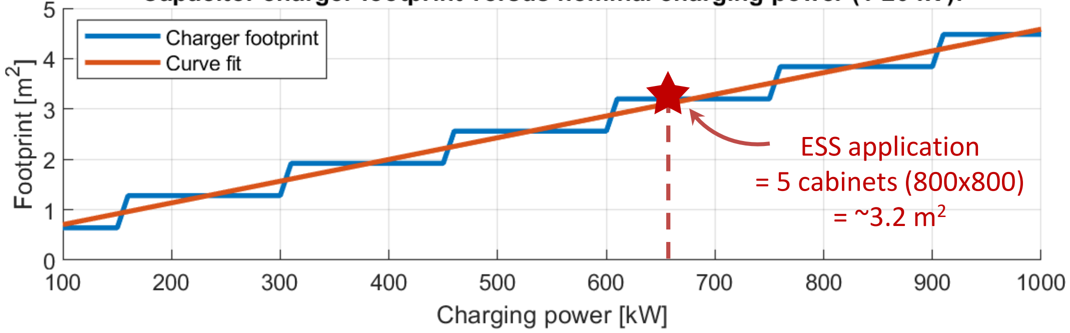
- ❑ Study of offerings from TDK, Poynting, Technix, Spellman, …, indicate-
  - ❑ General utilization of standardized 800x800x2000 cabinets
  - ❑ Power density of around 150 kW/cabinet
  - ❑ Efficiency range from 85%-95% at nominal operating condition

… in practice, the impact on system efficiency is somewhat greater due to generated line-side harmonics, reactive power, the fact that the charger cannot be operated at full load, …

- ❑ Study of high power chargers valid for approximate output voltage range 1 kV-20 kV:



Capacitor charger volume versus nominal charging power (1-20 kV):

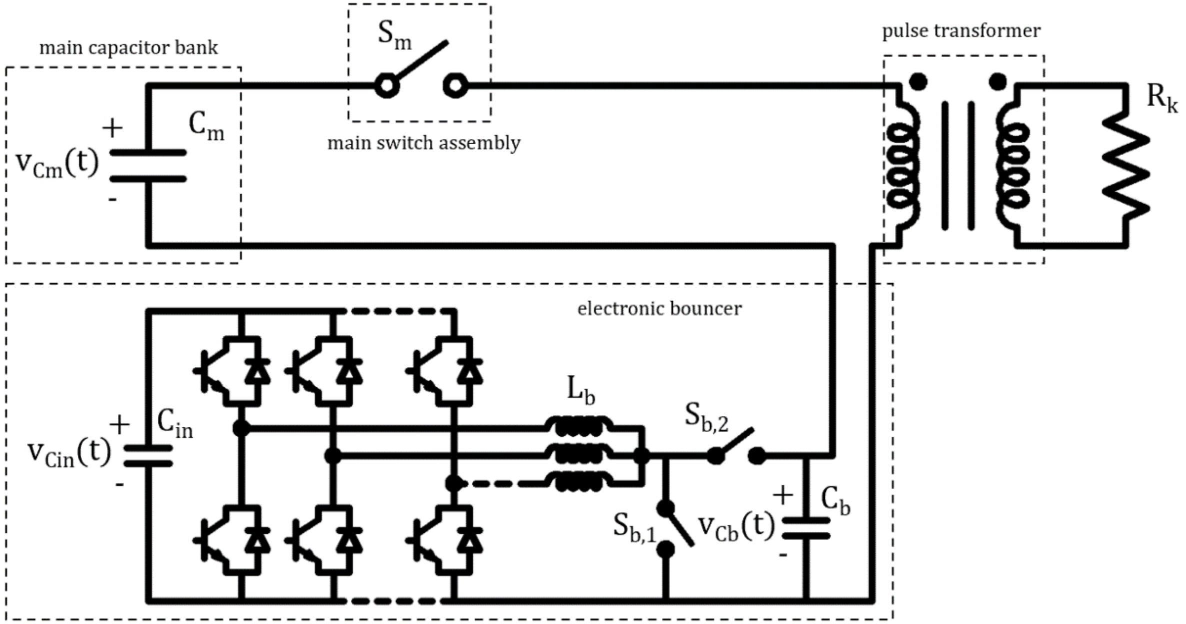


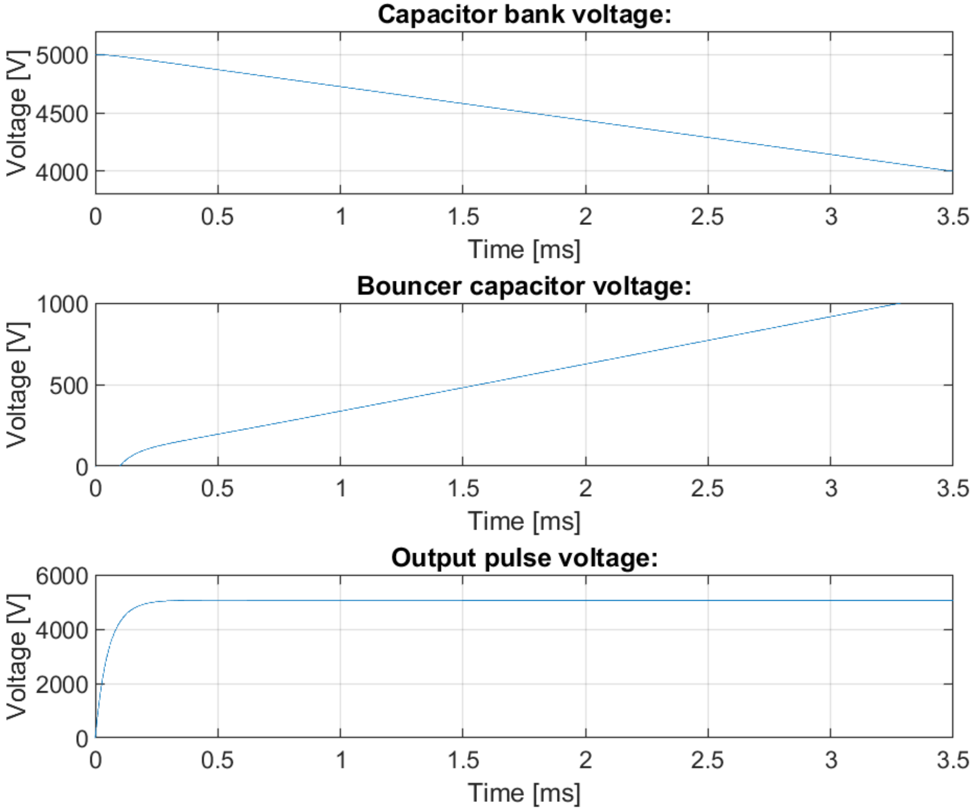
Capacitor charger footprint versus nominal charging power (1-20 kV):

ESS application
= 5 cabinets (800x800)
= ~3.2 m^2

Capacitor bank and droop compensation system (I)

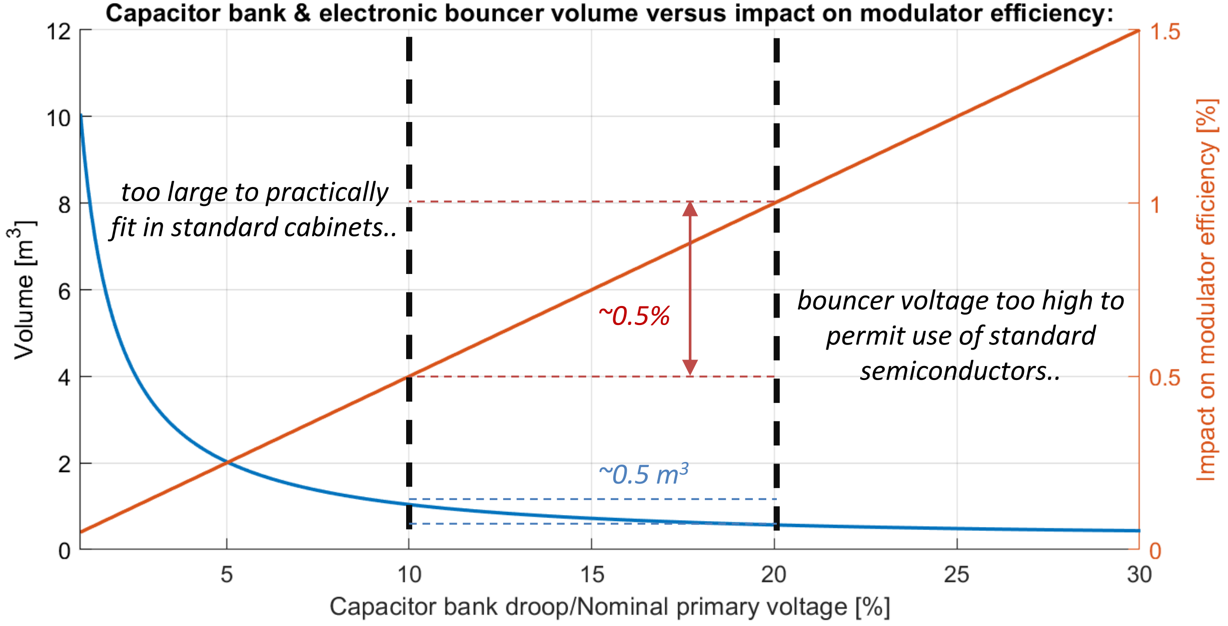
- ☐ The capacitor bank voltage droops in pulse generation – this is amplified by the pulse transformer and seen in the pulse flat top
- ☐ Maximum flat top droop is limited by application requirements, typically to ~1%
- ☐ Oversizing the capacitor bank to meet this requirement for long pulse high power applications is unfeasible
- ☐ Instead, a droop compensation system or "bouncer" is utilized, significantly reducing overall system size
- ☐ For long pulse applications, electronic (switch-mode) bouncers are used:





Capacitor bank and droop compensation system (II)

☐ Case study[1] assuming ESS klystron modulator requirements:



1) PWM switching generates ripple, amplified and seen in the pulse flat top = { flat top ripple limited to 0.15% of amplitude … }
   use high switching frequency (10-20 kHz) = requires standard semiconductor switches (< 1.7 kV) = upper limit on droop that can be compensated; ~1 kV, i.e. 20% of 5 kV
2) Should also practically fit in standard electrical cabinets = lower limit on droop, e.g. ~10%

☐ Compared to simply oversizing the capacitor bank, typical reduction in capacitor bank volume of a factor 10-20(!)

☐ Impact on modulator electrical efficiency between 0.5-1.0% of nominal output power

☐ Trade-off between system volume and system efficiency

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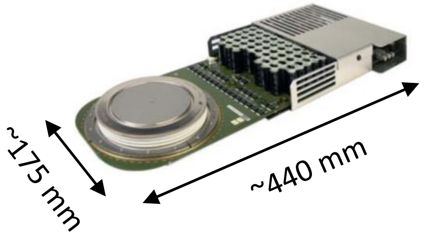
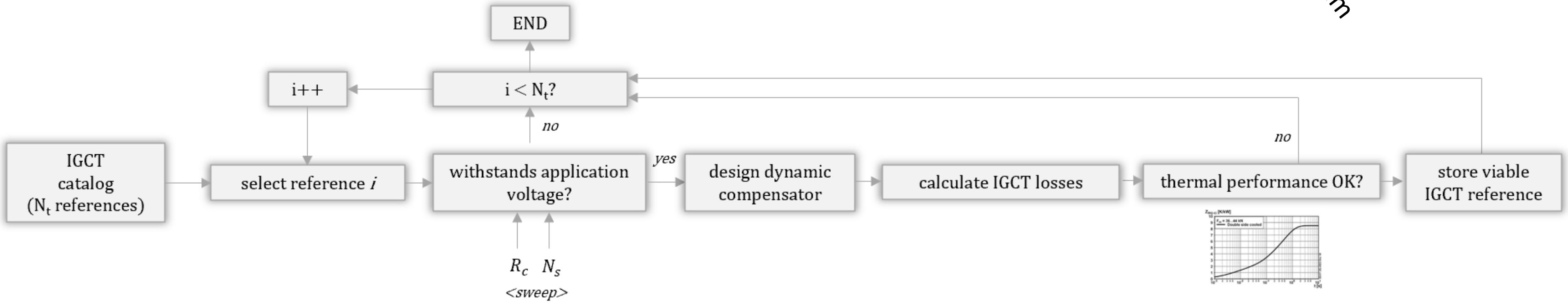
[1] M. Collins and C.A Martins, "Optimal Design of Electronic Bouncers for Long-Pulse High-Power Modulators", IEEE Trans. Plasma Sci., vol. 49, no. 2, pp. 819-829, Feb. 2021

High voltage solid state switch assembly

- The HV switch assembly connects the capacitor bank voltage to the primary windings of the transformer for pulse generation
- Therefore, the switch must be…
  - ✓ fully controllable
  - ✓ able to block the full capacitor bank voltage
  - ✓ able to conduct the full load current referred to the primary
  - ✓ able to operate at the desired pulse repetition rate
- Typically, solutions based on multiple IGCT switches in series are developed
- With series connected switches, the IGCT units must be equipped with compensation circuits for voltage balancing-
  - Generally, a large number of switches is required to handle the full voltage
  - Additionally, further switches are often added for redundancy in ensuring long term reliability



example: ABB switch assembly rated 12 kV/300 A-
7x IGCT switch rated 4.5 kV



IGCT catalog (N_t references)

select reference i

withstands application voltage?

R_c N_s

<sweep>

yes

design dynamic compensator

calculate IGCT losses

thermal performance OK?

store viable IGCT reference

no

no

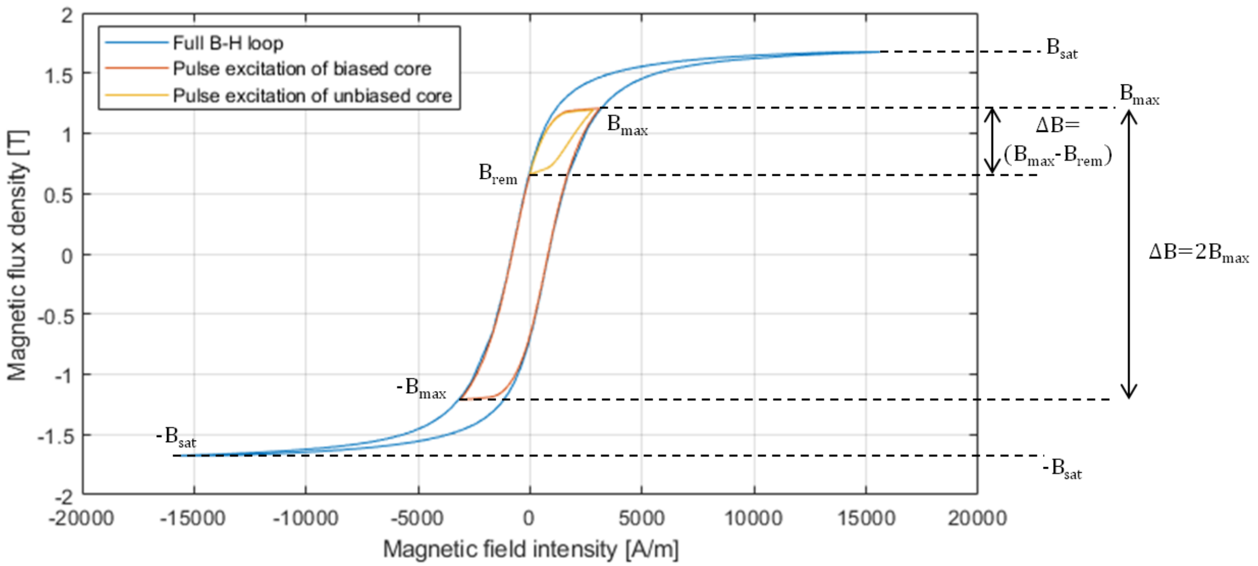
$i < N_t$?

i++

END

Pulse transformer auxiliary circuit (I)

- During pulse generation, the pulse transformer is magnetized over time…



- The magnetic flux density is defined by 1) the integral of the applied voltage over the pulse length; and 2) the turns-area product of the transformer
- Since the voltage-time integral is defined by the application (long pulse…), the pulse transformer must be sized appropriately to handle the flux

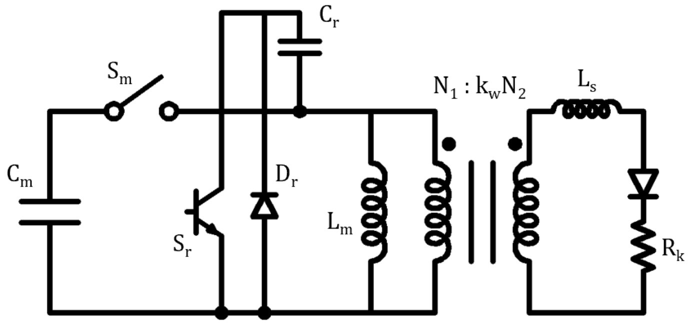
Therefore:

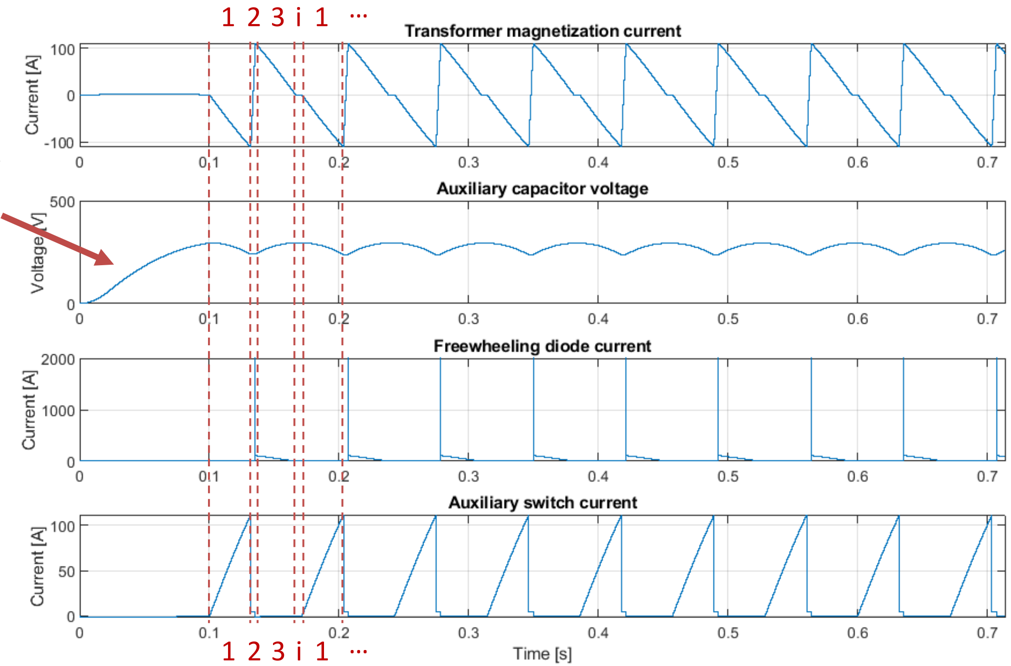
1) In long pulse high power applications, it is absolutely vital that the transformer is pre-magnetized to minimize pulse transformer size
2) Following a given pulse event, the transformer must be de-magnetized to avoid saturation during the next pulse event

- Typically, these tasks are handled by passive auxiliary circuits – <u>NOT PRACTICAL</u> in long pulse high power applications…

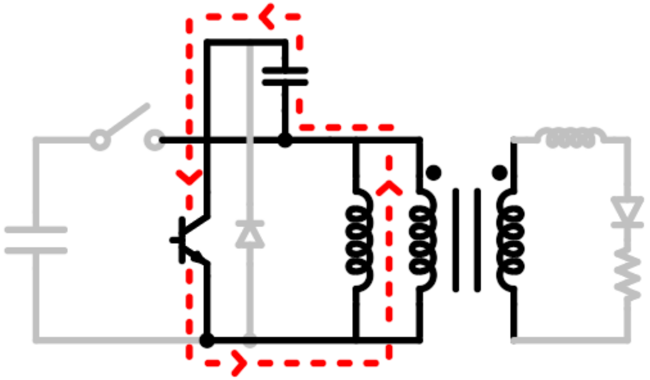
Pulse transformer auxiliary circuit (II)

☐ Development: active auxiliary circuit

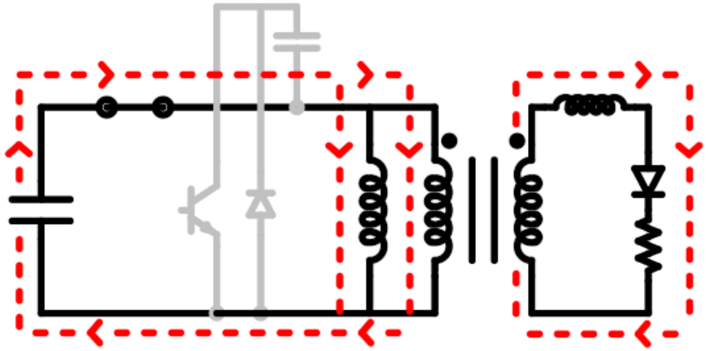




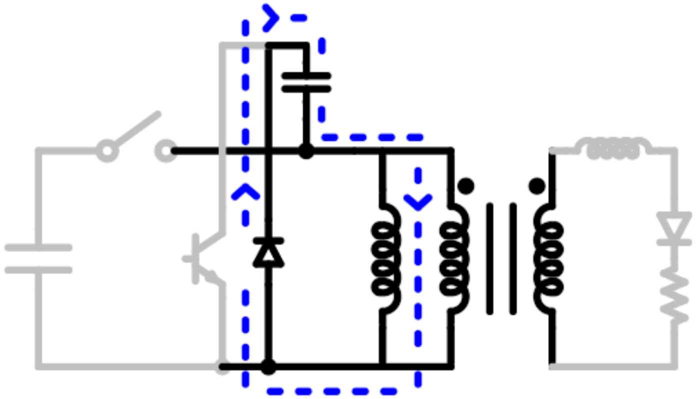
auxiliary capacitor is pre-charged



Step 1: pre-magnetization



Step 2: pulse generation



Step 3: de-magnetization

☐ For the purposes of assessing overall volume/losses, this auxiliary circuit may be assumed to be lossless and to be fitted in the switch cabinet

☐ Still- requires additional power supply, active control and timing, … (more complex)

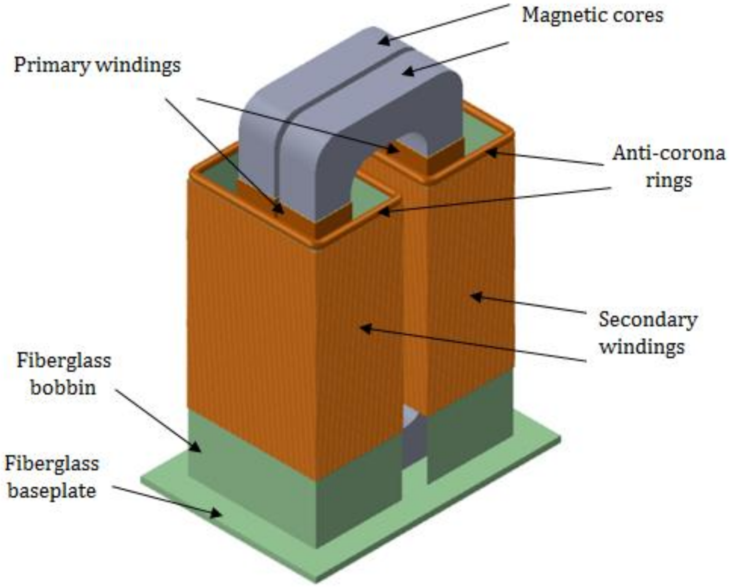
Pulse transformer (I)

- ❑ Long pulse high power applications…
    - ❑ Magnetic cores: tapewound double-C cores (size..)
    - ❑ Primary windings: low voltage, single layer windings
    - ❑ Secondary windings: high voltage, <u>pancake stack windings</u>
    - ❑ Fiberglass isolators to provide support and maintain distance
    - ❑ Integrated in high voltage oil tank assembly
- ❑ The product of the number of winding turns and the magnetic core cross-section must be chosen to be able to handle the peak magnetic flux density associated with the applied voltage-time (long pulse..);
- ❑ The longer the pulse the greater the required product of turns and magnetic core area;
- ❑ Minimize transformer & modulator size by increasing number of turns?
- ❑ <u>Not possible:</u> increasing the number of turns increases the leakage inductance (~N^2) and thereby the pulse rise time ($\sim L_s$), deteriorating the pulse efficiency…

= maintaining decent pulse efficiency implies limiting the number of turns

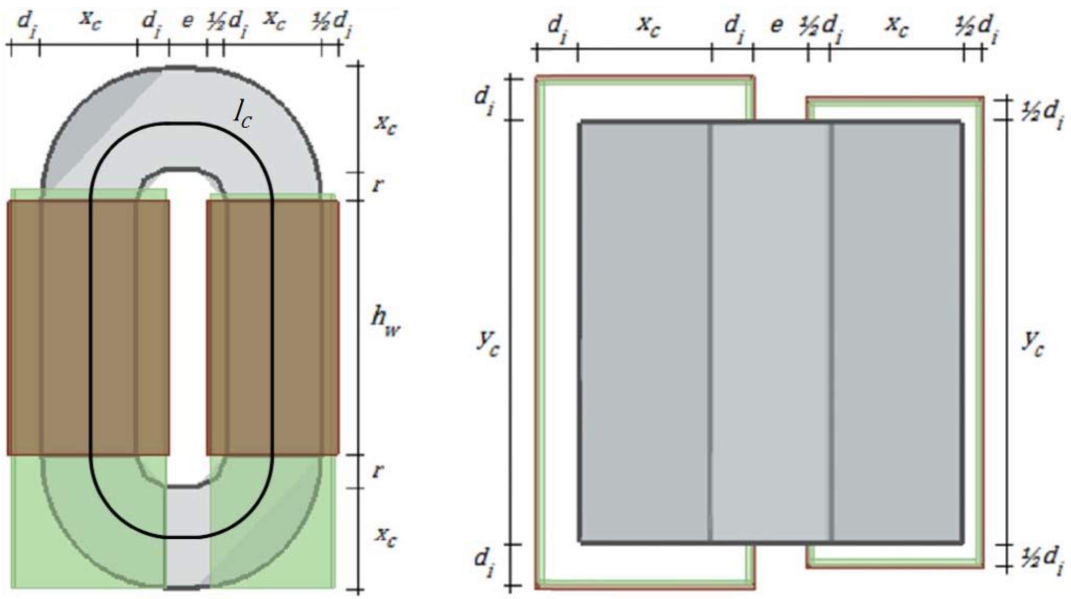
= very large cross-sectional area required to handle the flux density…

<u>fundamental problem of pulse transformers in long pulse high power applications…</u>



generic pulse transformer geometry…

… into mathematical formulation for design optimization



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[2] M. Collins and C.A Martins, "Evaluation of Feasibility of High-Power Long-Pulse Transformer Using Single-Layer and Pancake Winding Techniques," IEEE Trans. Plasma Sci., vol. 49, no. 7, pp. 2217-2226, Jun. 2021

Pulse transformer (II)

- ❑ Optimization results for ESS pulse power requirements[2], limiting transformer height to ~1.5 m
- ❑ Required pulse length is swept to study the impact on pulse transformer design, rise time limited to 3.43% of pulse length (120 µs @ 3.5 ms)
- ❑ Objective function: <u>minimize volume</u> – implications for pulse transformer losses are dismissed

assessment of losses:

- *magnetic core losses may be neglected*
- *winding copper losses are generally given according to…*

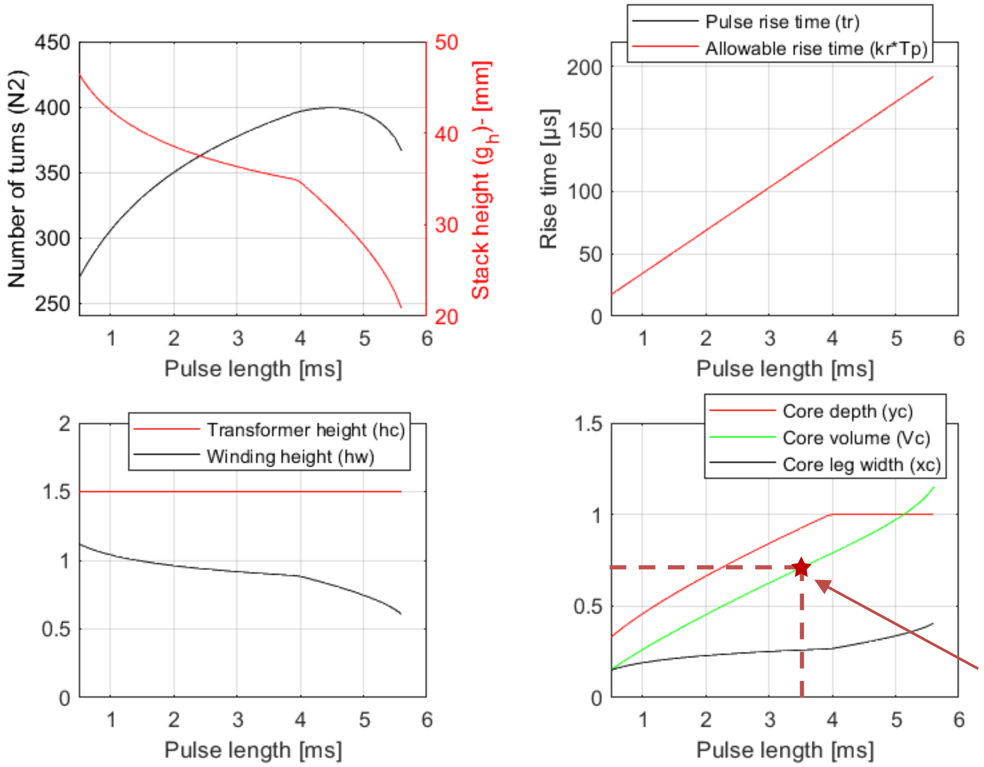
$$\bar{P}_{cu} = 2(\rho_{cu} I T_p f_r) J N [MPL]_{cu}$$

material constant…

given by the application…

mean path length is determined by the cross-sectional area and isolation distances

- *number of turns cannot be increased due to pulse efficiency requirement*
- *number of turns should not be reduced given the transformer size*



magnetic core material volume ~0.75 m³
= core material weight ~5.7 ton…

transformer assembly ~2 m…

+ windings..
+ structures…
+ sensors…
+ …

- ❑ The resulting pulse transformer and associated oil tank assembly is large and unpractical…
- ❑ Resulting efficiency of ~99% is good, but cannot readily be improved..

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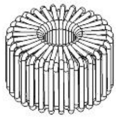
[2] M. Collins and C.A Martins, "Evaluation of Feasibility of High-Power Long-Pulse Transformer Using Single-Layer and Pancake Winding Techniques," IEEE Trans. Plasma Sci., vol. 49, no. 7, pp. 2217-2226, Jun. 2021

PT-based modulator for ESS application requirements (I)

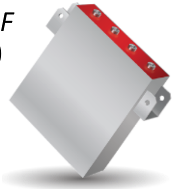
limit flat top ripple&droop < 0.15%

3x bouncer filter inductors
40 µH, 2.5 kA$_{pk}$



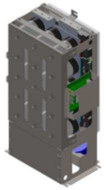
1x input capacitor
38 mF, 1.1 kV, 2.5 kA$_{pk}$

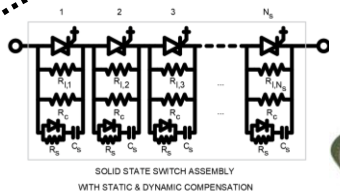
3x13.6 mF = ~40.8 mF
(FFLC, AVX-Kyocera)



1x output capacitor
1 mF, 1 kV

1x multi-phase dc/dc converter
3Φ, 1.1 kV, 2.5 kA$_{pk}$, 20 kHz





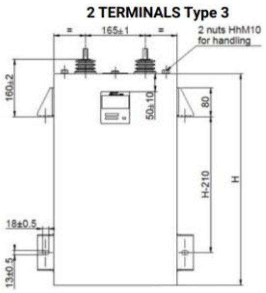
5x IGCT switches
5SHY 35L4522
2.8 kV$_{DC}$, 4 kA$_{pk}$

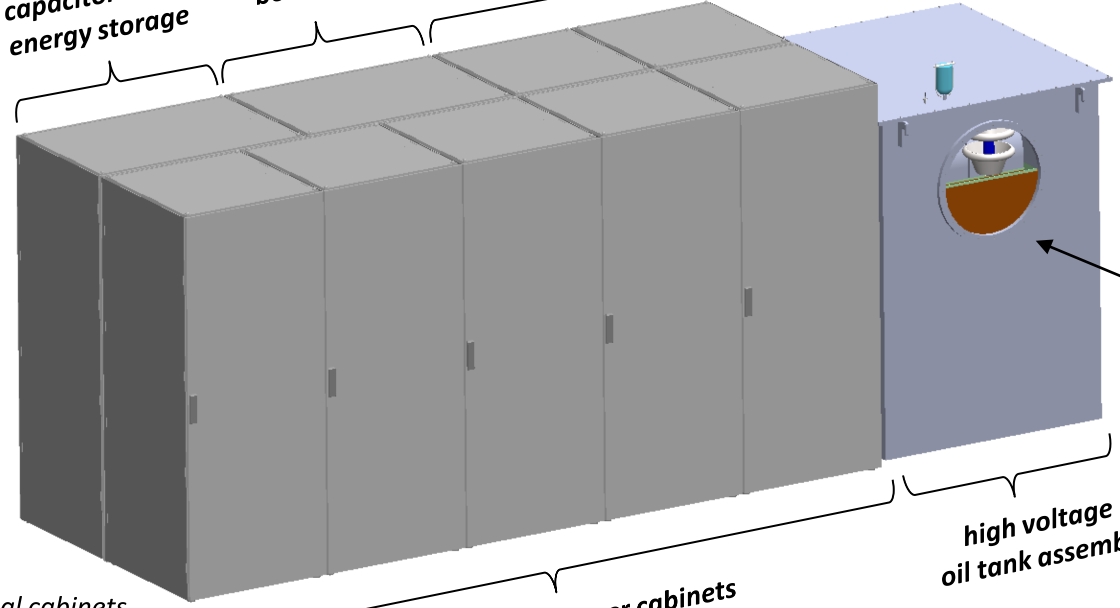
auxiliary switch

15x capacitor
ALS30A222NP500

+ low power supply
+ …

~20% droop
9x910 µF = 8.2 mF
6 kV capacitors
(TRAFIM, AVX-Kyocera)





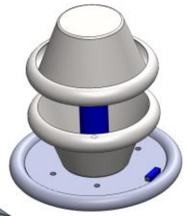
capacitor bank energy storage

electronic bouncer

switch assembly & auxiliary circuits

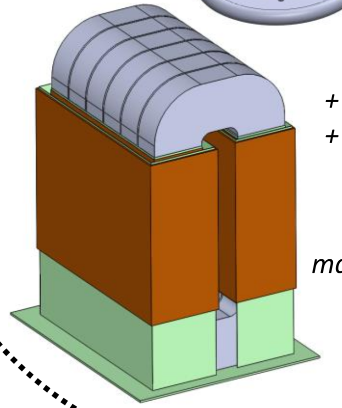
high voltage oil tank assembly

capacitor charger cabinets



HV divider voltage sensor

+ current transformer
+ …



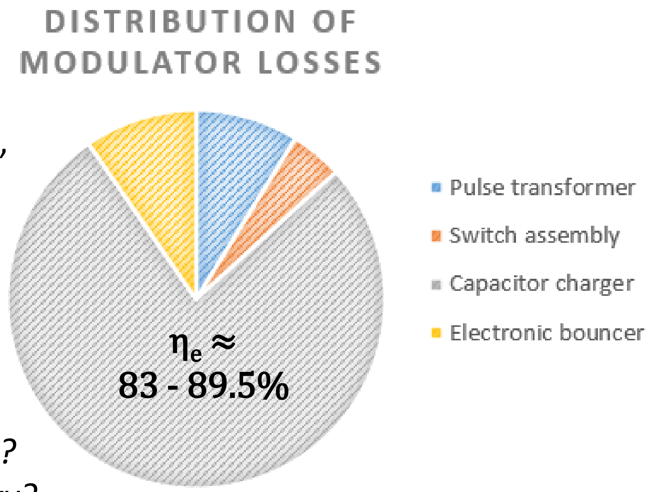
HV long pulse matching transformer

nominal power: 660 kVA
= 5x standard 800x800x2000 electrical cabinets

each cabinet fitted with 2x75 kW or 3x50 kW charger modules
+ controller, junction box, …

PT-based modulator for ESS application requirements (II)

- Modulator electrical efficiency between 83% - 89.5%
- Considerable uncertainty regarding the accuracy of capacitor charger efficiency: “85%-95% under nominal load”
  - Furthermore: impact of harmonics, reactive power, compensators, not operating at nominal power, …?
- Total modulator efficiency is a function of electrical efficiency, waveform factor, and pulse rise time:

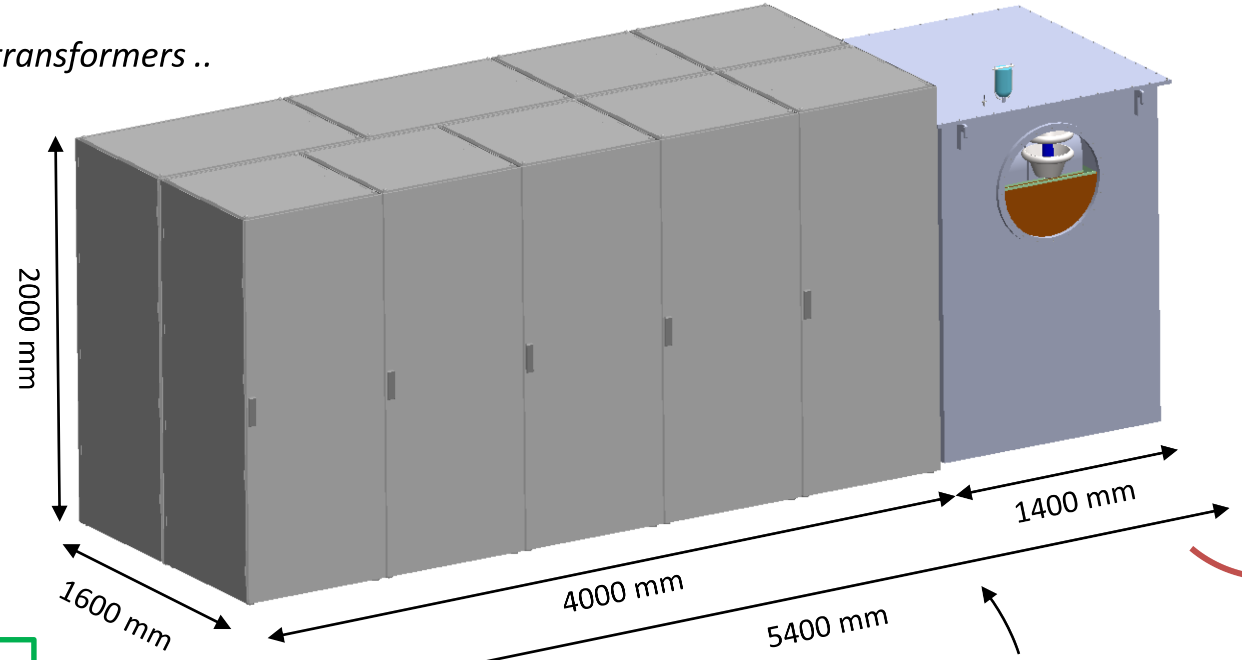


$$\eta_m = f(\eta_e, K, t_r) = \{\ t_r = 120\ \mu s\ \} = 71.2\% - 76.7\%$$

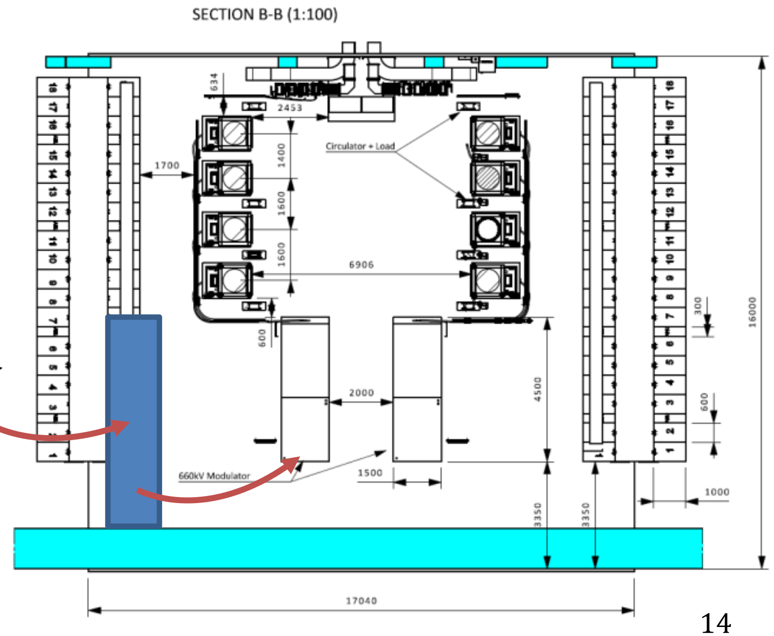
.. but fixed K = 2/3 for long pulse transformers ..

ESS SML modulators: η_m**=78%**
($\eta_e = 90\%$, η_p=86.6%)

… maintainability?
… manufacturability?



.. might not fit in ESS RF gallery ..



ESS SML modulators:
footprint: 1.6 x 4.2 = **6.7 m²**

1.6 x 5.4 = **8.64 m²**
(30% greater than SML modulators)

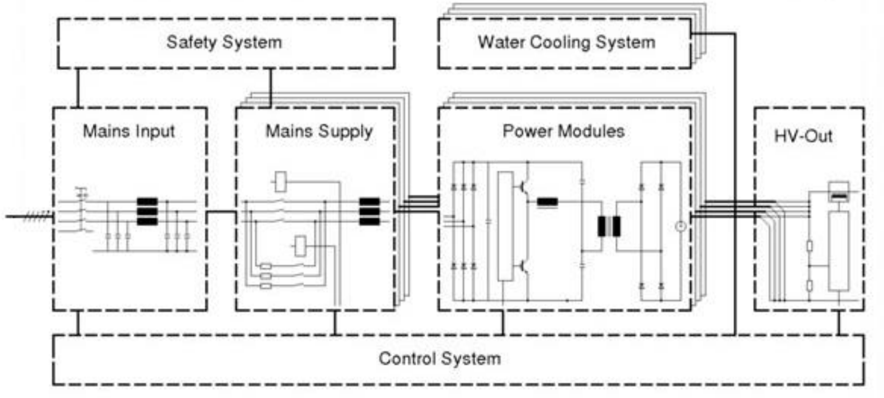
What can we do with respect to modulator efficiency?

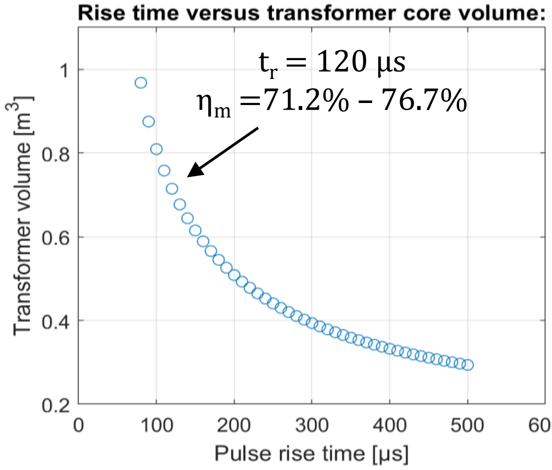
- ☐ Modulator efficiency for pulse transformer-based modulators in long pulse high power applications:

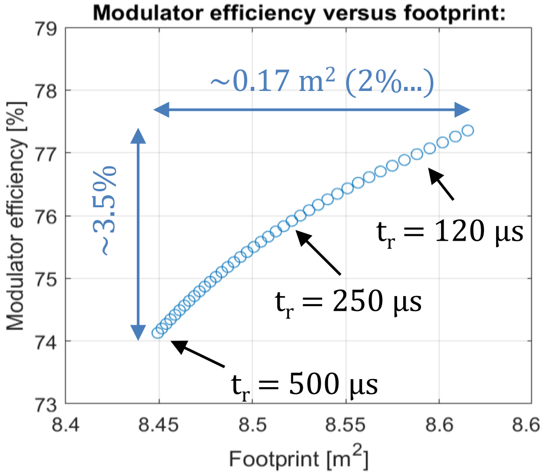
  $\eta_m = f(\eta_e, t_r) = \{ t_r = 120\ \mu s \} = 71.2\% - 76.7\%$

- ☐ Improve electrical efficiency?
  - ☐ Chargers- consider <u>customized charger design</u>? Impact on size? Reliability?
    Still- medium voltage capacitor chargers require at least 4 conversion stages… ?
  - ☐ Switch? ✗
  - ☐ Bouncer? … +0.5% at the expense of doubling the size of the capacitor bank
  - ☐ Pulse transformer? ✗
- ☐ Improve (shorter) rise time?
  - ☐ The existing rise time already severely limits the number of turns, requiring a very large transformer magnetic cross-sectional area.. ✗

capacitor chargers are a strong driver of both modulator size and efficiency







allowing a longer rise time simplies transformer design, but represents a modest reduction in footprint and at a severe reduction in modulator efficiency..

Conclusions

- ❑ The simplicity of the conventional pulse transformer-based modulator topology limits performance in long pulse applications:
  - ❑ The pulse transformer number of turns must be limited to ensure decent pulse efficiency ($\eta_m \sim t_r \sim L_s \sim N^2$ …)
  - ❑ Limiting number of turns requires an enormous magnetic cross-sectional area to handle the flux associated with the long pulse
  - ❑ … = **either very bulky** and impractical pulse transformer, or **poor pulse efficiency** …
- ❑ Fixed electrical efficiency (straightforward system design…)
- ❑ **Capacitor charger is a strong driver of both system volume and system electrical efficiency**; <u>opportunity for improvement?</u>
- ❑ Pulse transformer-based modulator topology **cannot easily be scaled** for increased pulse repetition rate/pulse length/average power/… in view of long pulse high power applications

- ❑ **SML-type modulators**, specifically developed for long pulse applications, are (topologically) more complex, but **allow greater freedom in design**
  - ❑ Can vary, e.g., the combination of switching frequency/number of output modules/filter parameters/… in design
- ❑ SML modulators allow capacitor chargers based on standardized low voltage semiconductors = **improved efficiency and volume**
- ❑ The SML topology is based on a pulse modulation/demodulation scheme…
  - ❑ **Decouples modulator size from pulse length**
  - ❑ **Significantly simpler to scale up** in terms of increased pulse repetition rate/pulse length/average power/…