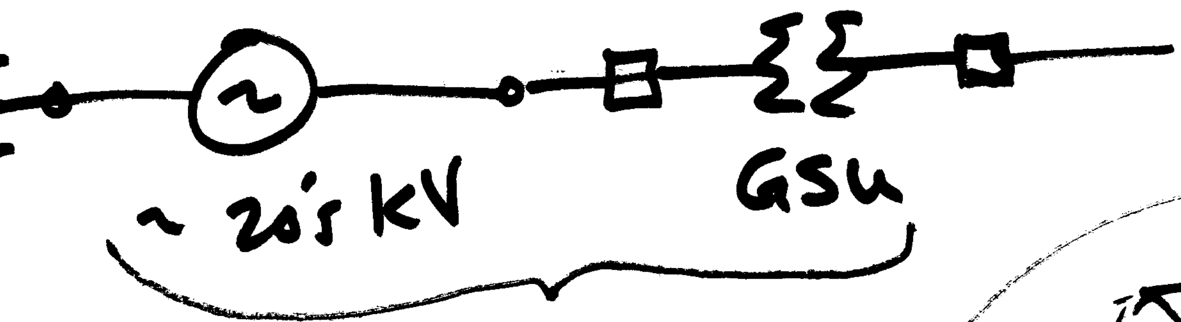
EE 5223 - Lecture 34

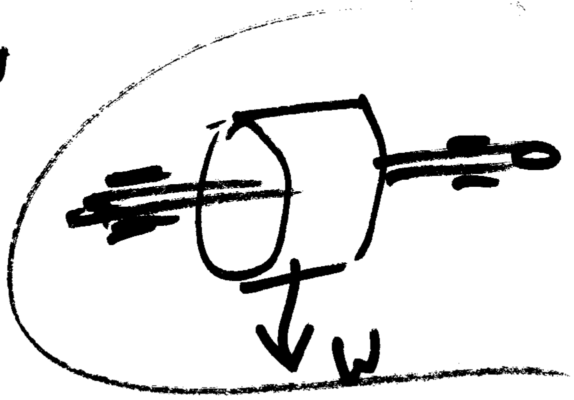
Mon April 3, 2023

Ongoing List of Topics:

- URL: https://pages.mtu.edu/~bamork/EE5223/index.htm
- Term Project
    - Follow timeline, see posting on web page
    - Formal outline w/complete references complete, get/keep cranking...
- Homework
    - Problem 10.1 -one short calc, big concept
- Volts/Hz protection for generators and unit transformers
- Protection of Shunt Capacitor Banks (print out “Cap Bank Prot” at Week 12)
    - Basic protection concerns.
    - Capacitor “can” design - externally fused, internally fused, fuseless.
    - 115-kV example: https://pages.mtu.edu/~bamork/EE5223/115kVcapsElev2.JPG
    - Cap bank configuration, design calculations.
    - Implications of failure of individual capacitor elements.
    - Cascading failure.
    - Protection strategies for wye-connected cap bank.
- Next:
    - Overview of Cap Bank protection strategies for various configurations
    - Example - calc spreadsheet set up for externally fused grounded-wye.



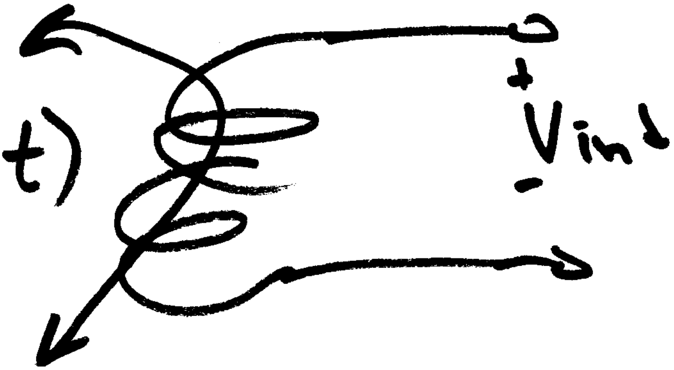
$\frac{V}{Hz}$ protection



$$\boxed{E_{RMS} = \underline{4.44}\, f\, B\, \underline{\underline{A}}\, \underline{\underline{N}}} \Rightarrow$$

$E \propto f B$

$\underline{\underline{B}} \propto \frac{E}{f}$



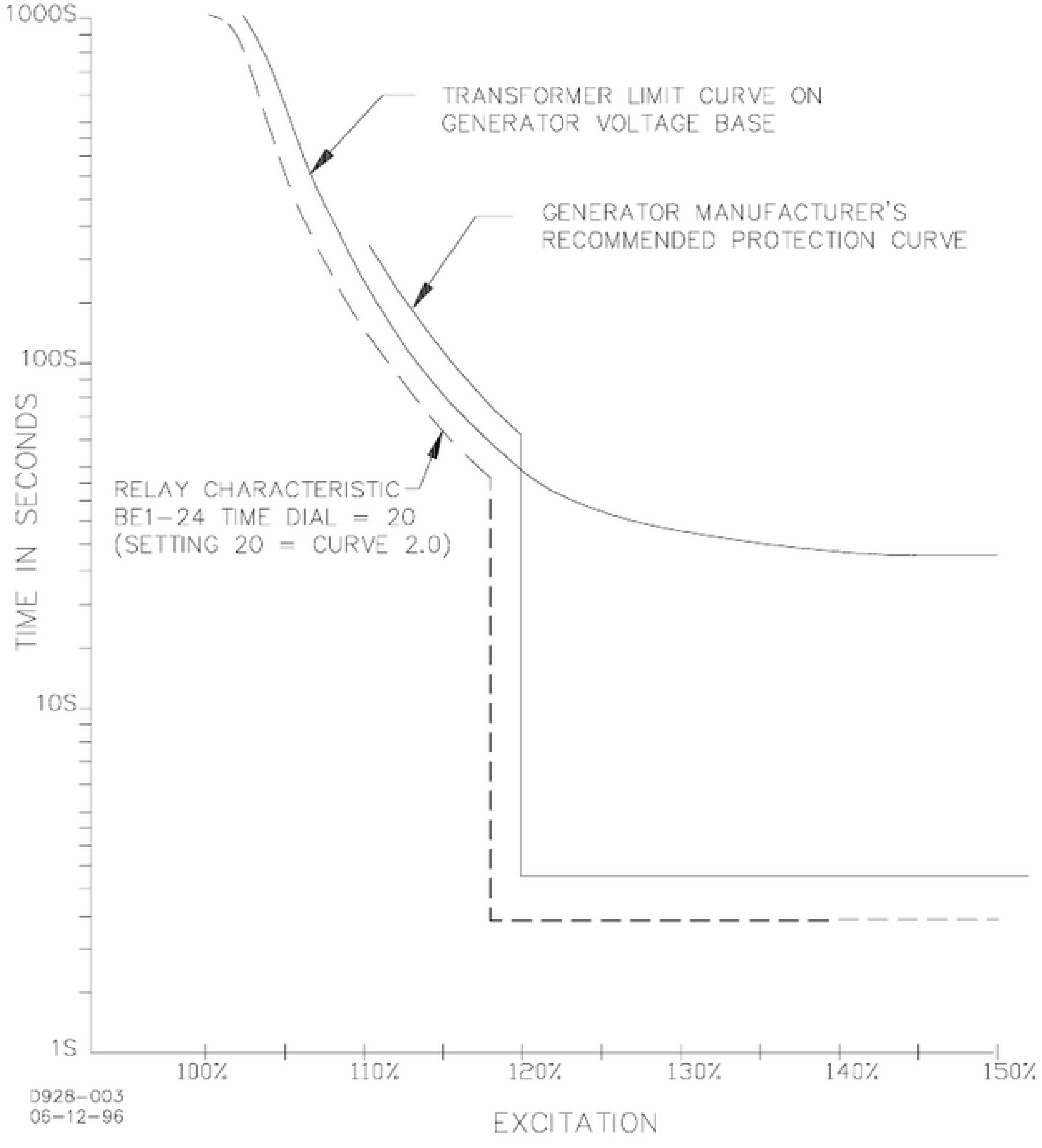


Figure 1-2. Protection Characteristics of the BE1-24

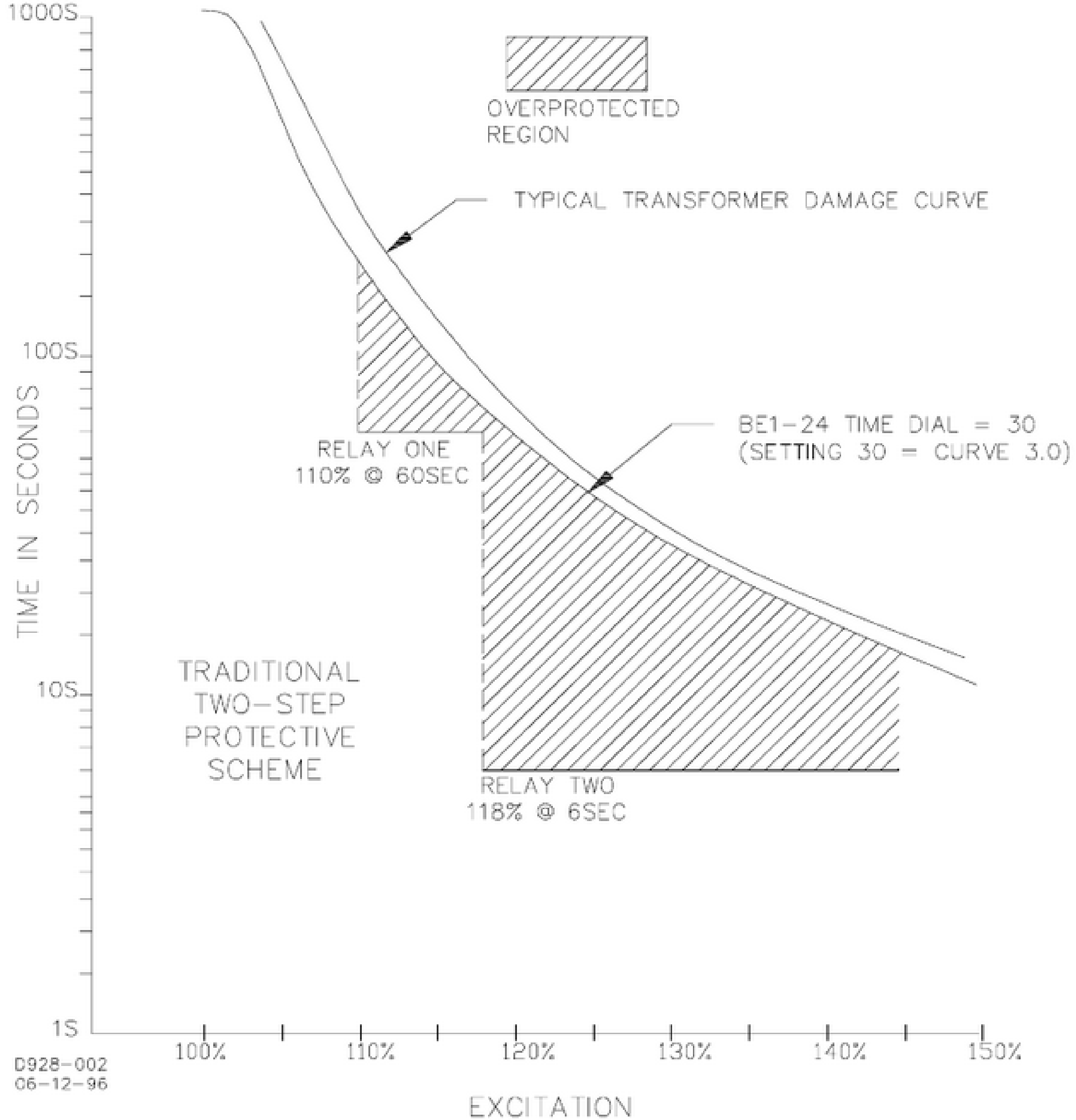
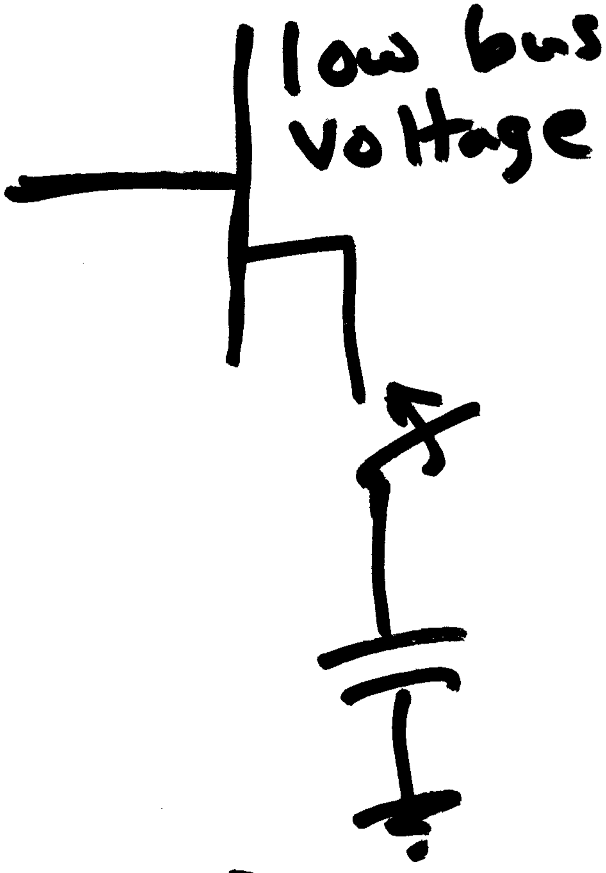
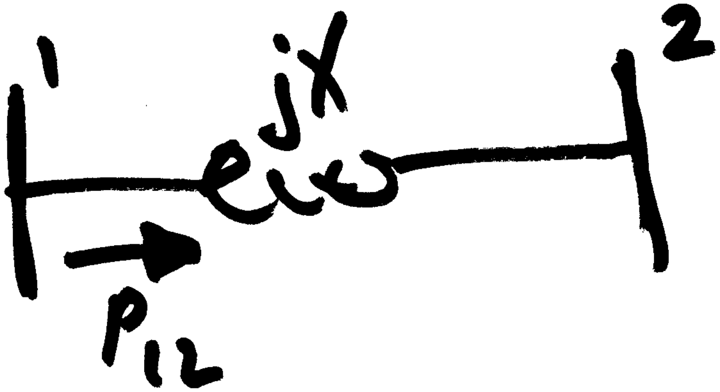


Figure 1-1. Inverse Square vs. Two-Step

Shunt Cap Banks

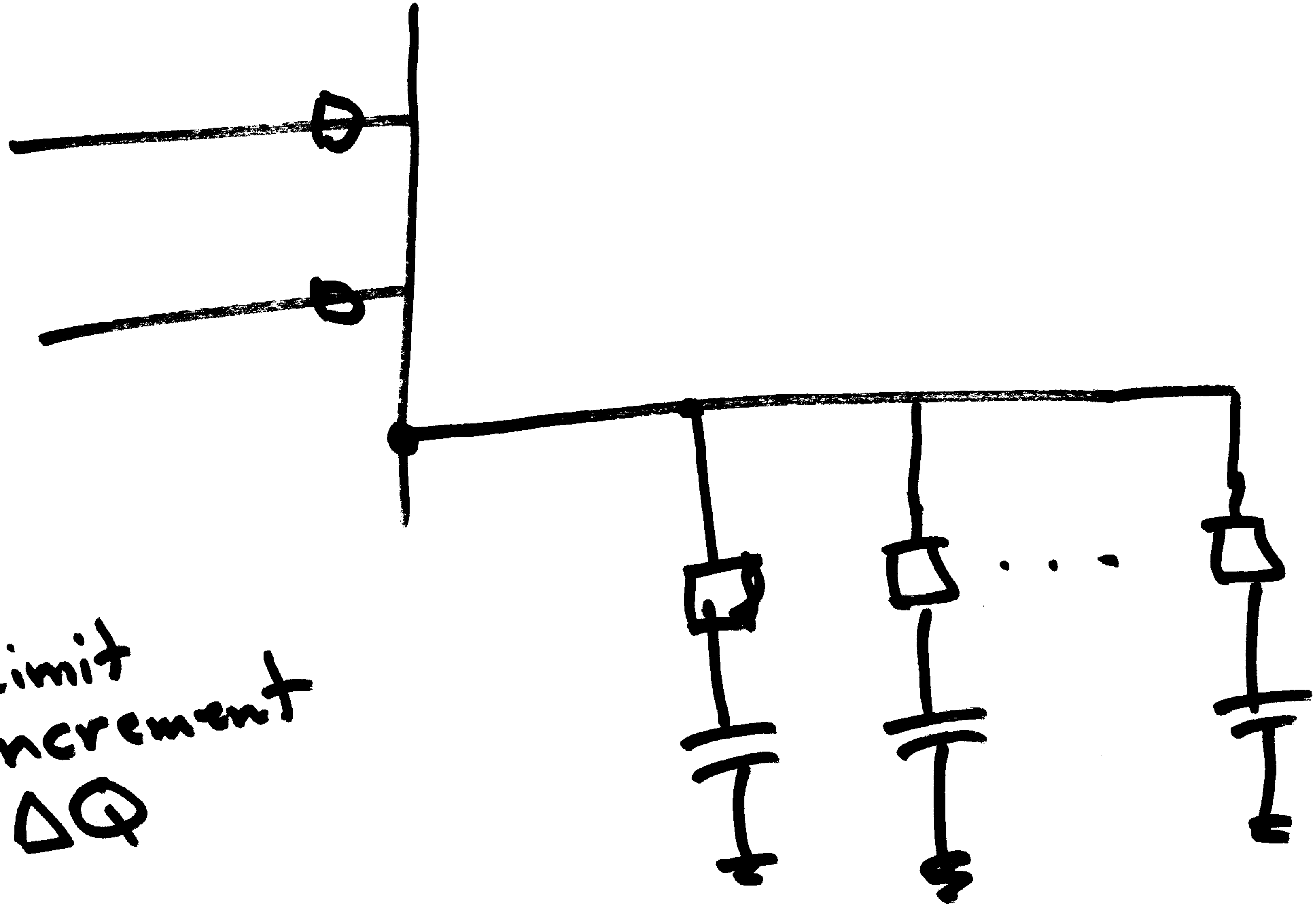
- P.F. Correction (Customer Side of meter).
- Voltage Support
- Power Transfer





$$P_{12} = \frac{V_1 V_2}{X} \sin(\delta_1 - \delta_2)$$

$$\left(\frac{1.05}{.95}\right)^2 = \underline{\underline{1.22}}$$



- Limit increment ΔQ

Long experience and extensive R&D ensure high quality capacitors

The HiQ capacitors are available in sizes up to 1200 kvar per unit (at 50 Hz), characterized by negligible losses and high reliability. The capacitors consists of thin dielectric polypropylene film wound together with electrodes of aluminium foils.

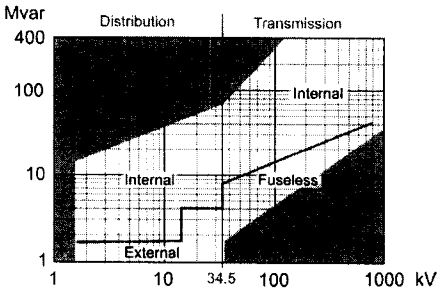
A bio-degradable hydrocarbon compound with excellent electrical properties is used as the impregnation fluid. The container is of surface-treated high-quality steel and the bushings and terminals are of the highest quality and reliability.

Different fuse technologies
HiQ capacitor units are available with Internal or External Fuses or Fuseless.

Fusing
A high voltage capacitor unit is made up of a number of elements, each consisting of very thin layers of dielectric materials and thin foils of aluminium as electrodes. The elements are stacked inside the capacitor container and connected in series and parallel to accommodate the voltage and capacitance rating specified for the whole capacitor unit.

The dielectric materials in modern high voltage capacitors are utilized electrically to their maximum and the operating stress is typically very high compared to other power electric products. The long term aging take place in some "weak spots" that are always present in the dielectric. The dielectric is certainly the most influencing factor for the reliability of the whole capacitor or capacitor bank. However, it is also very much depending on the fuse technology and the unbalance protection arrangements.

Choice of technology
The choice of suitable fusing technique is due to voltage and power as shown in the diagram below:



More information concerning the different fusing techniques under the design tab.

HiQ is a single-phase power capacitor of the all film type, with very low dielectric losses and long lifetime. The capacitors are impregnated with Faradol, a bio-degradable, non-PCB fluid with a high insulation strength. The edges of the electrode foils are folded, enabling higher electrical stress. The ABB capacitor units have an extremely low failure rate and high reliability.

The HiQ capacitor container is made of ferritic stainless steel and painted with corrosion resistant paint. This protects the container for many years in service. The porcelain bushings are welded onto the container to prevent fluid leaks.

Different fuse technologies

HiQ capacitor units are available with Internal or External Fuses or Fuseless.

Internally Fused Concept

When it comes to internally fused capacitors, ABB is recognized as the world leader with over 50 years of experience. The internal fuses are current-limiting fuses in action. One fuse is connected in series with each element within the capacitor. They are designed and coordinated to isolate internal faults at the element level and allow continued operation of the remaining elements of that capacitor unit. This results in a very small part of the capacitor being disconnected; therefore, the capacitor and the bank remain in service. The fundamental concept is that by dividing a large system into small, individually protected elements, the overall reliability is greatly enhanced. Advantages include higher reliability, less space, lower installation and maintenance costs, and fewer live parts.

Externally Fused Concept

This design has been the technology of choice in North America for over 70 years due to its simplicity. The bank consists of many capacitor units connected in parallel. Each unit has its own fuse to disconnect a failed capacitor unit from the bank. Once a capacitor unit is removed, an overvoltage on the remaining parallel capacitors results. This overvoltage must be limited to a maximum value of 110% voltage, or the bank must be tripped offline. Concerns with excessive parallel energy and fuse limitations require the capacitors to be relatively small (average of 200 kvar). Although the external fuses provide a visual indication of a failure, banks tend to occupy more substation space, are more expensive, have many live parts subject to possible damage by animals, and have higher installation and maintenance costs.

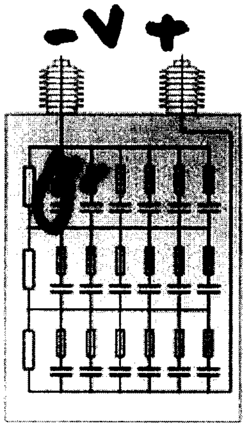
Fuseless Concept - conventional

This concept was developed by ABB in the 1980s and is a result of the high reliability of today's all film dielectric where capacitor case ruptures are a rare event. The internal design of fuseless capacitors (many elements in series) combined with the method by which the banks are connected (many "strings" of capacitor units in series), account for this design's excellent performance. A bank containing failed elements will operate continuously and withstand switching transients without rupturing the capacitor case. This is possible due to a strong welding of the two foil electrodes within the failed element; therefore, diminishing
the possibility of continued arcing. Extensive field experience has conclusively proven that fuseless capacitor banks are highly reliable. Compared to other technologies, fuseless banks are most effectively applied at 35 kV and above. Advantages include reduced cost, less space, fewer live parts,
vermin resistant, lower losses, and lower installation and maintenance costs.

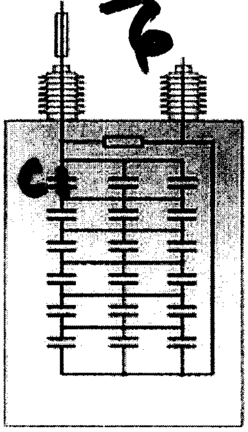
Fuseless Concept - internal strings

As an alternative to the conventional fuseless concept ABB has developed a fuseless design based on a different internal connection of the element matrix. The elements are connected in parallel strings which has the benefits of less capacitance deviation at element failure, limitation of parallel energy inside the capacitance deviation at element failure, limitation of parallel energy inside the unit and normal bank connection can be used. This technology does not restrict the capacitor unit size.

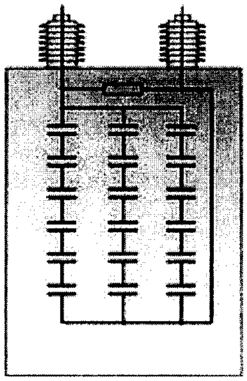
$\frac{3C}{6} = C_{TOT}$



Internally fused unit



Externally fused unit

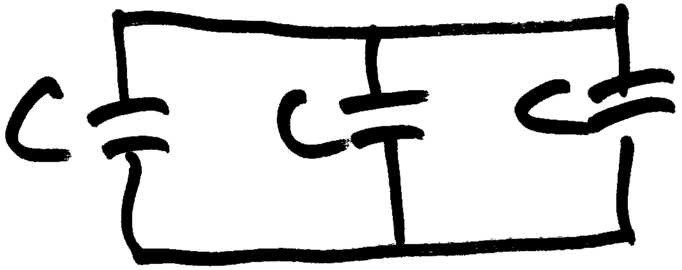


Fuseless unit

ABB Advantages:

- Welded bushing and solid terminal stud prevents fluid leaks
- Folded foil electrodes reduce partial discharge generation
- Extended foils are soldered, providing superior internal connections
- Superior paint system with oven cured process
- Nameplate includes microfarads for easy field testing
- Nameplate positioned on cover for easy reading
- Impregnation process under vacuum to ensure lowest possible humidity content

$$C_{TOT} = \frac{1}{\frac{1}{3C} + \frac{1}{3C} + \frac{1}{3C} + \frac{1}{3C} + \frac{1}{3C} + \frac{1}{2C}}$$



$N_p = 3$

$-jX_{c\,(\text{indv})} = \frac{1}{j\omega C}$

$Z_{parall} = \frac{1}{j\omega 3C}$

internally fused:

$N_p = 2$

$Z_{parall} = \frac{1}{j\omega 2C}$

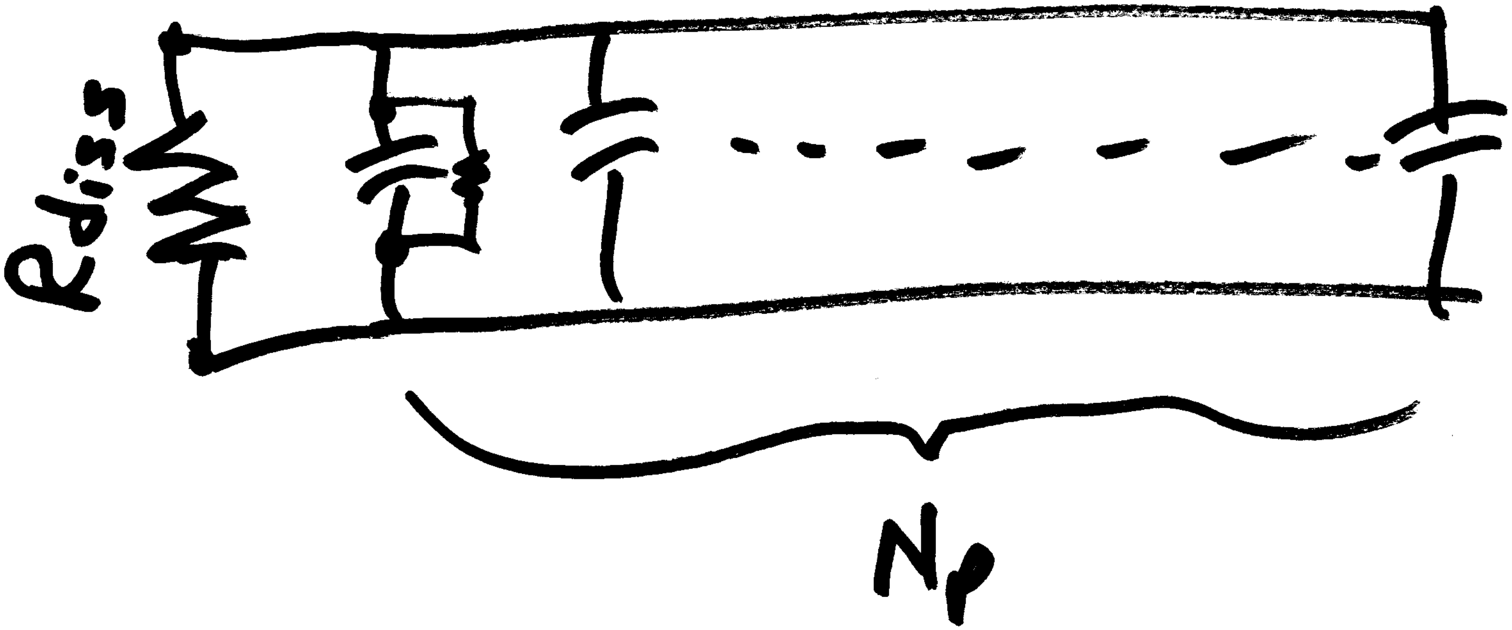
$V_{parall} = \frac{V_{TOT}}{N_s}$

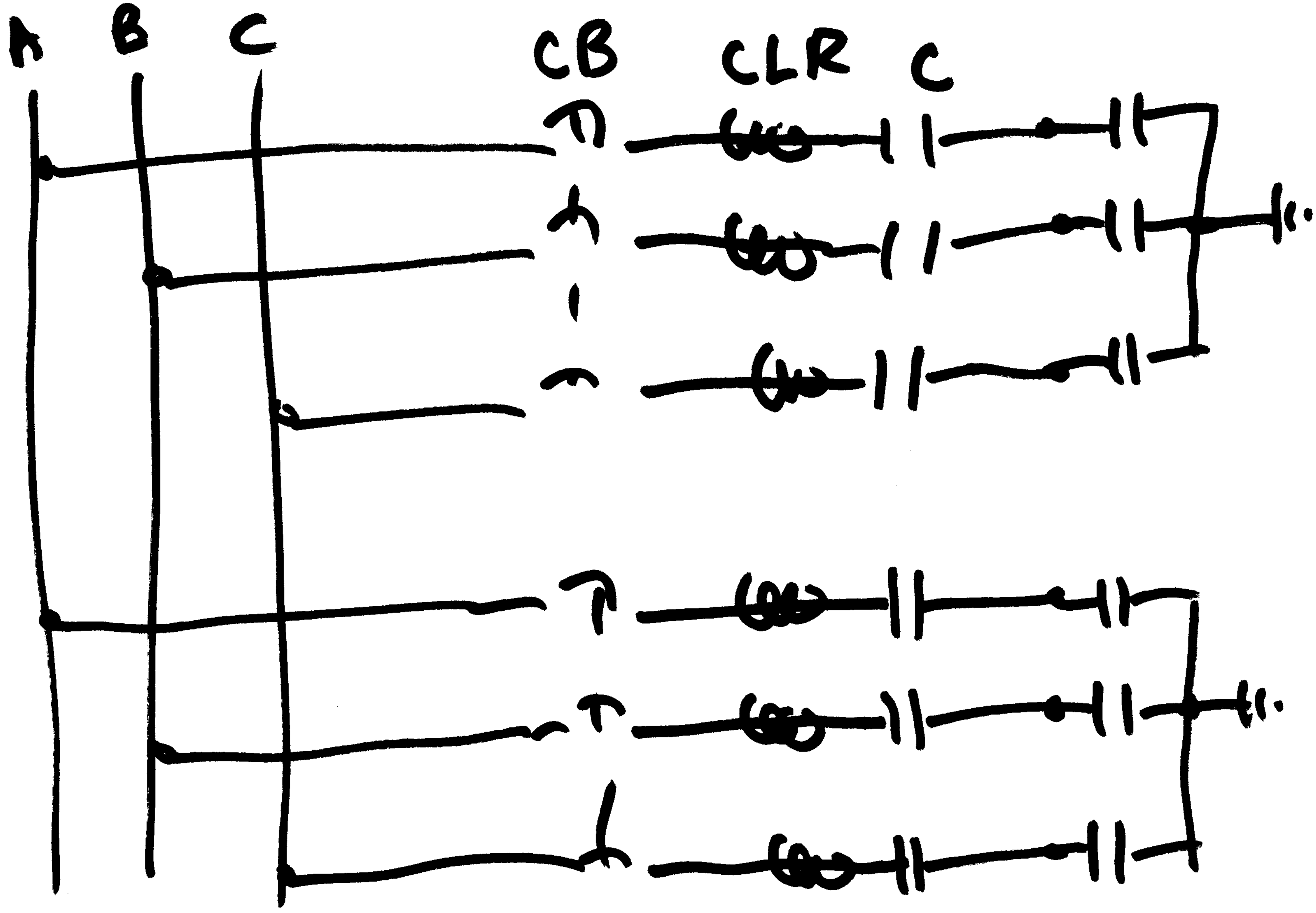
Z increases with loss of caps

Z↑ as N_p↓

Cascading Failure:

- Voltage on remaining Caps > 110% of voltage rating.





"Fuseless"
Cap Bank

Protection Issues

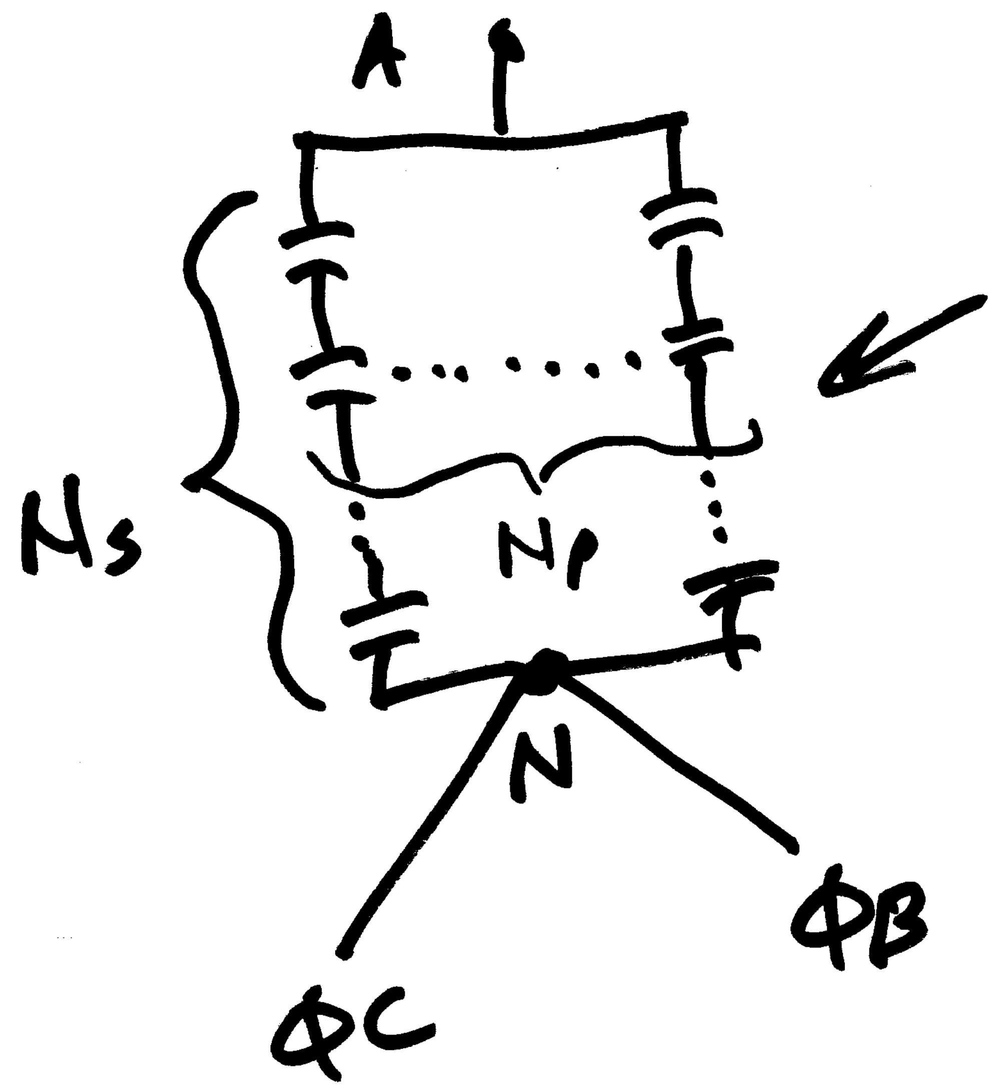
- Fused - interrupt w/fuse (ext. or int.)
- Fuseless or unfused - hope they "~~fail open~~": fail shorted.
- Major Problems to protect Bank against
  - Harmonics
  - Cascaded Failure
  - Be aware of transients
  - S.S. overvoltages ≥ 1.10 p.u. of can's rating.

M Sound Strategy

- Monitor bank for shifts in voltages on series sections.
  - Issue alarm for change in V.
  - Trip if V is <u>too</u> close to 1.1 p.u. for comfort (or exceeds).

<u>Note:</u> <u>FIRST</u>, print out "<u>CAP BANK PROT</u>" from week [redacted] on course web page!

Cap Bank MVAR



1/3 of Total MVars

Cans:

$$\frac{\text{Cans:}}{V_{Rated}} \geq \frac{V_{LN}}{N_s}$$

$$Q_{can} = \frac{V_{can}^2}{X_{can}}$$

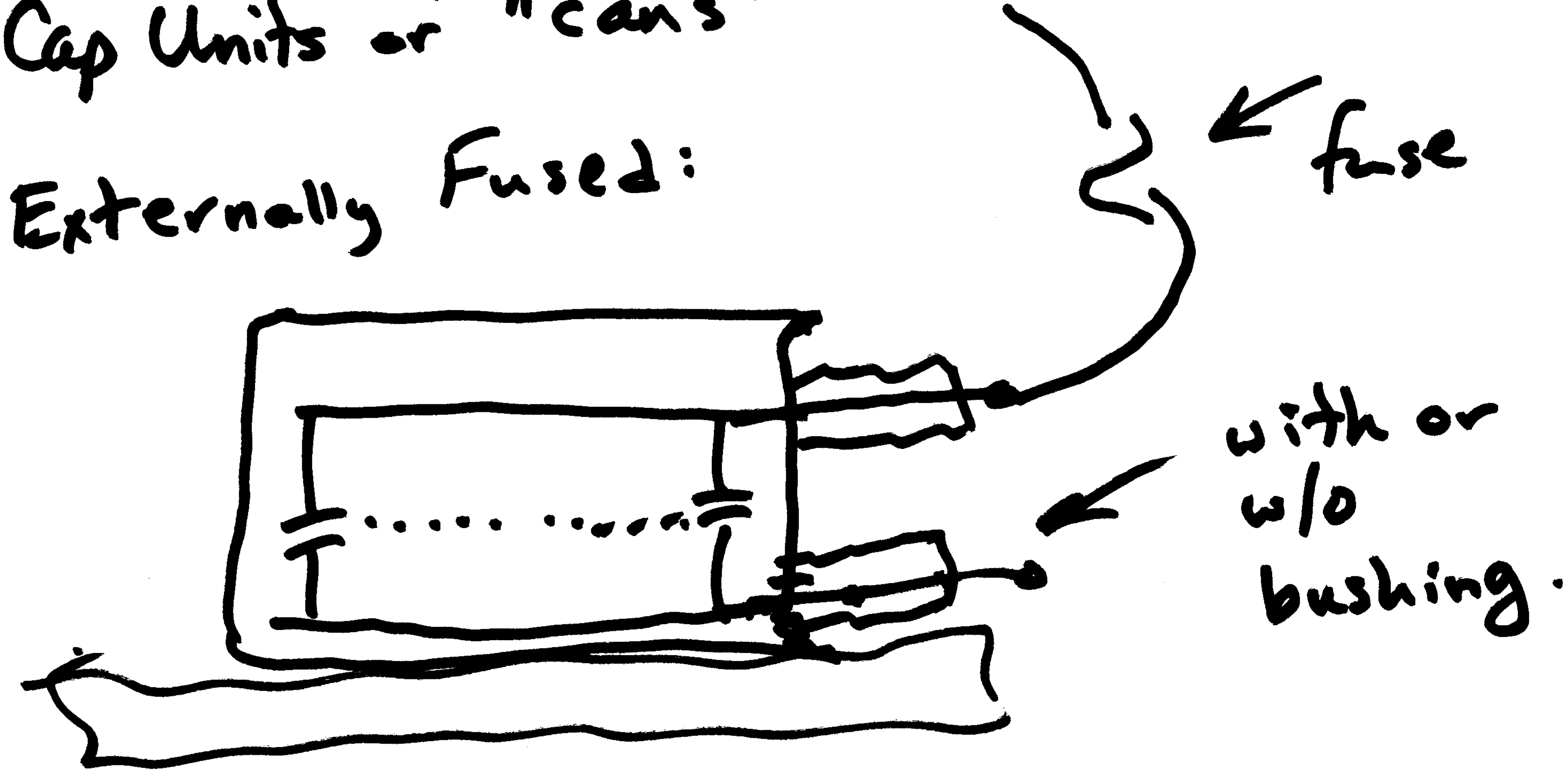
$$Q_{can} = \frac{(V_{LN}/N_s)^2}{X_{can}}$$

$$Q_{\text{series string}} = N_s Q_{can}$$

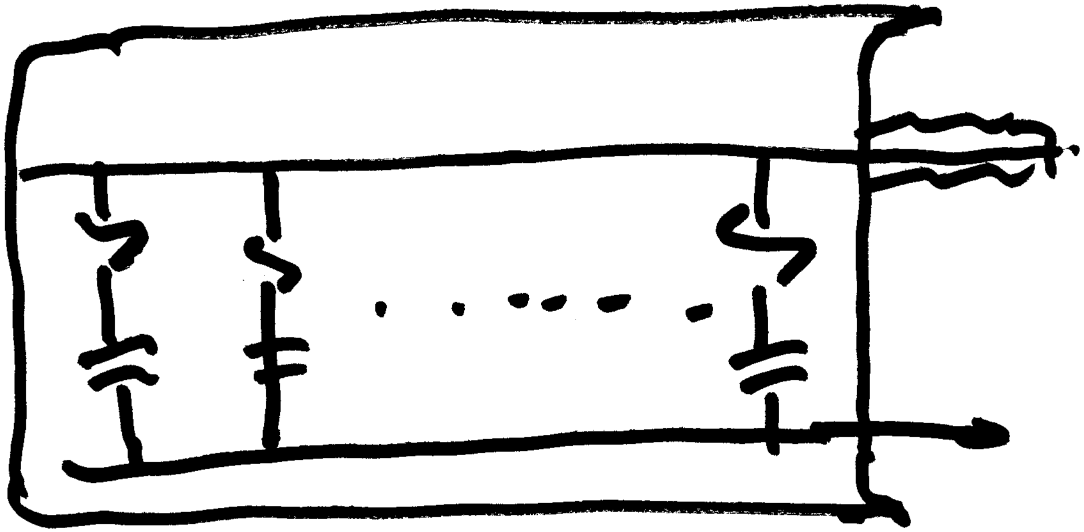
$$Q_{phase} = Q_{series} \times N_p \leftarrow Q_{\text{series string}}$$

Cap Units or "cans"

Externally Fused:



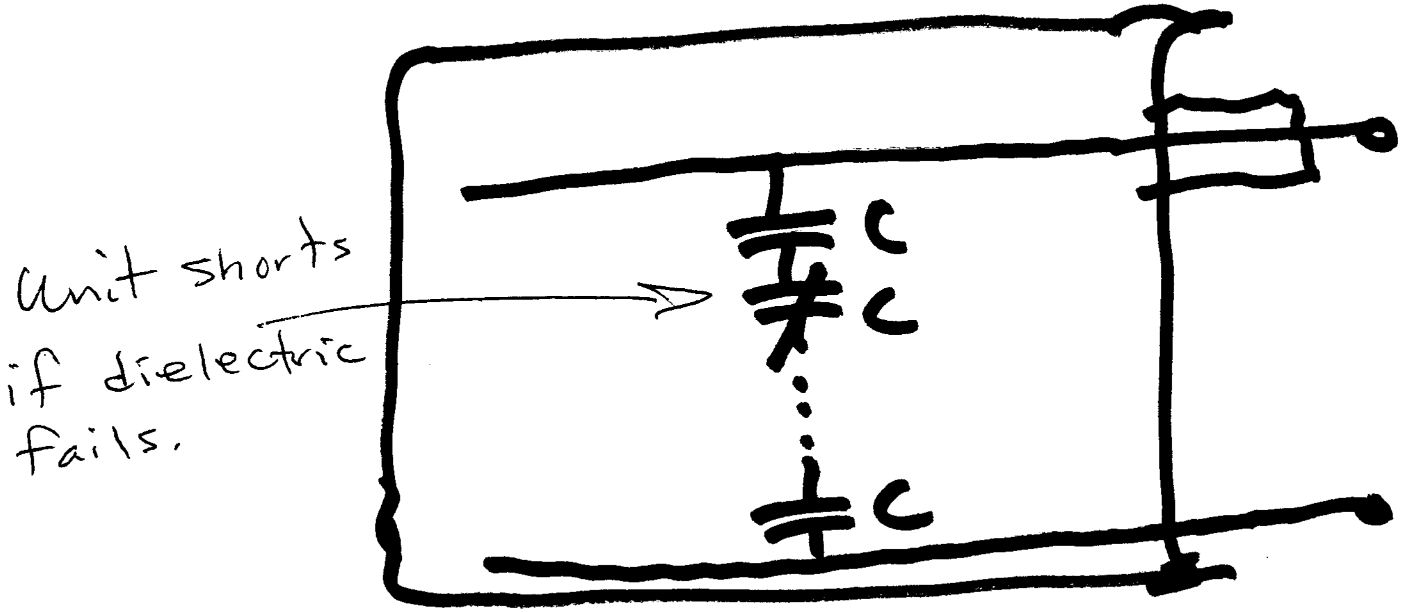
Internally Fused



$C_{TOT} = n \times C$

$C_{TOT}\downarrow$ if we lose one or more Indiv. Cs.

Fuseless Caps



Unit shorts if dielectric fails.

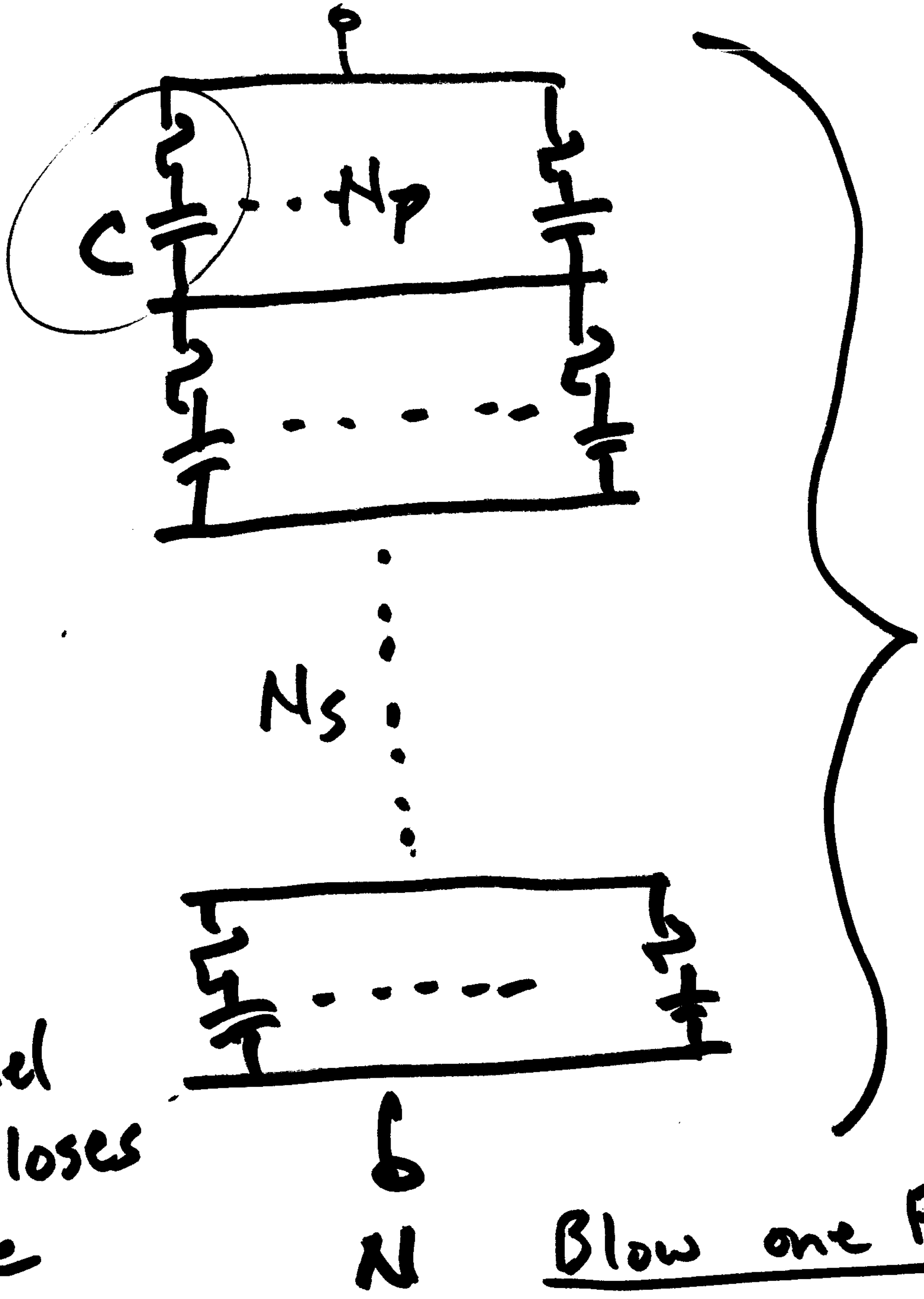
$$C_{TOT} = \frac{c}{n} = \frac{c}{6}$$

Ex: if $n = 6$ and we "lose" one, then $C_{TOT} = \frac{c}{5}$

Fused:

$X_c = \frac{1}{\omega C}$

$\bar{Z} = -jX_c$



$X_{c,PHASE}$

$= \left[X_c / N_p\right] N_s$

Conclusion:

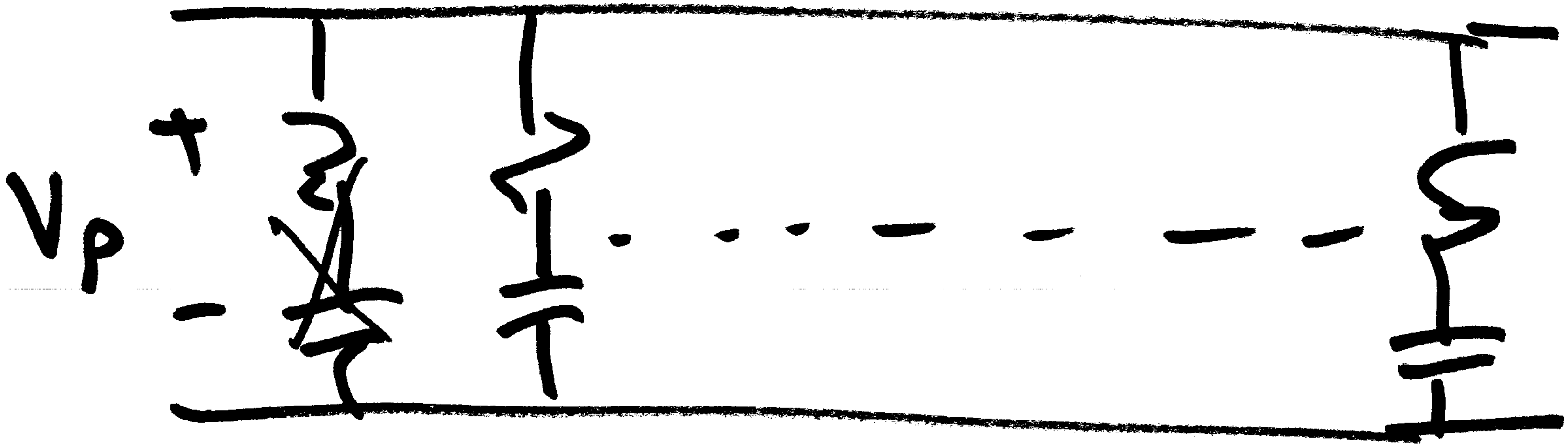
V↑ on parallel group that loses one or more caps!

Blow one Fuse:

$X_{c,PHASE} = \left[\frac{X_c}{N_p}\right](N_s - 1) + \frac{X_c}{(N_p - 1)}$

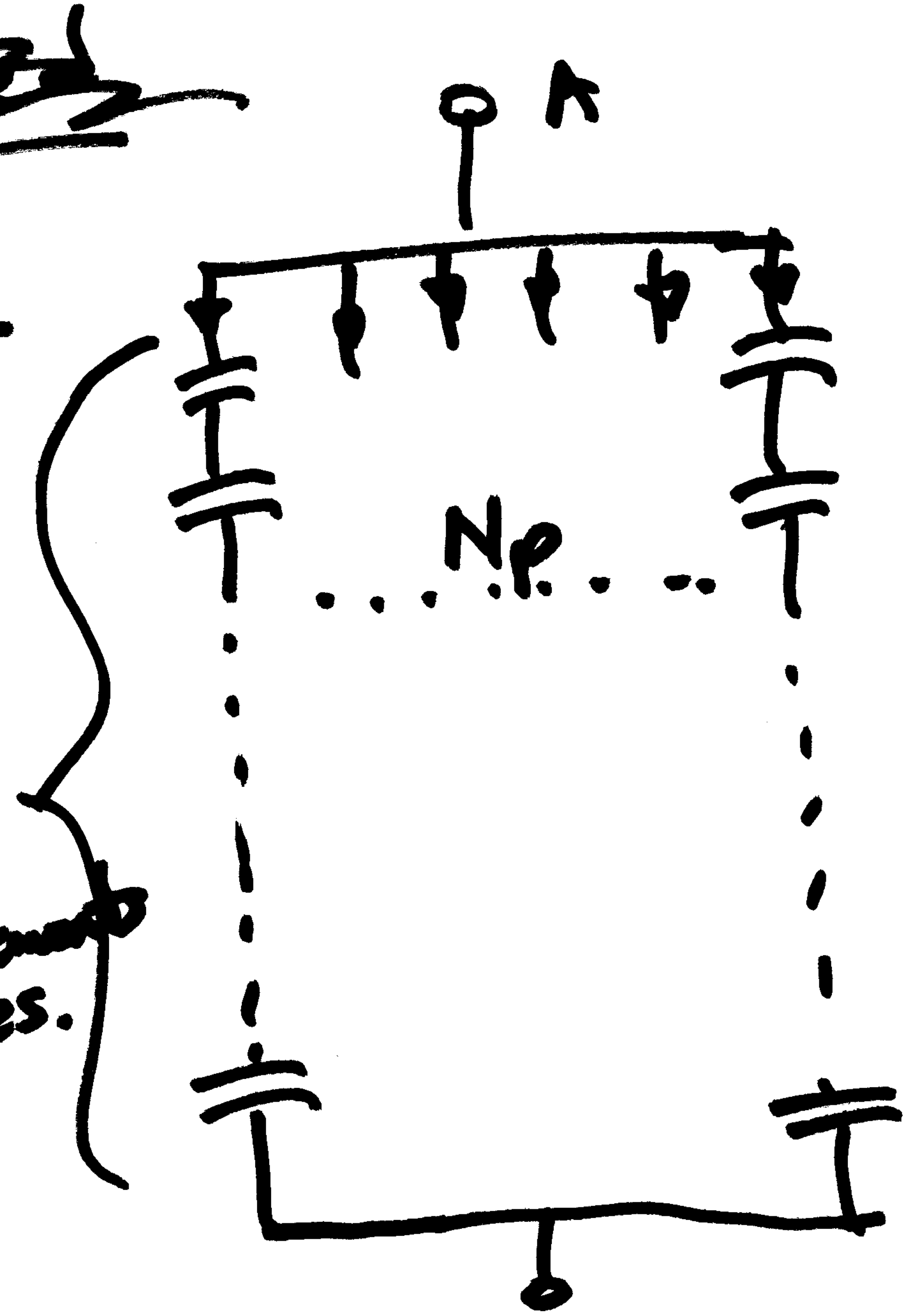
Cascading Failure:

parallel group



remaining caps stressed more than before, i.e. V_p increases.
V_p increase is much less for int. fused.

Fuseless



36 Cap Elements in series.

Ex: 120-KV, $N_s = 6$, $N_{int} = 6$
$N_p = 6$