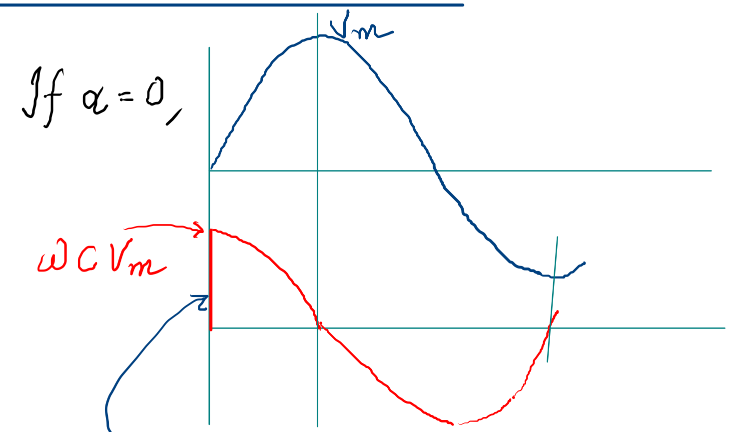
The TSC-TCR Static VAr Generator and Control

[You can use the following as Text books for this portion.

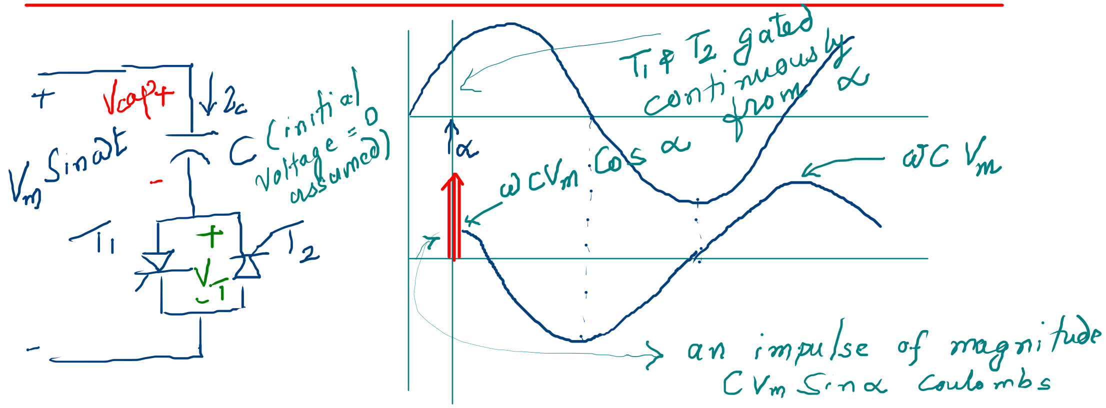
1. Understanding FACTS by Hingorani & Gyugyi
   Section 5.2
2. Thyristor-based FACTS Controllers for Electrical Transmission Systems by R. Mohan & Rajiv K Varma IEEE Press, Wiley Interscience
   Section 3.8]

If $\alpha = 0$,

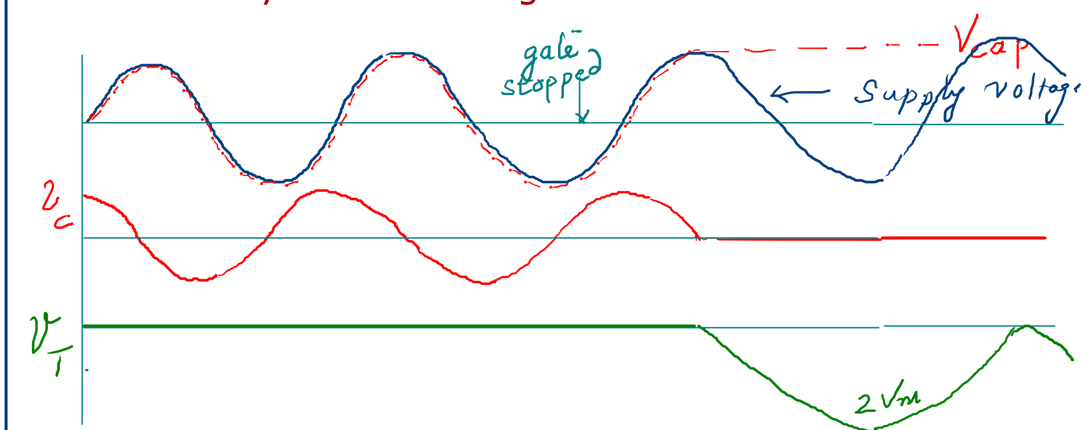


Sudden rise of current from 0 to $\omega C V_m$ results in large $\frac{di}{dt}$ in thyristors and they fail.

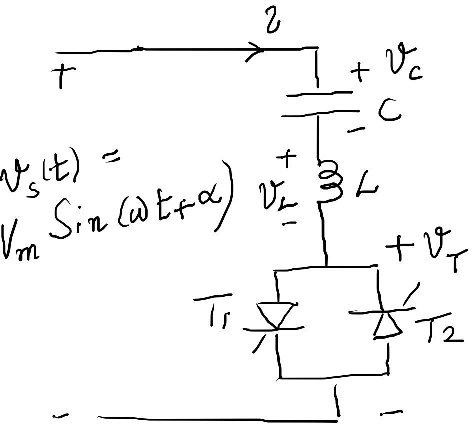
Why a Thyristor Controlled Capacitor Similar to TCR is not practical?



When Thyristor Gate Signals Are Withdrawn....



Transient-free Switching-ON of a Capacitor With the help of a Reactor in Series



T_1 & T_2 are gated continuously starting from $t = 0$

$v_C(0^-) = V_{C0}$

$i(0^-) = 0$

$$v_s(t) = \frac{1}{C}\int_0^t i\,dt + V_{C0} + L\frac{di}{dt}$$

$$\therefore \quad L\frac{d^2 i}{dt^2} + \frac{1}{C} i = \frac{d\,v_s(t)}{dt}$$

$$\frac{d^2 i}{dt^2} + \frac{1}{LC} i = \frac{\omega V_m}{L}\cos(\omega t + \alpha), \quad t \geq 0$$

$$i(0^+) = i(0^-) = 0$$

v_L at $t = 0^+$ is $V_m \sin\alpha - V_{C0}$

$$\therefore \quad \left.\frac{di}{dt}\right|_{0^+} = \frac{V_m \sin\alpha - V_{C0}}{L}$$

Particular Solution :

$$= \frac{V_m}{\omega L - \frac{1}{\omega C}} \sin(\omega t + \alpha - 90^\circ)$$

$$= \frac{-\omega C V_m}{1 - \omega^2 LC} \sin(\omega t + \alpha - 90^\circ)$$

$$= \frac{\omega C V_m}{1 - \omega^2 LC} \cos(\omega t + \alpha)$$

Let $n \triangleq \sqrt{\dfrac{1/\omega C}{\omega L}} = \sqrt{\dfrac{1}{\omega^2 LC}} = \dfrac{\omega_0}{\omega}$ with $\omega_0 \triangleq \dfrac{1}{\sqrt{LC}}$

$$= \frac{n^2}{n^2 - 1}\omega C V_m \cos(\omega t + \alpha)$$

Complementary Solution is

$$A\cos\omega_0 t + B\sin\omega_0 t$$

where A & B are constants and $\omega_0 = \frac{1}{\sqrt{LC}}$

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$$\therefore i(t) = \frac{n^2}{n^2-1}\omega C V_m \cos(\omega t+\alpha) + A\cos\omega_0 t + B\sin\omega_0 t$$

Since $i(0^+) = 0$, $A = \frac{-n^2}{n^2-1}\omega C V_m \cos\alpha$ — (1)

Since $\left.\frac{di}{dt}\right|_{0^+} = \frac{V_m \sin\alpha - V_{co}}{L}$

$$-\frac{n^2\omega^2 C V_m \sin\alpha}{n^2-1} + \omega_0 B = \frac{V_m \sin\alpha - V_{co}}{L}$$

$$\omega_0 B L = V_m \sin\alpha - V_{co} + \frac{n^2\omega^2 LC}{n^2-1} V_m \sin\alpha$$

$$= V_m \sin\alpha\left(1 + \frac{1}{n^2-1}\right) - V_{co}$$

$$\therefore (\omega_0 L) B = \frac{n^2}{n^2-1} V_m \sin\alpha - V_{co} \quad \text{— (2)}$$

From (1) & (2) it follows that transient-free switching is possible if $\alpha = \frac{\pi}{2}$ and $V_{co} = \frac{n^2}{n^2-1}V_m$ OR $\alpha = \frac{3\pi}{2}$ & $V_{co} = \frac{-n^2}{n^2-1}V_m$

If these conditions are not met, there will be a ringing transient at $\omega_0 = \frac{1}{\sqrt{LC}}$ rad/sec in capacitor current, capacitor voltage and inductor voltage. This ringing transient usually gets damped down to 0 in a few cycles due to losses in reactor and thyristors. After that, steady-state solution is

$$i(t) = \frac{n^2}{n^2-1}\omega C V_m \cos(\omega t+\alpha)$$

$$V_c(t) = \frac{n^2}{n^2-1} V_m \sin(\omega t+\alpha)$$

$$V_L(t) = \frac{-1}{n^2-1} V_m \sin(\omega t+\alpha)$$

$$V_T(t) = 0$$

till gate signal is withdrawn for T_1 & T_2

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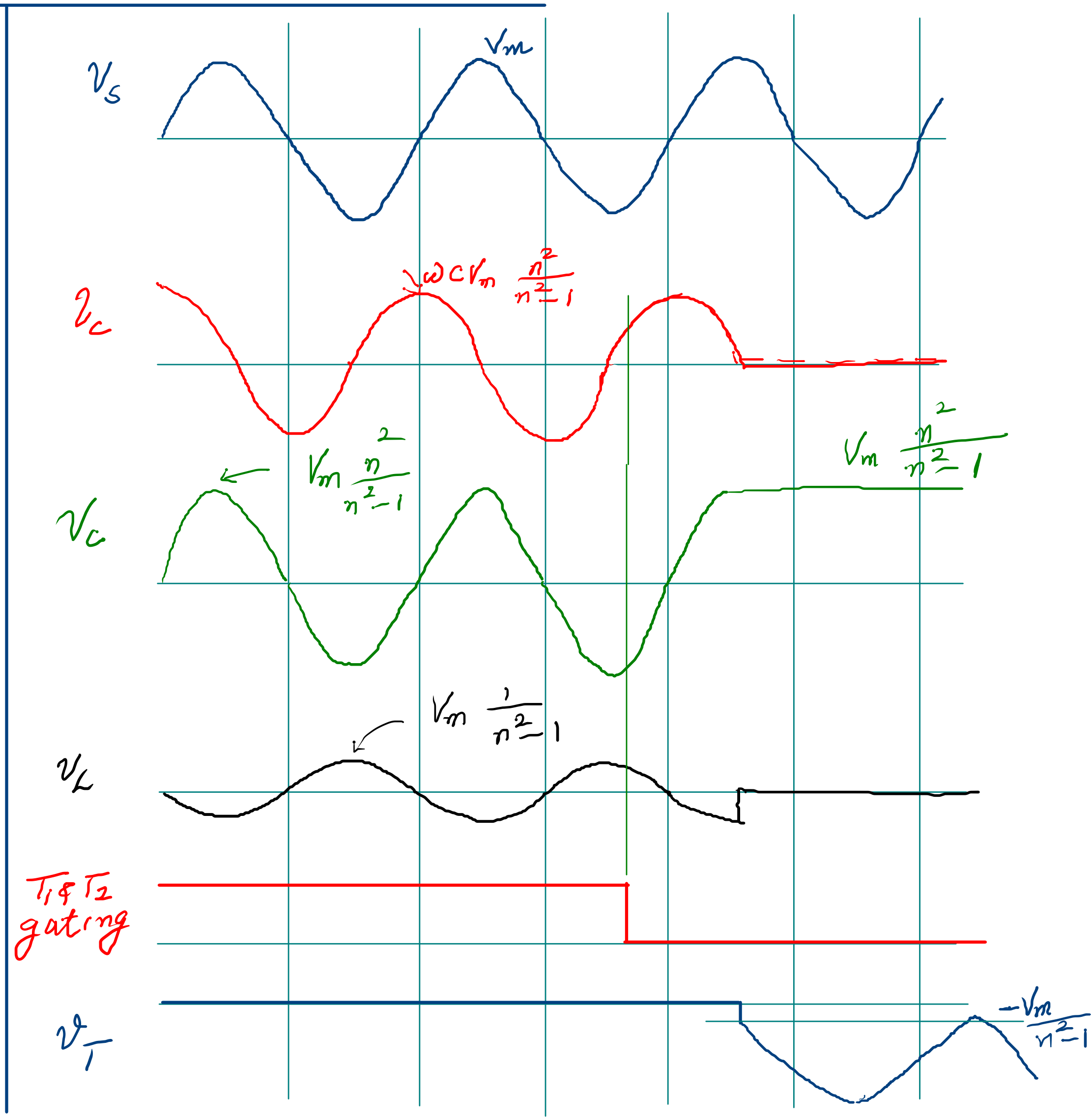
ωL value is usually 4 to 10 % of $\frac{1}{\omega C}$ value. Usually it is 4%. With 4% L, the series combination will work as a passive tuned harmonic filter at 5^{th} harmonic as well. With 4% L, value of n is 5 and the amplification factor of capacitor voltage is $\frac{25}{24} = \frac{1}{1-0.04}$ $= 1.04$

Maximum delay in obeying OFF command $= T/2$

If capacitor voltage does not leak down and if V_m does not change over time, releasing gate triggers to T_1 & T_2 at the peak of input voltage will result in transient-free switching ON of TSC next time.



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Further look at transient component in current

$$i(t) = \frac{n^2}{n^2-1}\omega C V_m \cos(\omega t+\alpha) + A\cos\omega_0 t + B\sin\omega_0 t$$

where $n^2 = \frac{1}{\omega^2 LC} = \left(\frac{\omega_0}{\omega}\right)^2$, $\omega_0 = \frac{1}{\sqrt{LC}}$

$$A = \frac{-n^2}{n^2-1}\omega C V_m \cos\alpha$$

$$B = \frac{1}{\omega_0 L}\left(\frac{n^2}{n^2-1}V_m \sin\alpha - V_{co}\right).$$

Total amplitude of transient $= \sqrt{A^2+B^2}$

Case(i) – $V_{co} < V_m$, with V_{co} +ve

Say, we release gate to T_1 & T_2 when source voltage is equal to V_{co} & $V_T = 0$

i.e $V_m \sin\alpha = V_{co}$

Then $V_m \cos\alpha = \sqrt{V_m^2 - V_{co}^2} = V_m\sqrt{1-\left(\frac{V_{co}}{V_m}\right)^2}$

$$A = \frac{-n^2}{n^2-1}\omega C V_m \sqrt{1-\left(\frac{V_{co}}{V_m}\right)^2}$$

$$B = \frac{V_{co}}{\omega_0 L}\left(\frac{n^2}{n^2-1} - 1\right) = \frac{V_{co}}{(n^2-1)\omega_0 L}$$

Skipping the algebraic steps,

$$\sqrt{A^2+B^2} = \underbrace{\left(\frac{n^2}{n^2-1}\omega C V_m\right)}_{\text{amplitude of fundamental current.}} \times \sqrt{1 - \left(\frac{V_{co}}{V_m}\right)^2\left(1-\frac{1}{n^2}\right)}$$

So, amplitude of transient component is < amplitude of fundamental current in this strategy.

Case (ii) : $V_{co} > V_m$, with V_{co} +ve

Say, we release gate to T_1 & T_2 when source voltage is at peak and thyristor voltage is minimum. i.e $\alpha = 90°$

Then $A = 0$, $B = \frac{1}{\omega_0 L}\left(\frac{n^2}{n^2-1}V_m - V_{co}\right)$

Amplitude of transient $= \left(\frac{n^2\omega C V_m}{n^2-1}\right)\left[n\left(\frac{n^2-1}{n^2}\frac{V_{co}}{V_m} - 1\right)\right]$

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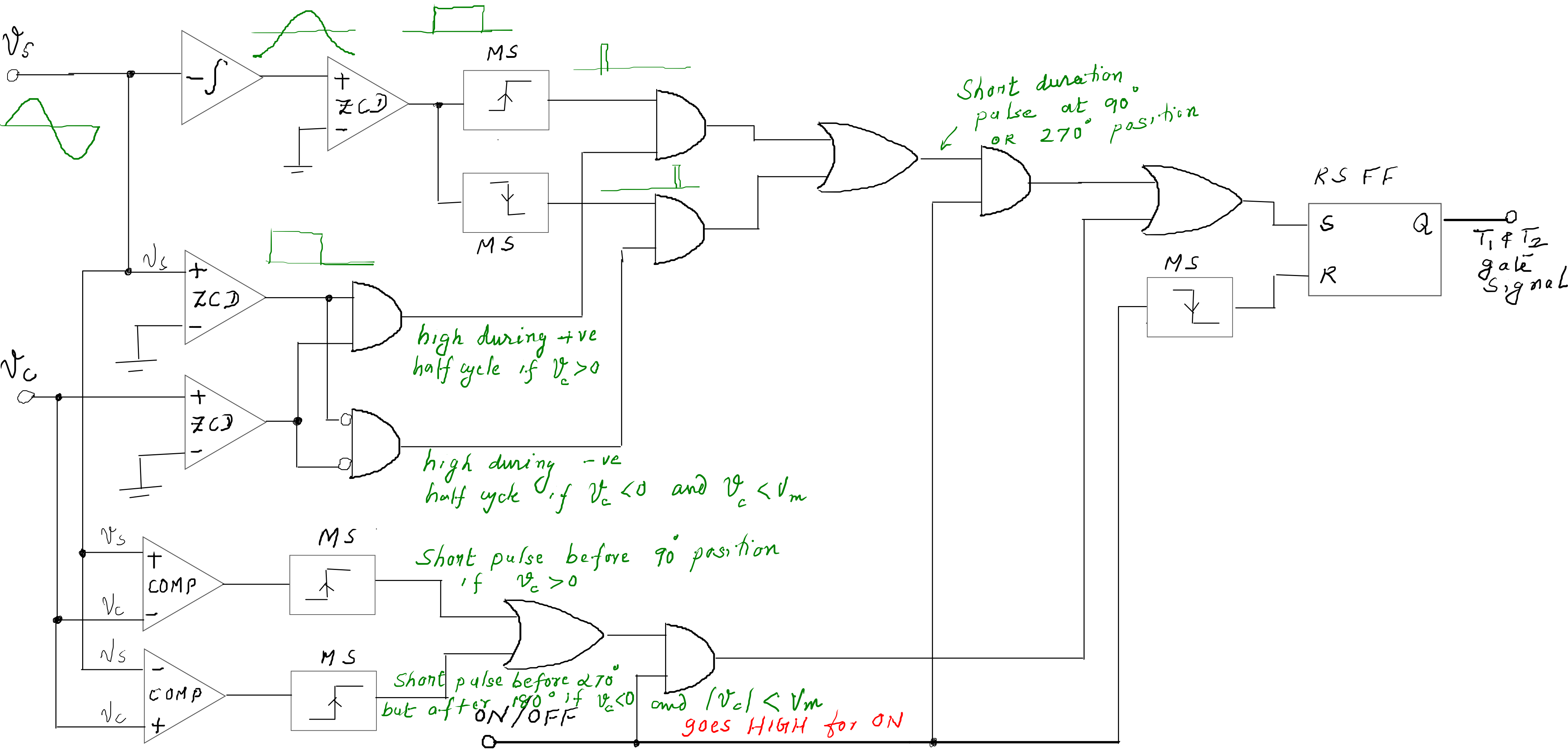
The ON/OFF Controller for a TSC Unit



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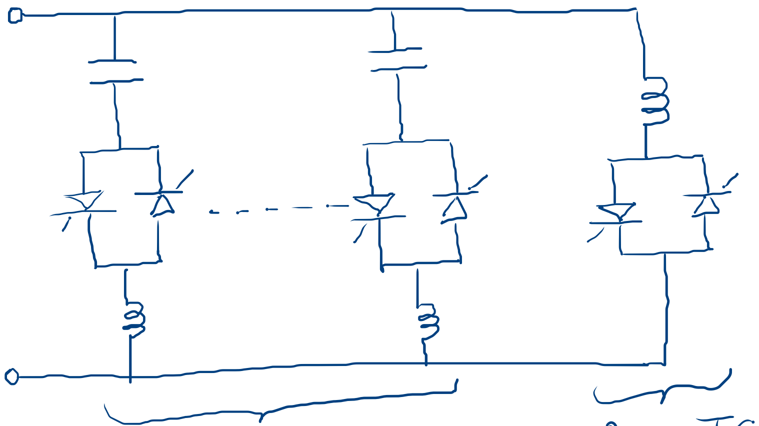
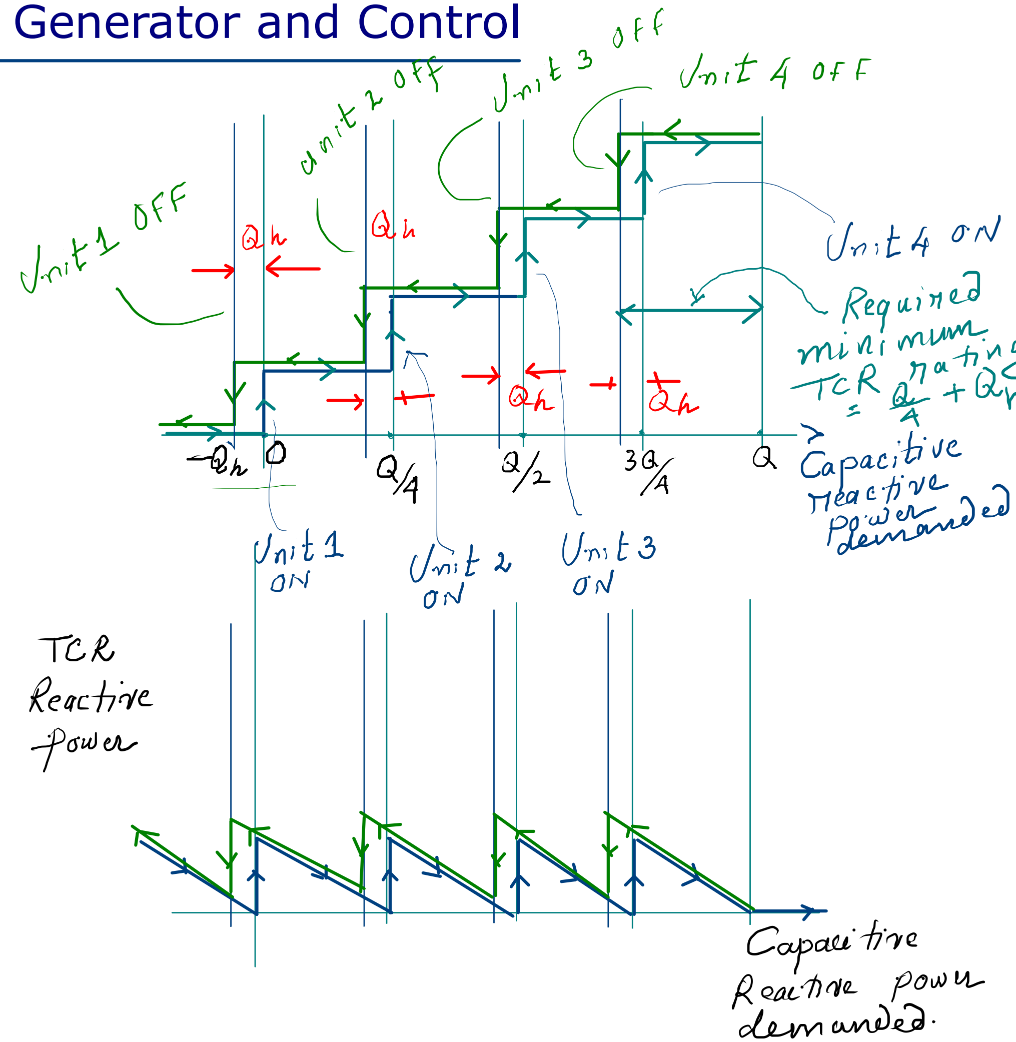
The Single-Phase TSC-TCR System : Why the rating of TCR has to be more than that of individual TSC Unit?



TCR Rating has to be > Q/n so that we can adopt hysteretic switching of TSC units and thereby avoid chattering in TSC units.



Example : 4 TSC Units + 1 TCR Unit

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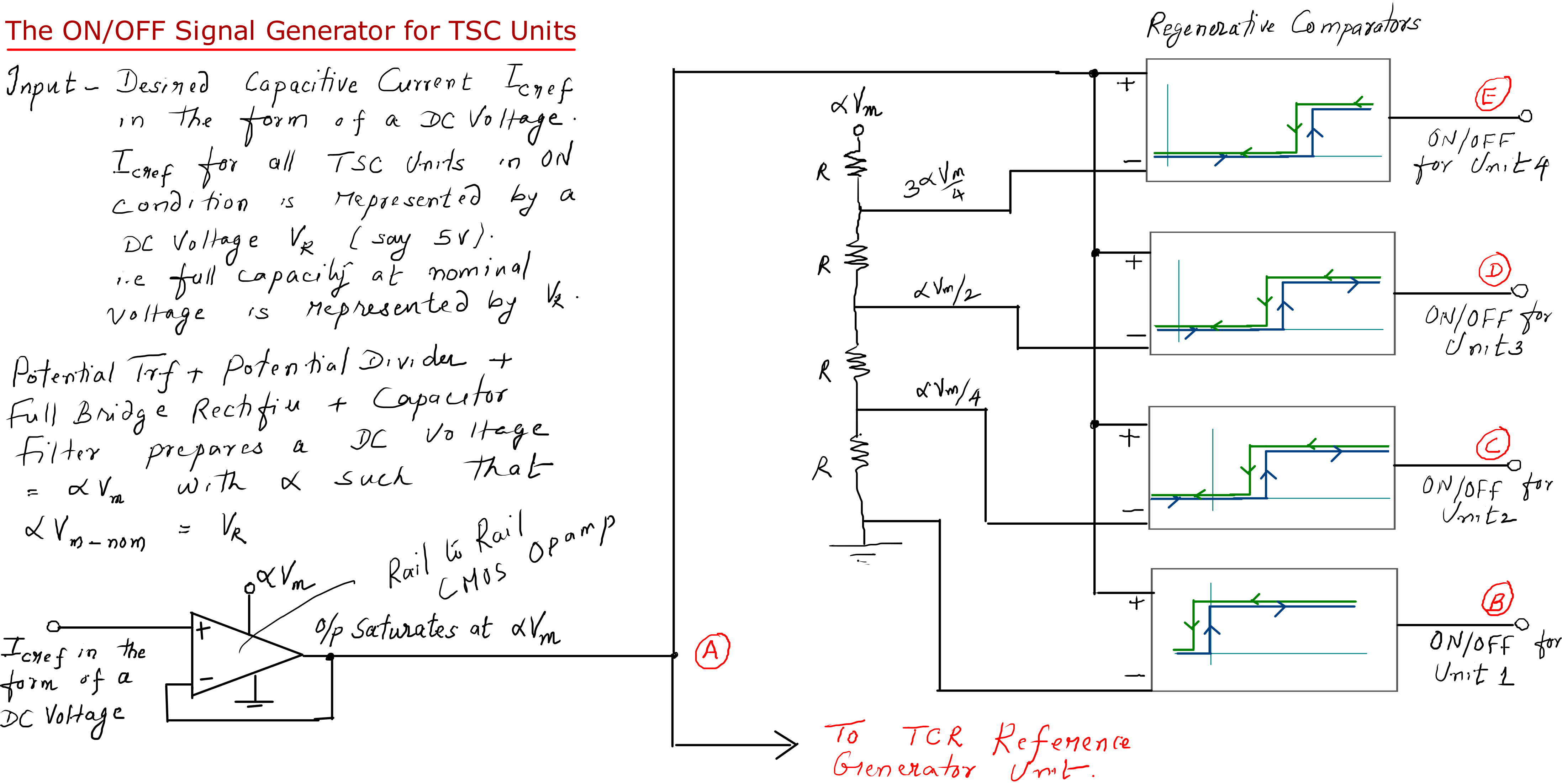
The ON/OFF Signal Generator for TSC Units

Input – Desired Capacitive Current I_{cref} in the form of a DC Voltage. I_{cref} for all TSC Units in ON condition is represented by a DC Voltage V_R (say 5V). i.e full capacity at nominal voltage is represented by V_R.

Potential Trf + Potential Divider + Full Bridge Rectifier + Capacitor Filter prepares a DC Voltage $= \alpha V_m$ with α such that $\alpha V_{m-nom} = V_R$



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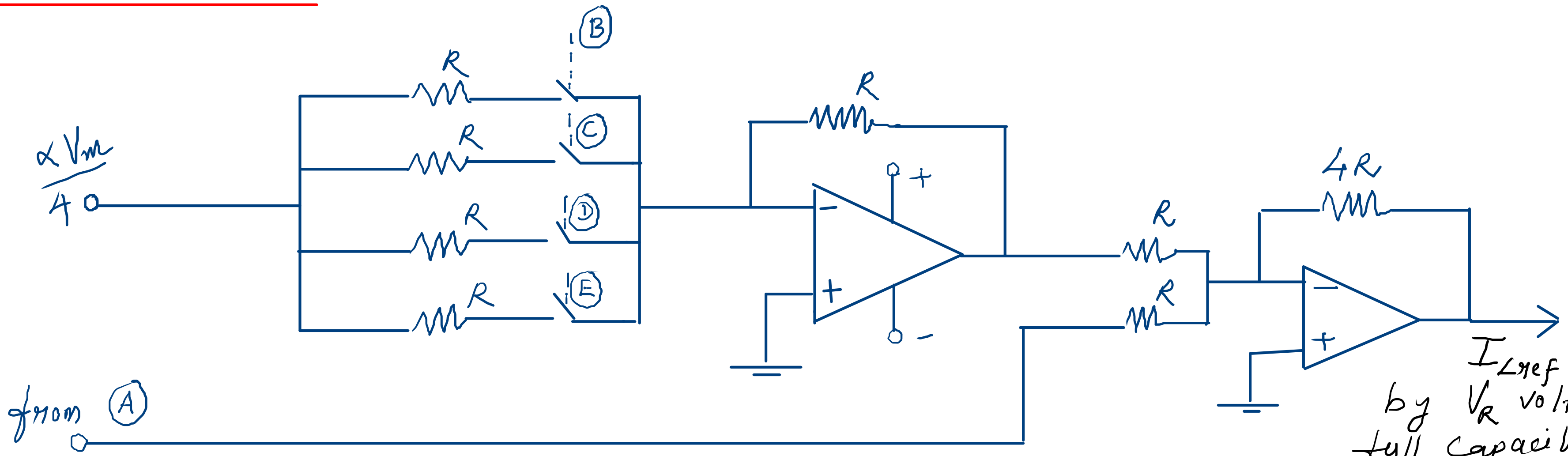
The TCR Reference Generator Unit



I_{Lref} represented by V_R volts for full capacity of TCR under V_{n-nom} condition.

In addition a TCR Internal Controller Unit will also be needed.
It was covered in an earlier lecture.