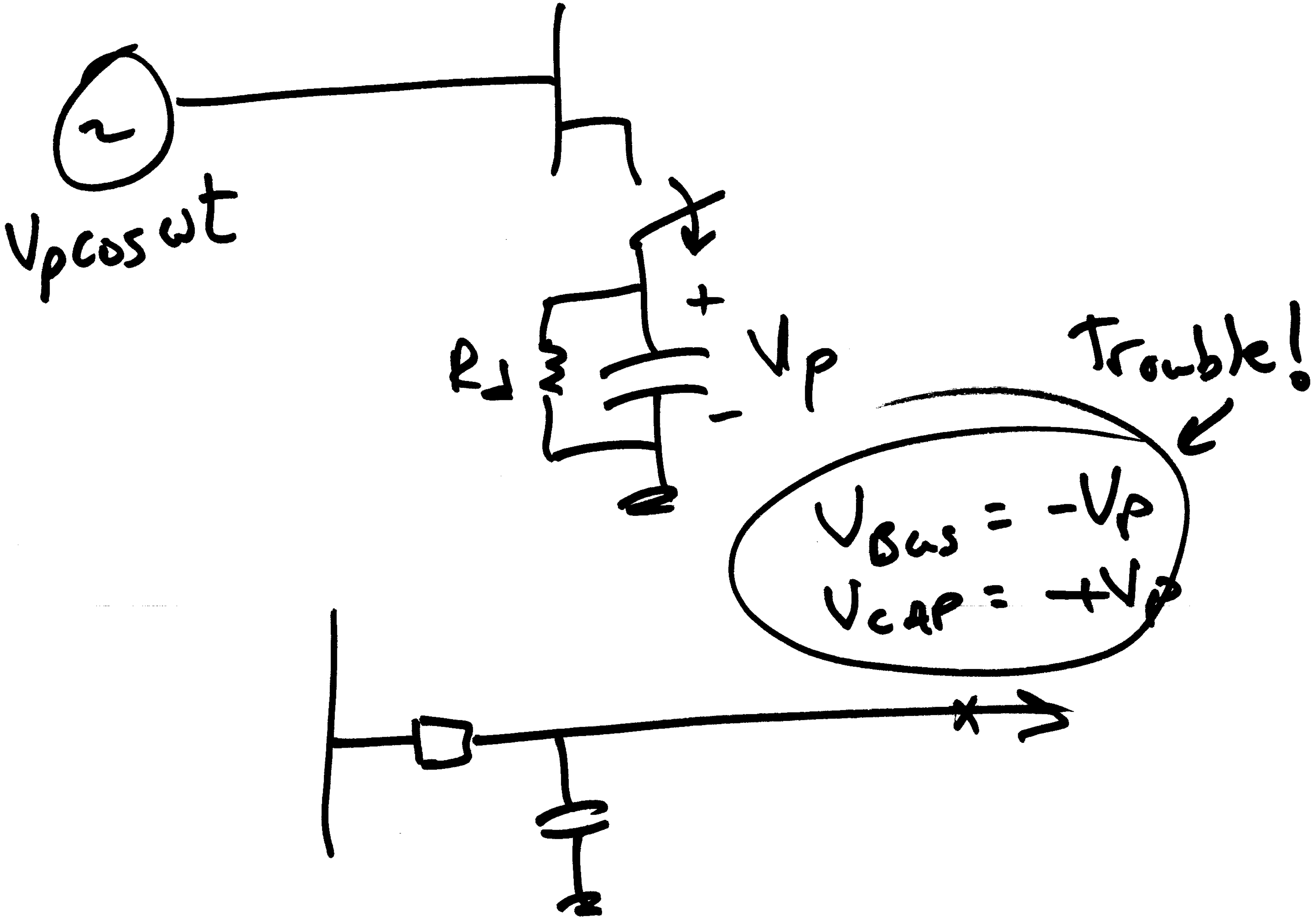
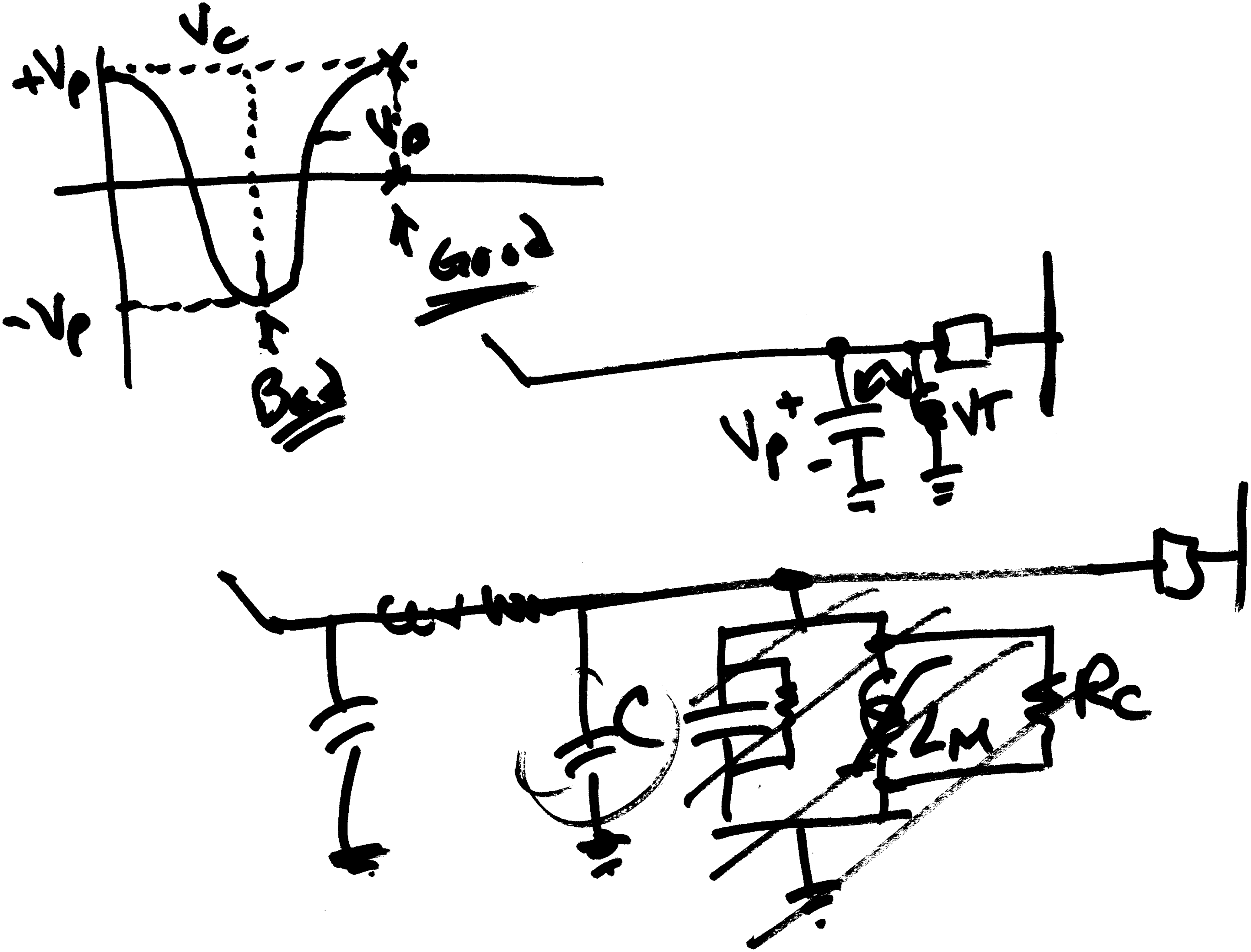
# EE 5223 - Lecture 37

Monday April 10, 2023

## Ongoing List of Topics:

- URL: https://pages.mtu.edu/~bamork/EE5223/
- Term Project -
  - Follow timeline, see posting on web page
  - Formal outline w/complete references complete, get/keep cranking...
- Cap Bank configuration & protection - main topics completed
- Protection of Shunt Capacitor Banks (print out “Cap Bank Prot” at Week 12)
  - Basic Methods of protection - IEEE C37.99-2012
  - Capacitor Bank Switching Transients - IEEE Pub 93EHO388-9-PWR
    - Energization Inrush (first bank)
    - Back-to-back energization
    - Outrush
    - Transient Recovery Voltage (TRV)
    - Voltage Magnification
- Next:
  - Gen Protection - Ch. 8, IEEE Publication 95TP102 - Prot of Synch Gens
  - Motor Protection
  - Electric Vehicle Charging Station Protection
  - Real-time Communications, SCADA Protocols
  - Smart Grid, IEC 61850 (substation automation), Wide Area Protection


Vpcos ωt
Rd
+
Vp
−
Trouble!
VBus = −Vp
VCAP = +Vp
x


Vc
+Vp
Vp
-Vp
Good
Bad
Vp
+
-
VT
C
LM
RC

**Capacitor Bank Design and Protection**

Bruce Mork 11.Apr.2007
Michigan Tech University

**Bank Specification:**

Grounded-Wye Bank

| | | |
|---|---|---|
| L-L System Voltage: | 138 | kV |
| Size of Bank: | 80 | MVAR |

**Can Specs:**

| | | |
|---|---|---|
| Voltage: | 13.28 | kV |
| Rating: | 200 | kVAR |
| Loss: | 0.1 | W/kVAR |
| Capacitance: | 3.008 | uFarads |
| Impedance: | 881.79 | Ohms |
| Current: | 15.06 | Amps |
| Diss Ohms: | 8.818 | MOhms |

**Configuration:**

| | Calc | Chosen | |
|---|---|---|---|
| Total No. Cans: | 400.00 | 414 | Cans |
| No. Cans/Phase: | 133.33 | 138 | Cans/Ph |
| Series Groups/Phase: | 6.00 | 6 | |
| Parallel Cans/Group: | 22.22 | 23 | |
| Impedance/Group: | | 38.34 | Ohms |
| Impedance/Phase: | | 230.03 | Ohms |
| Diss Ohms/Phase: | | 2.300 | MOhms |
| Discharge RC Time Constant: | | 26.53 | Secs |

**Performance:**

| System Voltage, pu: | **0.95** | **1.00** | **1.05** | |
|---|---|---|---|---|
| Total MVAR | 74.72 | 82.79 | 91.27 | |
| Line Current, Amps: | 329.04 | 346.36 | 363.68 | |
| Voltage/Group, kV: | 12.615 | 13.279 | 13.943 | |
| Voltage/Group, pu: | 0.950 | 1.000 | 1.050 | |
| Losses, kW: | 7.472 | 8.279 | 9.127 | kW |
| Dischg Time to 50V: | 203.43 | 204.79 | 206.08 | Seconds |

**Group Voltages:**

| | kV | V |
|---|---|---|
| VT Ratio: | 13.279 | 120 |

1 Blown Fuses

| | | | | |
|---|---|---|---|---|
| This Group: | 13.089 | 13.778 | 14.467 | kV |
| | 0.986 | 1.038 | 1.089 | Per Unit |
| | 118.29 | 124.51 | 130.74 | VT Sec Volts |
| Other Groups: | 12.520 | 13.179 | 13.838 | kV |
| | 0.943 | 0.992 | 1.042 | Per Unit |
| | 113.14 | 119.10 | 125.05 | VT Sec Volts |

3 Blown Fuses

| | | | | |
|---|---|---|---|---|
| This Group: | 14.154 | 14.898 | 15.643 | kV |
| | 1.066 | 1.122 | 1.178 | Per Unit |
| | 127.90 | 134.63 | 141.37 | VT Sec Volts |
| Other Groups: | 12.307 | 12.955 | 13.603 | kV |
| | 0.927 | 0.976 | 1.024 | Per Unit |
| | 111.22 | 117.07 | 122.93 | VT Sec Volts |

4 Blown Fuses

| | | | | |
|---|---|---|---|---|
| This Group: | 14.753 | 15.530 | 16.306 | kV |
| | 1.111 | 1.169 | 1.228 | Per Unit |
| | 133.32 | 140.34 | 147.36 | VT Sec Volts |
| Other Groups: | 12.187 | 12.829 | 13.470 | kV |
| | 0.918 | 0.966 | 1.014 | Per Unit |
| | 110.14 | 115.93 | 121.73 | VT Sec Volts |

EE5210\CAPBANK.WK3

Mipsycon-Nov '99

4a

# SHUNT CAPACITOR BANK SWITCHING TRANSIENTS: A TUTORIAL AND CASE STUDY

Govind Gopakumar, Huihua Yan, Dr. Bruce A. Mork
Michigan Technological University
Houghton, MI 49931

Kalyan K. Mustaphi
Northern States Power Company
Minneapolis, MN 55401

## INTRODUCTION

Transient disturbances in power systems may damage key equipment, potentially having a great impact on system reliability. These transients may be introduced during normal switching operations, interruption of short circuits, lightning strikes, or due to equipment failure. Phasor analysis or other simplified analysis methods are usually inadequate due to system frequency dependencies and nonlinearities. Therefore, time-domain computer models are typically developed as a means of predicting the severity of the transient occurrences. The simulations are typically performed using simulation software such as the Electromagnetic Transient Program (EMTP). In this work, a royalty-free version of EMTP, called the Alternative Transients Program (ATP) was used.

During the switching of shunt capacitor banks, high magnitude and high frequency transients can occur [1, 5, 6, 7]. In earlier years, shunt capacitor banks have been more commonly installed at distribution and lower subtransmission levels. However, there has been a recent proliferation of new capacitor banks at transmission levels. Since larger higher-voltage capacitor banks have more stored energy and there is a higher system X/R ratio and less damping, this has raised concerns at Northern States Power Company (NSP) and other utilities regarding the vulnerability of their equipment.

Over the past several years, NSP has been installing a large number of capacitor banks at the 69-kV and 115-kV levels. This has been motivated by the need to provide steady-state voltage support, to provide reactive power support, and to increase power transfer capability. For example, area load growths and the Manitoba-Minnesota Transmission Upgrade (MMTU) Project have directly or indirectly required NSP and other utilities to add over 2 GVAR of capacitor banks in the region. At NSP, 80-MVAR banks at the 115-kV Elm Creek substation and 120-MVAR banks at the 115-kV Elliot Park substation provide reactive power support. Two 80-MVAR 115-kV capacitor banks at Split Rock are installed to provide steady state voltage support.

This paper provides an introduction to capacitor bank switching transients, illustrated using a simple single-phase system. A case study for capacitor bank switching at Split Rock is presented next, followed by a discussion and interpretation of some of the results.

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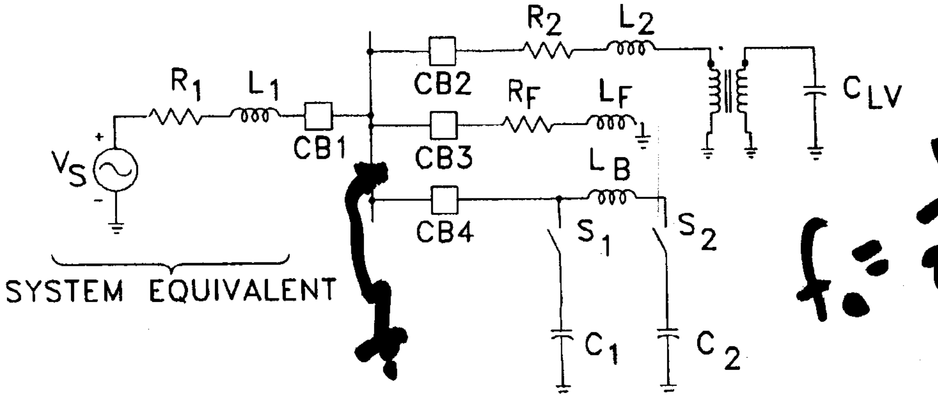
## CONCEPTUAL INTRODUCTION

The 34.5-kV per-phase system of Figure 1 is used to provide a conceptual introduction to some of the common transients involved in capacitor bank switching. It is built upon an example given in [1]. $R_1$ and $L_1$ represent the system source impedance. CB4 feeds two capacitor banks, represented by $C_1$ and $C_2$. S1 and S2 represent the circuit breakers used to switch the capacitor banks. $L_B$ is the inductance of the bus spanning between the capacitor banks. $R_2$ and $L_2$ are the total impedance of the feeder and distribution transformer. A distribution-level capacitor bank is attached to the transformer secondary. CB3 can be used to initiate and interrupt a ground fault on the bus at some distance down the feeder, depending on location of the ground. Parameters are given in the Appendix. Using different portions of this system, five transients can be addressed: 1) energization inrush, 2) back-to-back energization, 3) outrush into a nearby fault, 4) voltage magnification, and 5) transient recovery voltage (TRV).



$f_0 = \frac{1}{2\pi\sqrt{LC}}$

Figure 1. A simple 34.5-kV per-phase system used to illustrate capacitor bank transients.

1. Energization Inrush:

Energization inrush is a transient occurring when the first (or only) bank at the bus is energized. The transient is characterized by a surge of current having a high magnitude and a frequency as high as several hundred Hertz. There is also a transient overvoltage on the bus, caused by the surge of inrush current coming from the system source.

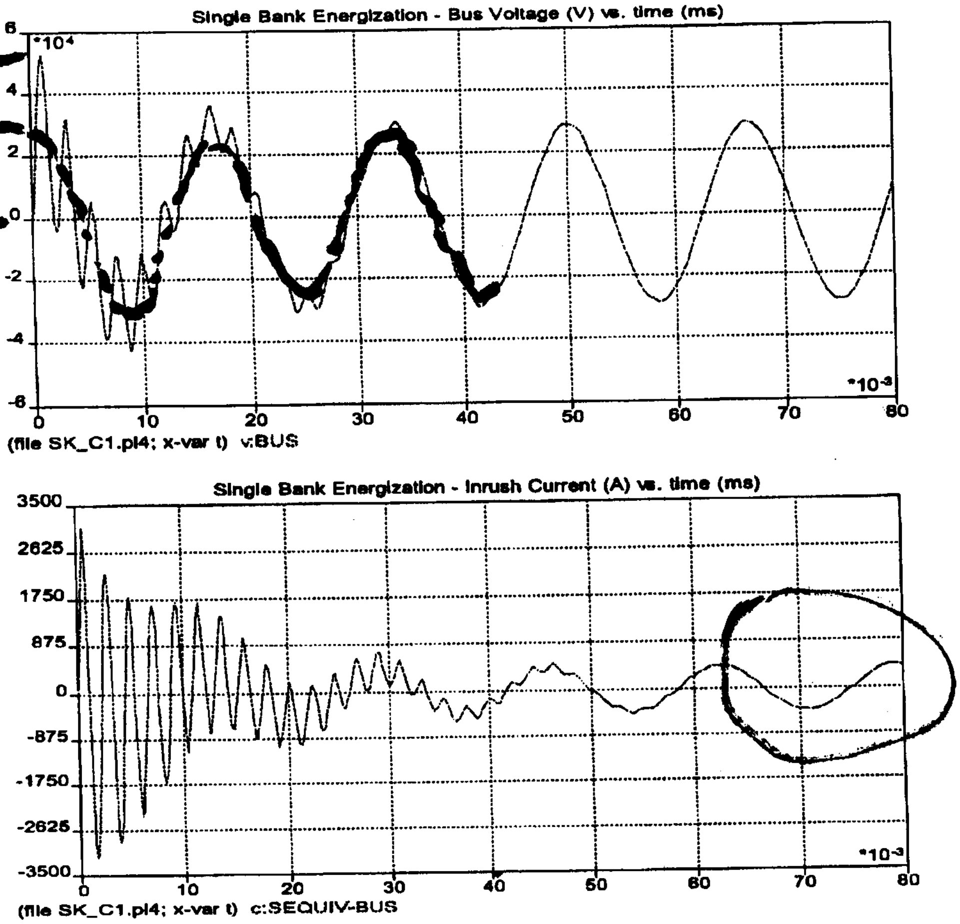
To illustrate, we begin with CB1 and CB4 closed, energizing $C_1$ by closing S1. The operative circuit consists of a Thevenin source in series with $C_1$. Analysis of switching transients typically makes use of superposition, breaking the transient into a) natural response caused by the switching and b) the forced response due to the 60-Hz system source. If we neglect system resistance, the natural response component of the inrush current into the capacitor may be approximated as:

4C

$$i(t) = \frac{V(0)}{Z_0} \sin \omega_0 t, \qquad (1)$$

where $Z_0 = \sqrt{\frac{L}{C_1}}$, $\omega_0 = \frac{1}{\sqrt{LC_1}}$,

and V(0) is difference between the source voltage and the initial voltage of the capacitor at the instant of energization. It can be seen that as a capacitor bank size increases, peak inrush current increases and its frequency decreases. Reference [4] provides approximate methods of calculating the inrush, although it is recommended that an EMTP simulation be run to determine the effects of system damping.



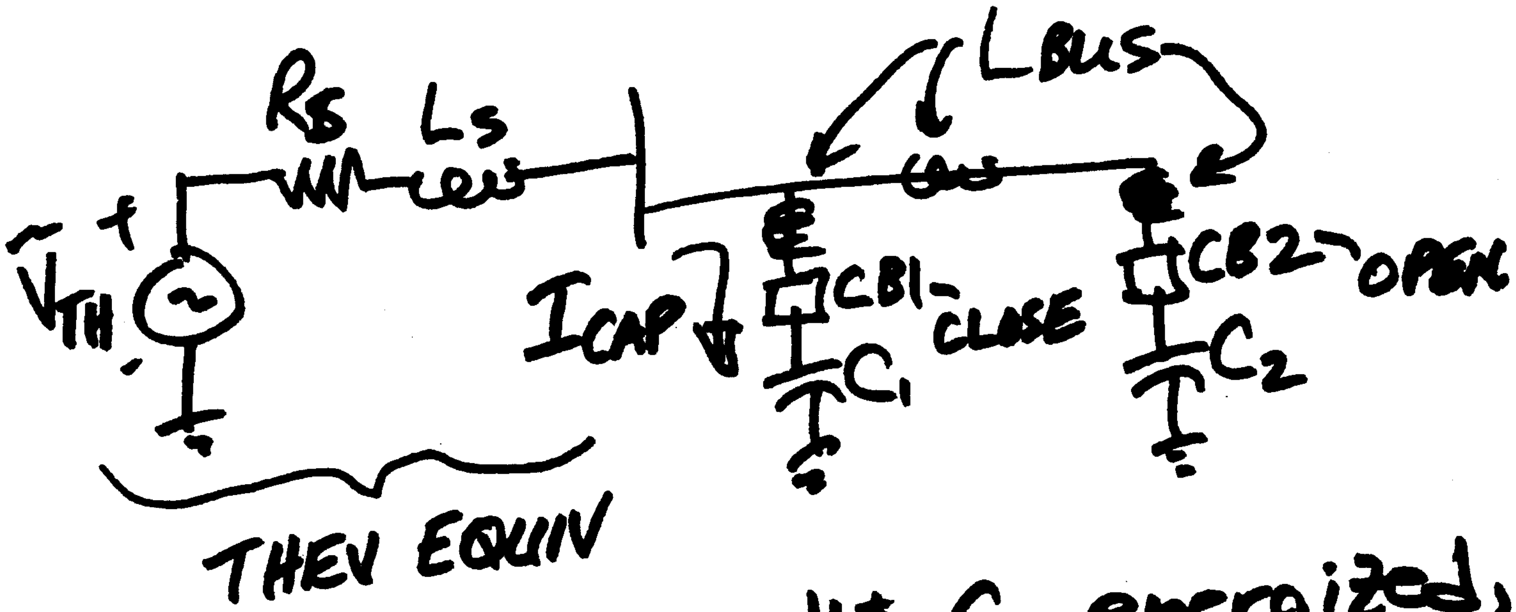
Single Bank Energization - Bus Voltage (V) vs. time (ms)

(file SK_C1.pl4; x-var t) v:BUS

Single Bank Energization - Inrush Current (A) vs. time (ms)

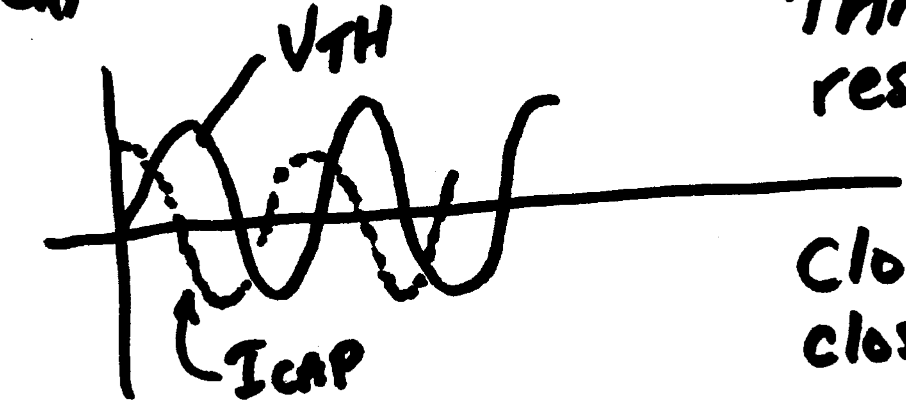
(file SK_C1.pl4; x-var t) c:SEQUIV-BUS

**Figure 2.** Energization inrush. Peak bus voltage = 1.87 pu. Peak current = 3041 Amps.



In steady-state, with $C_1$ energized, $\tilde{I}_{CAP}$ leads $V_{TH}$ by approx 90°

This is the forced response.

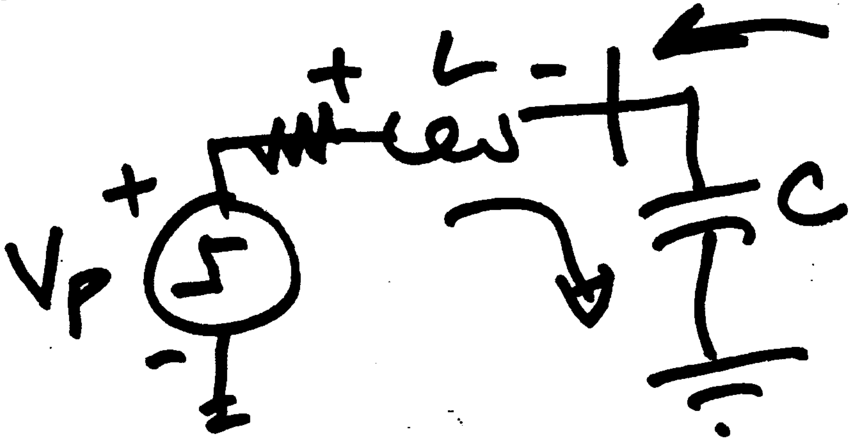


Worst case for closing transient is to close CB1 when $\boxed{\angle V_{TH} = +90^\circ}$ or $-90^\circ$

- Energization inrush
  - freq: 300-800 Hz
  - Voltage: $V_p$ of 1.4 - 1.9 p.u.
- Back-to-back
  - Several kHz: 3kz → 15kHz
  - Voltage: Smaller than above.

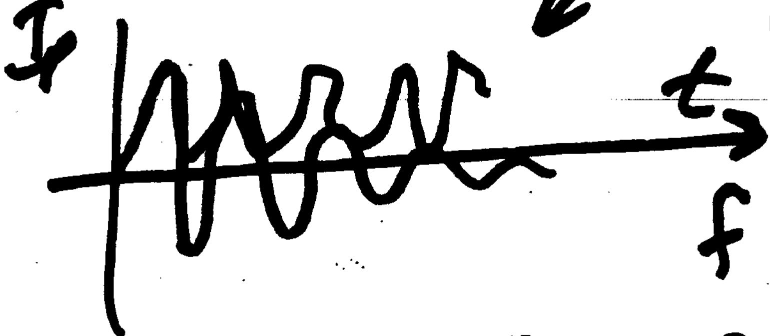
use $SF_6$ CBs to Switch banks.

# Transient Response:



$V_{bus}$ goes high

Natural Response

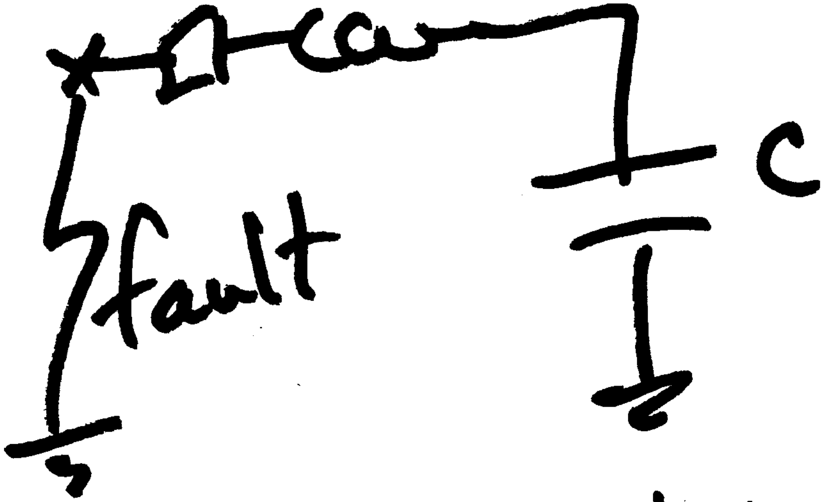


$$\omega_0 = \frac{1}{\sqrt{LC}}$$

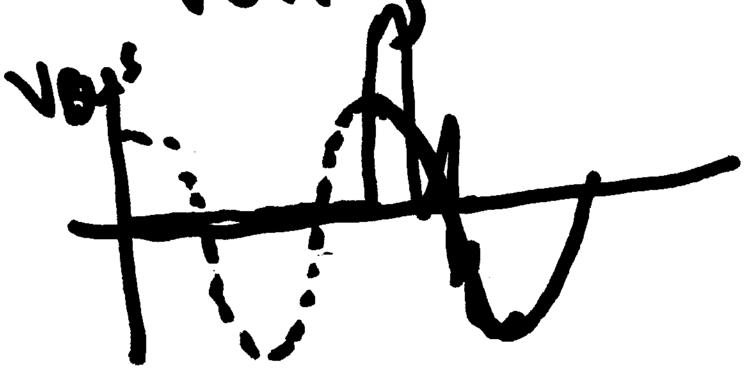
$$f = \frac{\omega_0}{2\pi}$$ usually 300-800 Hz

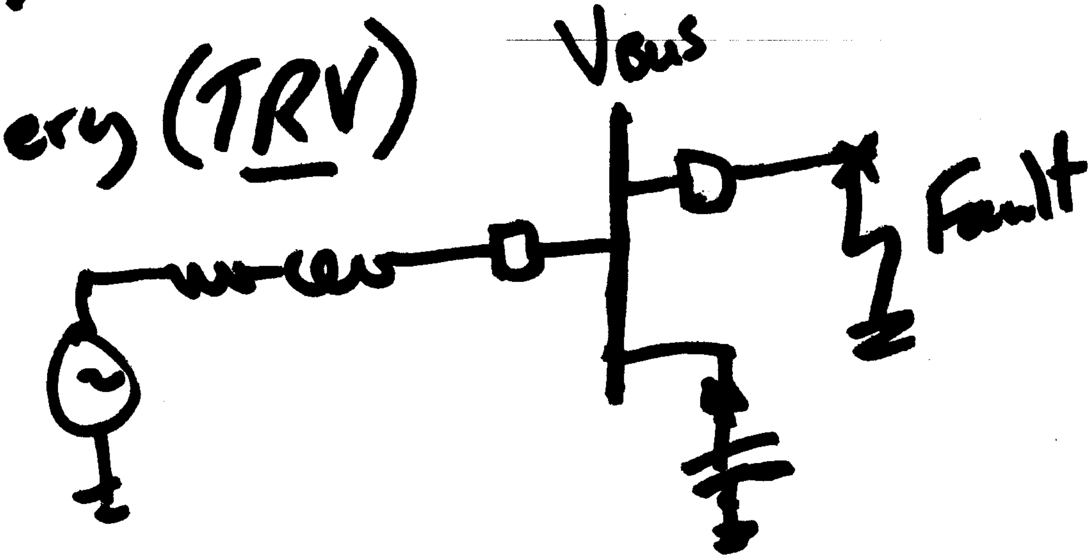
- Outrush

freq - Depends on LTOTAL



- Voltage Recovery (TRV)





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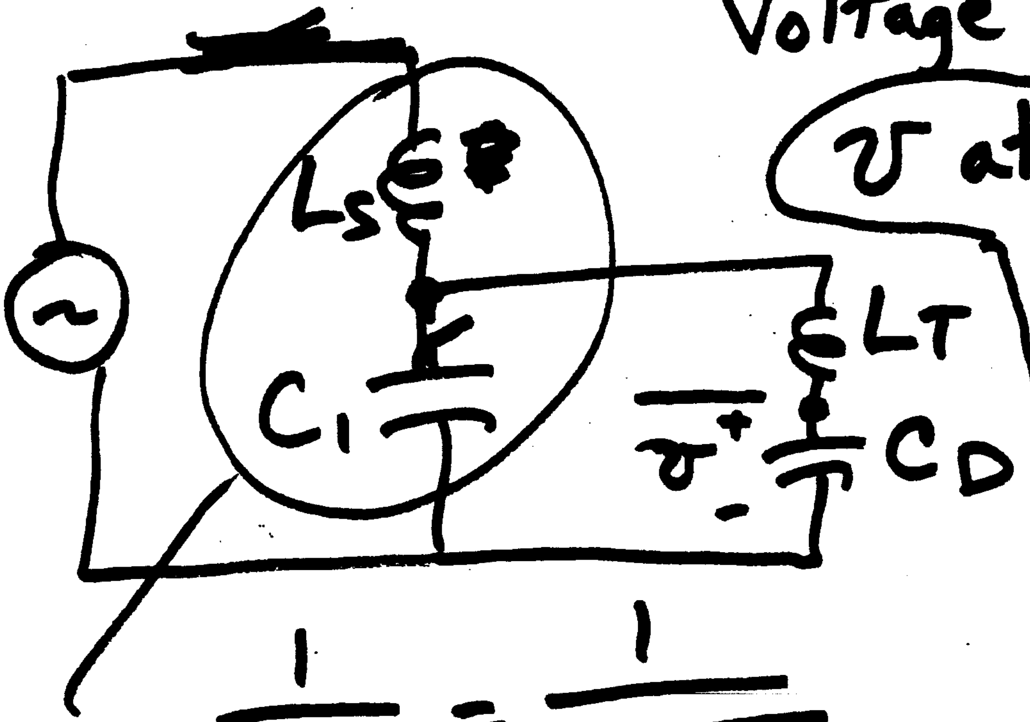
# Transient Probs Page 2:

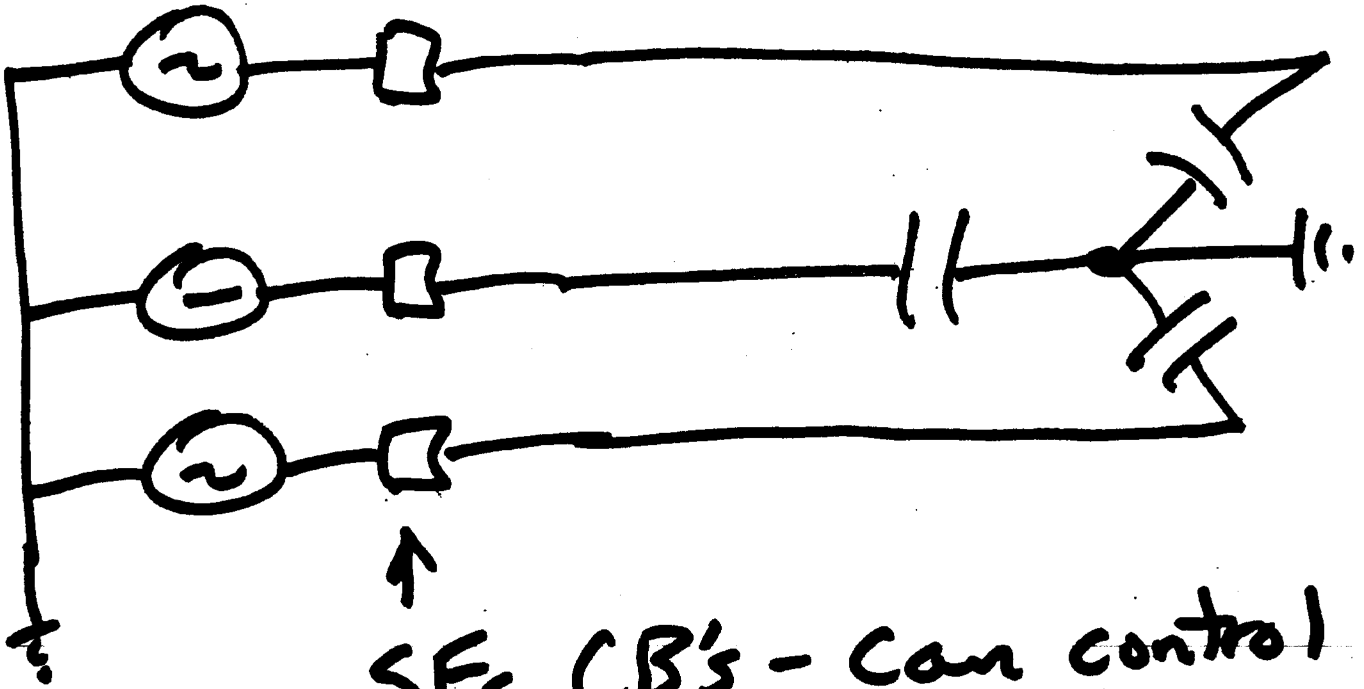
## Voltage Magnification



$v$ at $C_D$ is very high when switching $C_1$

$$\omega_0 = \frac{1}{\sqrt{L_S C_1}} = \frac{1}{\sqrt{L_T C_D}}$$

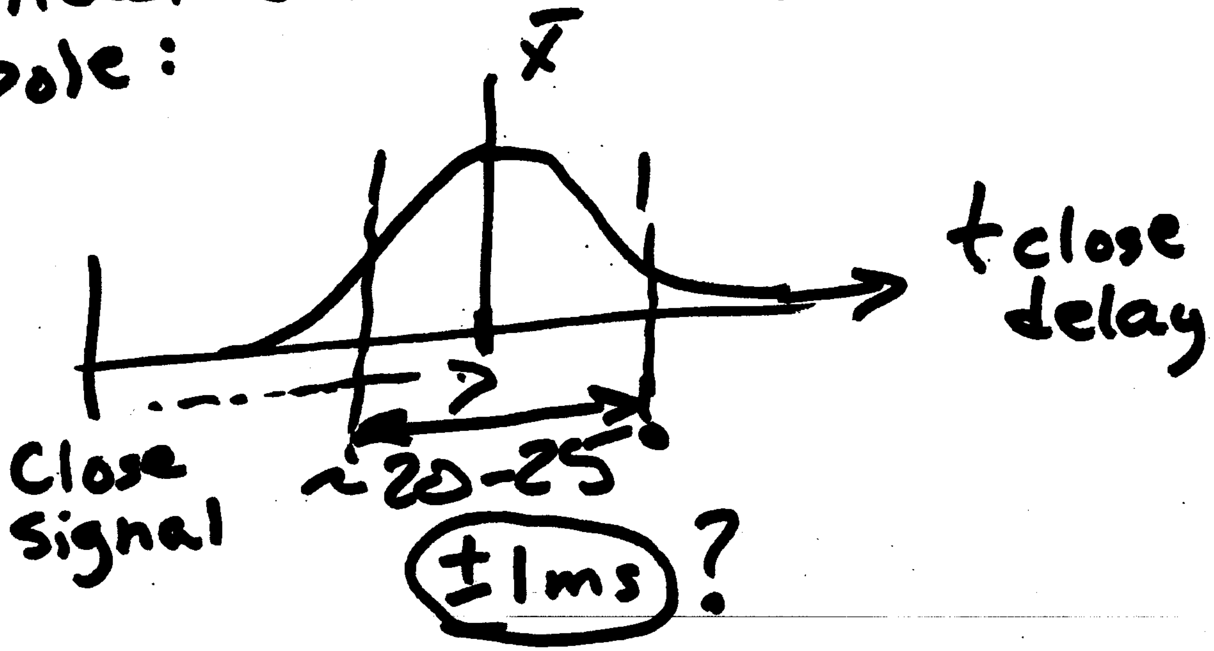
How to minimize transient?



SF6 CB's - Can control each pole separately.
Can control ±20°.

CB "timing"

- Statistical close times for each pole:



- When closing all 3 poles at once, the "pole span" is the time from 1st close to last.