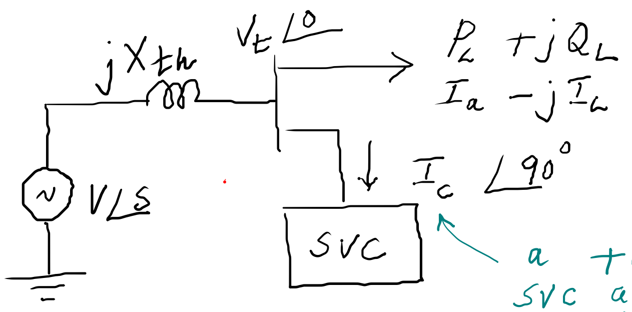
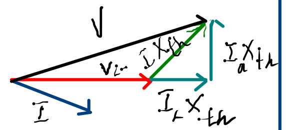
SVC Control

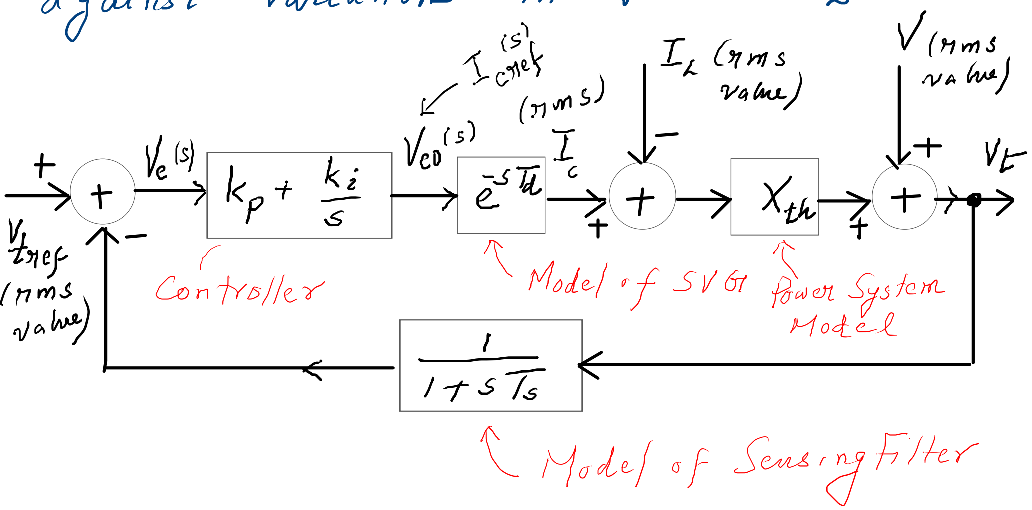
SVC Control for Bus Voltage Regulation





a +ve no when SVC absorbs leading reactive power

Control Objective – Maintain V_t at V_{tref} against variations in V and I_L

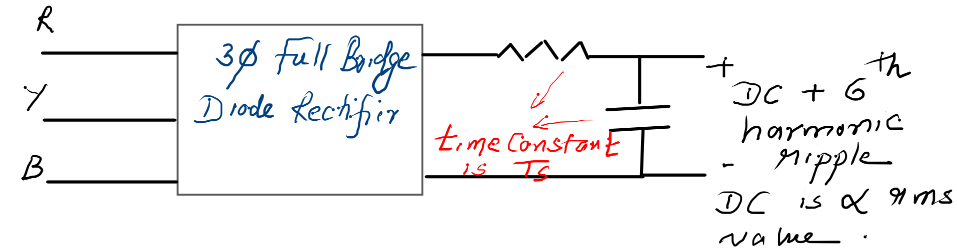


$T_d = T/6$ is used for a 3ϕ FC–TCR

$T_d = T/3$ is used for a 3ϕ TSC–TCR

for system studies.

The usual sensing strategy is



$\left|\frac{1}{1+j6\omega T_s}\right|$ must be at the most $\frac{1}{10}$ in practice.

$\therefore \; 6\omega T_s \simeq 10 \Rightarrow T_s = \frac{10}{6\omega} = 5.3$ ms

with $\omega = 100\pi$. So T_s has to be at least 5.3 ms or so.

$V_t + (I_L - I_c)X_{th} = V$

$V_t = V + (I_c - I_L)X_{th}$ load line

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The Steady-State Regulation Equation

PI Control is used; so steady-state error is 0. So under steady-state

$V_t = V_{tref}$, $V_e = 0$

What is the I_C that SVC must take under steady-state?

$$V_t = V + (I_c - I_L) X_{th} \qquad (1)$$

$(I_c - I_L) X_{th} + V$ must be V_{tref}.

$\therefore$ $I_c = \dfrac{V_{tref} - V}{X_{th}} + I_L$ will have to be produced by SVC if it can.

If it cannot produce this much, then, V_t will not be $= V_{tref}$ under steady-state. It will be more or less than V_{tref} depending upon I_L and V values.

But why can't SVC produce this much I_c?

Because at any value of V_t, the maximum I_c SVC can take is $\omega C V_t$ in the case of FC-TCR and $n\omega C V_t$ in the case of TSC-TCR (where n = no of TSC branches, C = effective capacitance in each branch) and the minimum I_c a SVC can take will be $-\frac{V_t}{\omega L} + \omega C V_t$ for FCTCR & $-\frac{V_t}{\omega L}$ for TSC-TCR where L is the inductor in TCR branch.

$\therefore$ V_t will be maintained at V_{tref} iff

$\dfrac{V_{tref} - V}{X_{th}} + I_L \leq I_{cmax}$; a +ve no

and $\dfrac{V_{tref} - V}{X_{th}} + I_L \geq I_{cmin}$; a -ve no.

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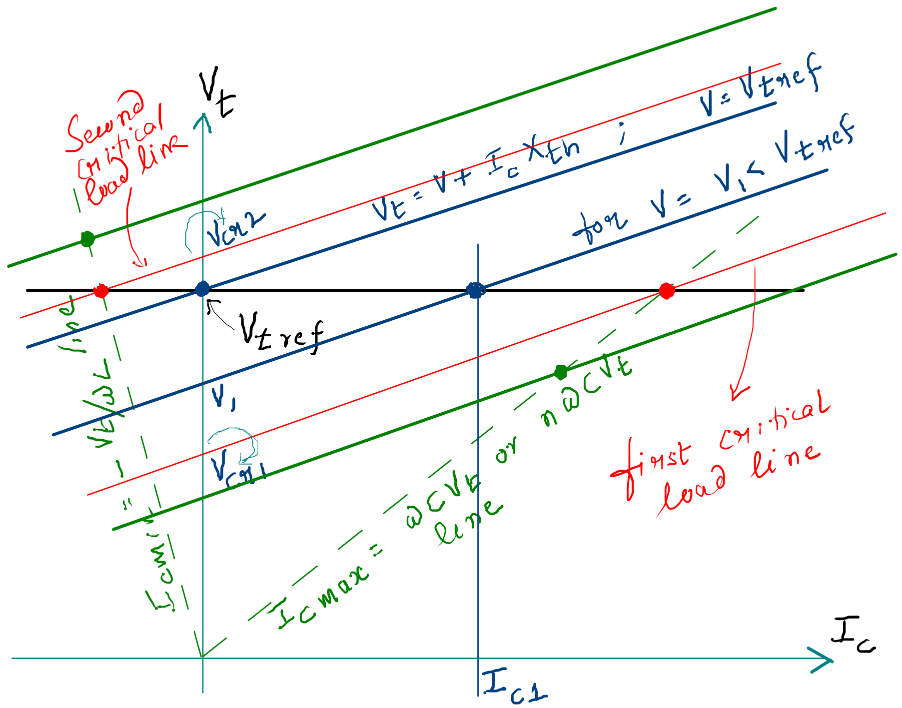
These relations and constraints are brought out clearly in the following regulation characteristic curves for a special case of UPF load i.e with $I_L = 0$.



Control Range

For critical operating points,

$$\frac{V_{tref} - V_{cr1}}{X_{th}} + I_L = I_{cmax} = \omega C V_{tref}$$

(C = Cap in FC TCR or Total Capacitance in TSC − TCR)

and
$$\frac{V_{tref} - V_{cr2}}{X_{th}} + I_L = I_{cmin} = -\frac{V_{tref}}{\omega L} \text{ for TSC-TC}$$

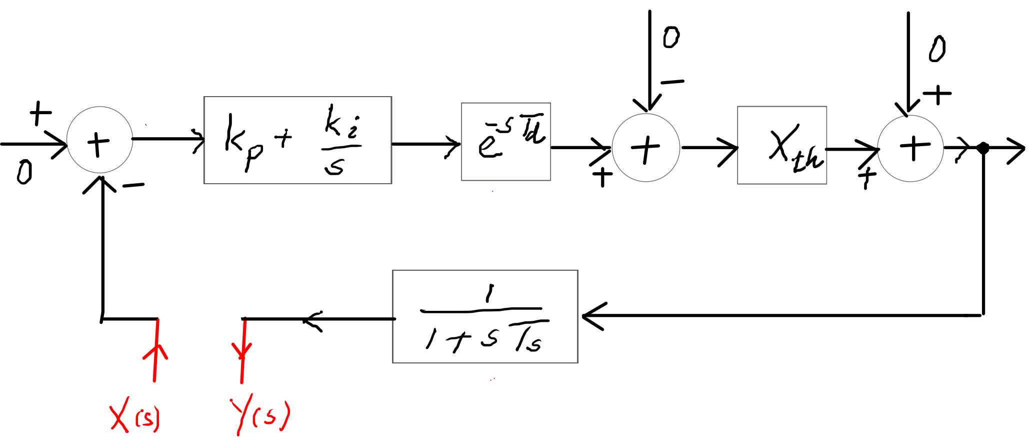
$$V_{cr1} = V_{tref} + I_L X_{th} - \omega C X_{th} V_{tref}$$
$$= (1 - \omega C X_{th}) V_{tref} + I_L X_{th}$$

$$V_{cr2} = \left(1 + \frac{X_{th}}{\omega L}\right) V_{tref} + I_L X_{th}$$

$$\underline{V_{cr2} - V_{cr1}} = X_{th}\left(\frac{1}{\omega L} + \omega C\right) V_{tref}$$
$$= \underline{X_{th}\,(I_{cmax} - I_{cmin}) \text{ at } V_{tref}}$$

Designing the Closed Loop System for a Given Phase Margin

Loop Gain Function $LG(s) = ?$



$$LG(s) = \frac{Y(s)}{X(s)} = -\frac{K_i(1+s\tau_i)}{s} e^{-sT_d} \frac{X_{th}}{1+sT_s}$$

where $\tau_i = k_p/k_i$

Let the specified phase margin for the closed loop system be ϕ degrees where ϕ is a +ve number.

Step 1: Choose the frequency at which loop gain magnitude crosses unity – is called ~~Gain~~ Crossover Frequency and is denoted by f_{co} or ω_{co}

With T_d transportation delay, the highest frequency content in I_{cref} signal can only be $\frac{1}{5T_d}$ to $\frac{1}{10T_d}$ ∴ Closed loop bandwidth must be around $\frac{1}{5T_d}$ at the most and preferably it must be close to $\frac{1}{10T_d}$.
Closed loop bandwidth is usually close to (but higher than) f_{co}. So $f_{co} = \frac{1}{10T_d}$ is tried first.
This gives $f_{co} = 30\,Hz$ for FC TCR system and $f_{co} = 15\,Hz$ for TSC – TCR system.

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Step 2: Calculate delay angle of $\angle G(s)$ at the chosen ω_{co} and make this angle $(360-\phi)$ or less.

$$\angle\angle G(j\omega_{co}) = 180^\circ + 90^\circ - \tan^{-1}\omega_{co}\tau_i + \frac{180}{\pi}\omega_{co}T_d + \tan^{-1}\omega_{co}T_s$$

This must be $\leq 360-\phi$. Since ω_{co}, T_d, T_s are known, τ_i can be found from this.

But what if $\tan^{-1}\omega_{co}\tau_i$ comes out $> 90^\circ$?

Ans: We have to try again with a lower value of f_{co} (and ω_{co}).

Step 3: Make $|\angle G(j\omega_{co})|$ equal to 1.

$$\frac{k_i}{\omega_{co}} \frac{\sqrt{1+(\omega_{co}\tau_i)^2}\, X_{th}}{\sqrt{1+(\omega_{co}T_s)^2}} = 1$$

From this k_i can be found.

Then, since $\tau_i = \frac{k_p}{k_i}$, k_p can be found.

Example: SVG Unit: FC-TCR $(-0.25, 1)$ pu

$X_{th} = 0.1$ pu

$T_d = T/6 = 3.33$ ms

Bandwidth of Sensing filter $= 30$ Hz

$\therefore$ Sensing Fn: $T_s = \frac{1}{2\pi \times 30} = 5.3$ ms

$$\text{Sensing Fn} = \frac{1}{1+0.0053s} = \frac{200}{s+200}$$

Choose $f_c = \frac{1}{10\,T_d} = 30$ Hz

Let required phase margin be 45°.

$\therefore$ Delay angle of $\angle G(j\omega_{co})$ at $j60\pi$ rad/sec must be $\leq 315^\circ$

$$180+90-\tan^{-1}\omega_{co}\tau_i + \omega_{co}T_d\frac{180}{\pi} + \tan^{-1}\frac{\omega_{co}}{200} = 315$$

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$$\frac{180}{\pi} \omega_{co} T_d = 60\pi \times 0.00333 \times \frac{180}{\pi} = 36^\circ$$

$$\tan^{-1}\frac{\omega_{co}}{200} = \tan^{-1}\frac{60\pi}{200} = 43.3^\circ$$

$$\therefore 180 + 90 + 36 + 43.3 - \tan^{-1}\omega_{co}\tau_i = 315^\circ$$

$$\therefore \tan^{-1}\omega_{co}\tau_i = 34.3^\circ$$

$$\therefore \omega_{co}\tau_i = 0.68215 \;\; \& \;\; \tau_i = 3.62\,ms.$$

From Unity Magnitude Condition,

$$\frac{k_i}{\omega_{co}} \frac{\sqrt{1+(\omega_{co}\tau_i)^2}\, X_{th}}{\sqrt{1+(\omega_{co}T_s)^2}} = 1$$

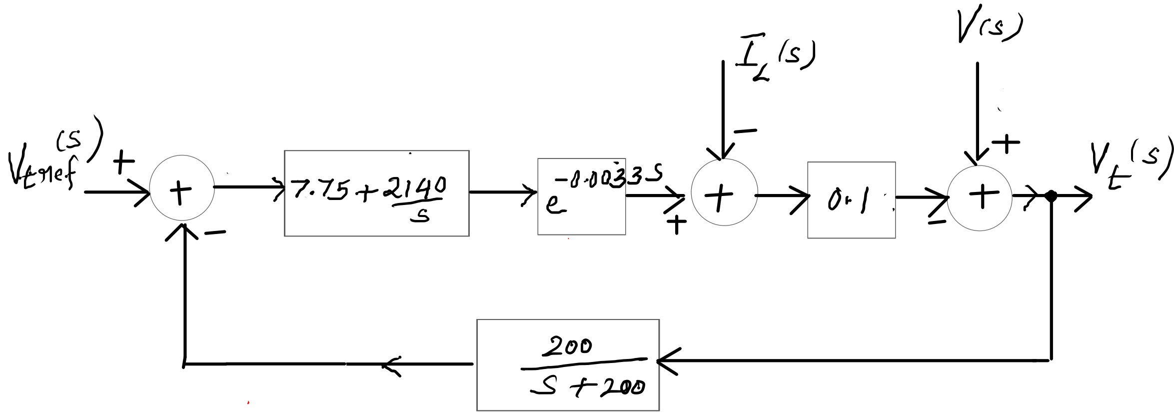
Solving with $\omega_{co} = 60\pi$, $T_s = 5.3\,ms$,

$\omega_{co}\tau_i = 0.68215$,

$$k_i = 2140$$

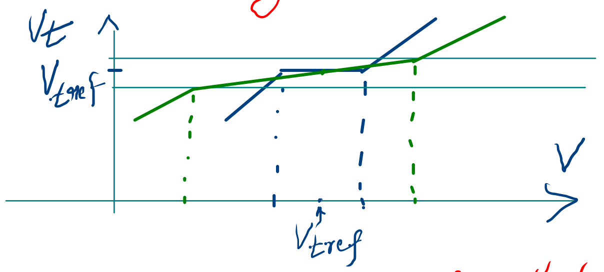
Since $\tau_i = 3.62\,ms = k_p/k_i$,

$$k_p = 7.75$$



Problems with this Simple Control Scheme –

- Limited Regulation Range.



- Load Sharing by Parallel Units not easy.

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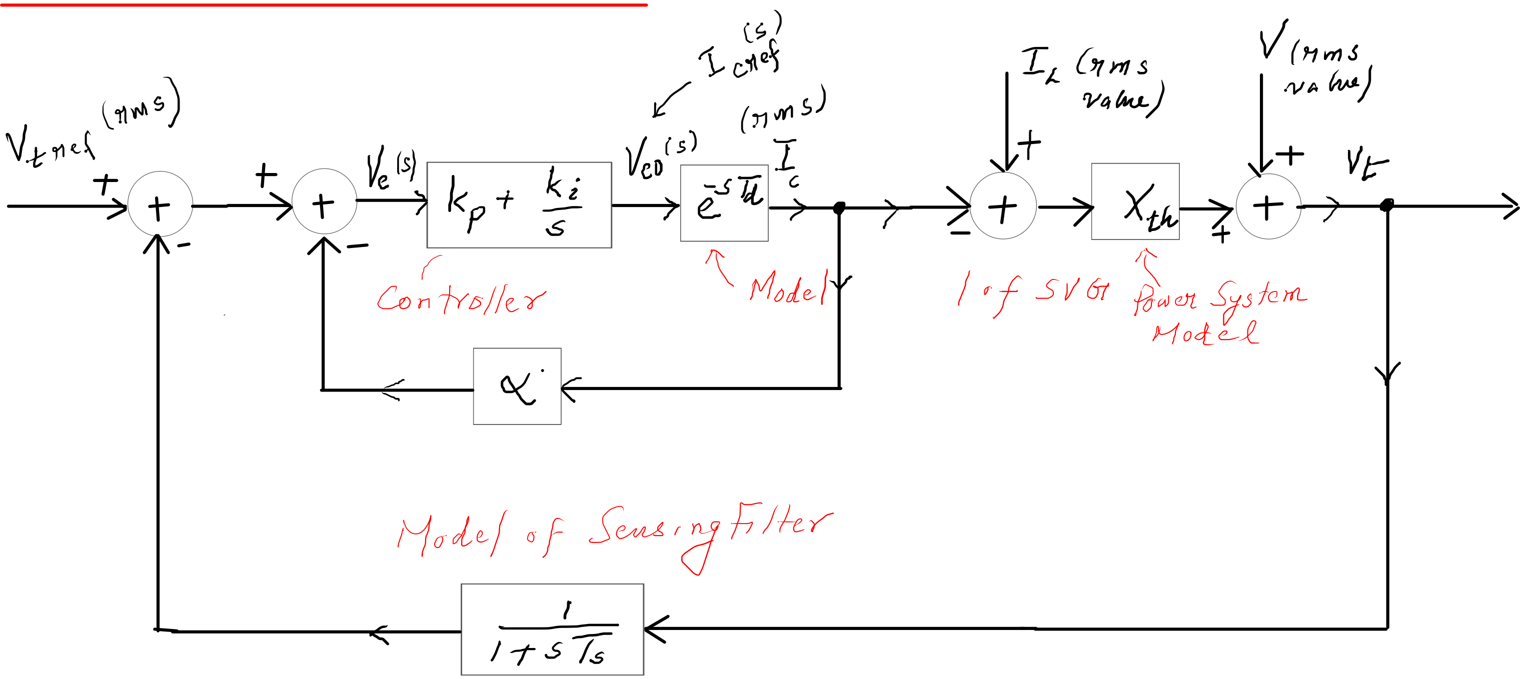
SVC Control With Regulation Droop



Load Line Equation is

$$V_t = V + X_{th}(I_c - I_L) \quad (1)$$

Regulation characteristic Equation is

$$V_t = V_{tref} - \alpha I_c \quad (2)$$

($V_e = 0$ under steady state

So $V_{tref} - V - \alpha I_c = 0$)

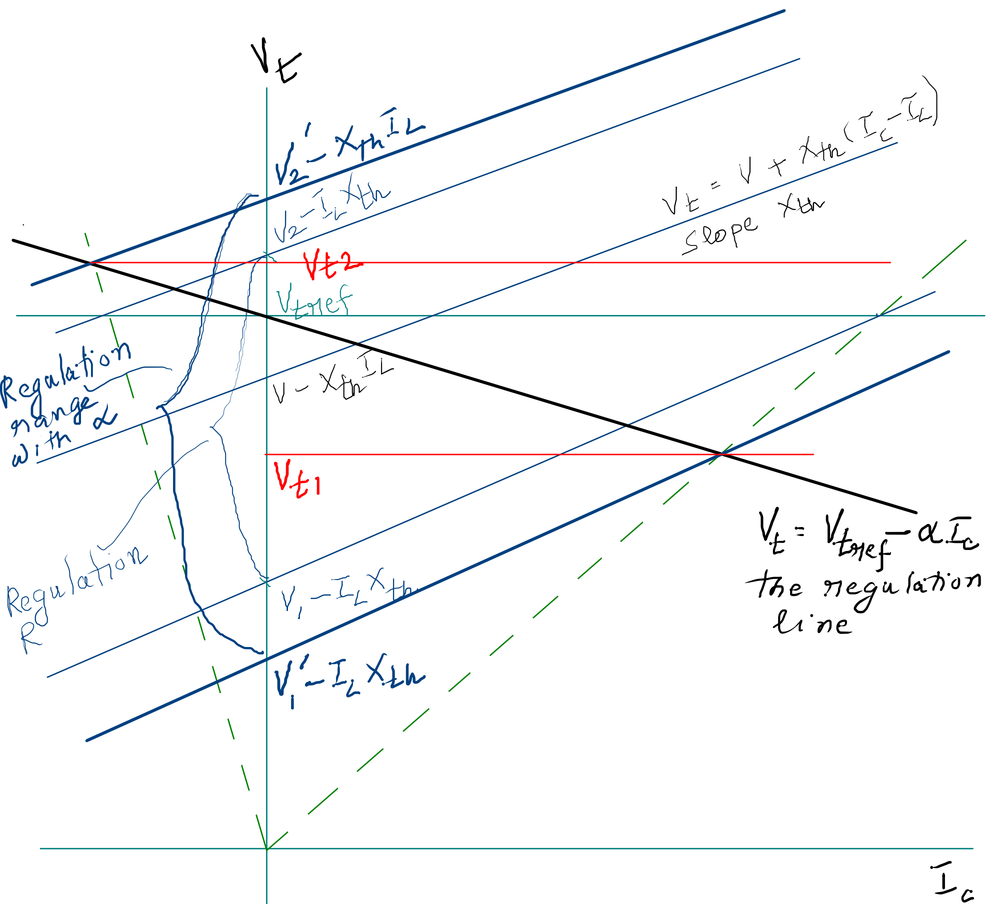
Operating point is the intersection between these two lines provided the I_c required at that operating point is within limits.

Solving (1) & (2) $V + X_{th}(I_c - I_L) = V_{tref} - \alpha I_c$

$$\therefore I_c = \frac{V_{tref} - V}{\alpha + X_{th}} + \frac{X_{th} I_L}{\alpha + X_{th}} \quad \text{and} \quad \text{—— } (3)$$

$$V_t = V_{tref}\frac{X_{th}/\alpha}{1 + X_{th}/\alpha} + V\frac{1}{1 + X_{th}/\alpha} - \frac{I_L X_{th}}{1 + \frac{X_{th}}{\alpha}} \quad \text{—— } (4)$$

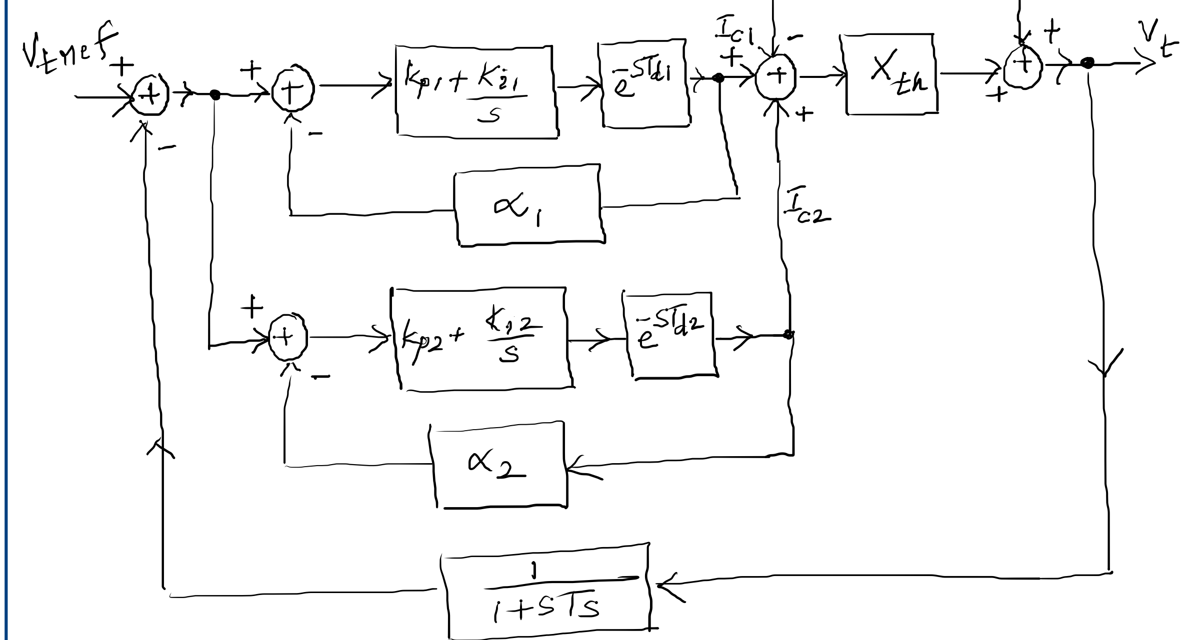
SVC Control



With $\alpha = 0$, V_t is maintained at V_{tref} when V varies over V_1 to V_2

With $\alpha \neq 0$, V_t is maintained between V_{t1} & V_{t2} when V varies over V_1' to V_2'

Control for Parallel Units



Under Steady-state,

$$\left.\begin{aligned} V_{tref} - V_t - \alpha_1 I_{c1} &= 0 \\ V_{tref} - V_t - \alpha_2 I_{c2} &= 0 \end{aligned}\right\} \Rightarrow \alpha_1 I_{c1} = \alpha_2 I_{c2}$$

$$\therefore \frac{I_{c1}}{I_{c2}} = \frac{\alpha_2}{\alpha_1} \Rightarrow \frac{I_{c2}}{I_{c1}+I_{c2}} = \frac{\alpha_1}{\alpha_1+\alpha_2}; \quad \frac{I_{c1}}{I_{c1}+I_{c2}} = \frac{\alpha_2}{\alpha_1+\alpha_2}$$

SVC Control

SVC Rating Calculation Given Ranges for V and Vt

Example: If $V \in [0.93\,pu,\ 1.05\,pu]$ and $V_{tref} = 1\,pu$, $V_t \in [0.95\,pu,\ 1.02\,pu]$ and $X_{th} = 0.1\,pu$ I_L can vary from 0 to 1 pu find rating of SVC.

$$V_t = V_{tref}\frac{X_{th}/\alpha}{1 + X_{th}/\alpha} + V\frac{1}{1+X_{th}/\alpha} - \frac{I_L X_{th}}{1+\frac{X_t}{\alpha}}$$

$$I_c = \frac{V_{tref} - V}{\alpha + X_{th}} + \frac{X_{th} I_L}{\alpha + X_{th}}$$

$$0.95 \le \frac{0.93}{1 + X_{th}/\alpha} + 1\,\frac{X_{th}/\alpha}{1+X_{th}/\alpha} - \frac{1 \times 0.1}{1 + X_{th}/\alpha}$$

$$\therefore \frac{X_{th}}{\alpha} \geq 2.4$$

$$\therefore \alpha \leq 0.0417$$

Then I_c needed $= \dfrac{1 - 0.93}{0.1417} + \dfrac{0.1 \times 1}{0.1417}$

$= 1.2\,pu$

But this I_c must be available from 0.95 pu voltage.

$\therefore$ Rated $I_{cmax} = \dfrac{1.2}{0.95} = 1.263\,pu.$

||| ly

$$1.02 \geq \frac{1.05}{1 + \frac{X_{th}}{\alpha}} + 1\,\frac{X_{th}/\alpha}{1 + X_{th}/\alpha} - 0 \times \frac{0.1}{1 + \frac{X_{th}}{\alpha}}$$

$$\therefore \frac{X_{th}}{\alpha} \geq 1.5 \Rightarrow \alpha \leq 0.0667$$

$\therefore \alpha = 0.0417$ accepted.

With this α, V_t when $V = 1.05$, $I_L = 0$ will be $V_t = \dfrac{1.05}{1 + 2.4} + 1\,\dfrac{2.4}{3.4} = 1.0147\,pu$

and I_{cmin} needed $= \dfrac{1 - 1.05}{0.1417} + \dfrac{0 \times 0.1}{0.1417}$

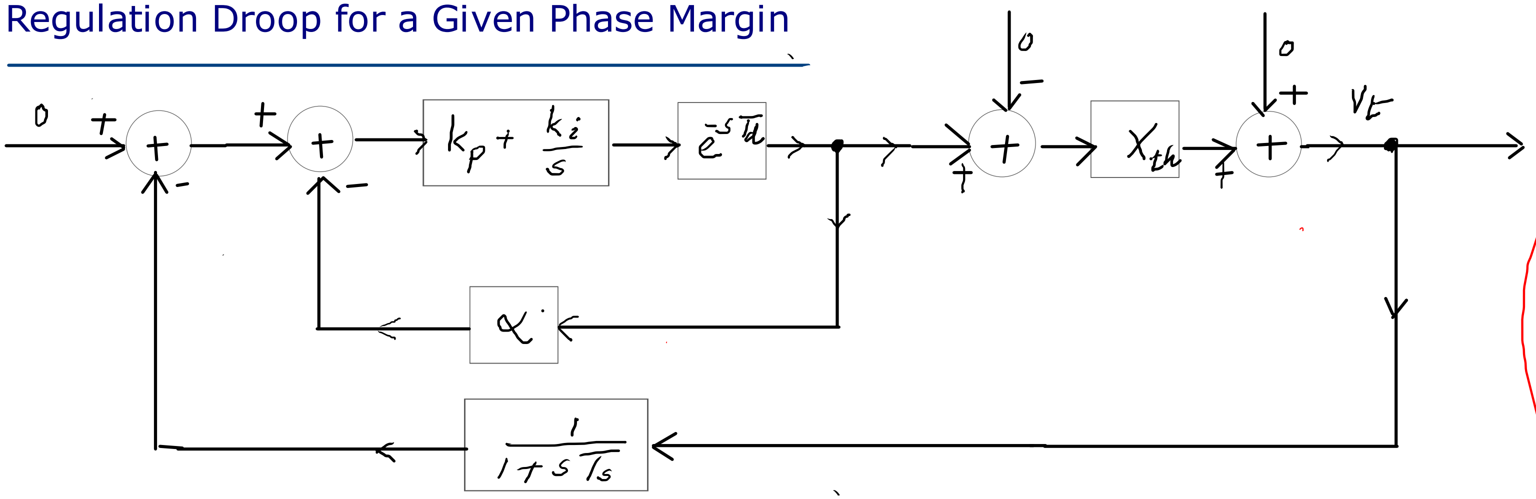
$= -0.352\,pu$ at 1.0147 pu voltage

$\therefore I_{cmin}$ at 1 pu voltage $= -0.348\,pu \simeq -0.35\,pu$

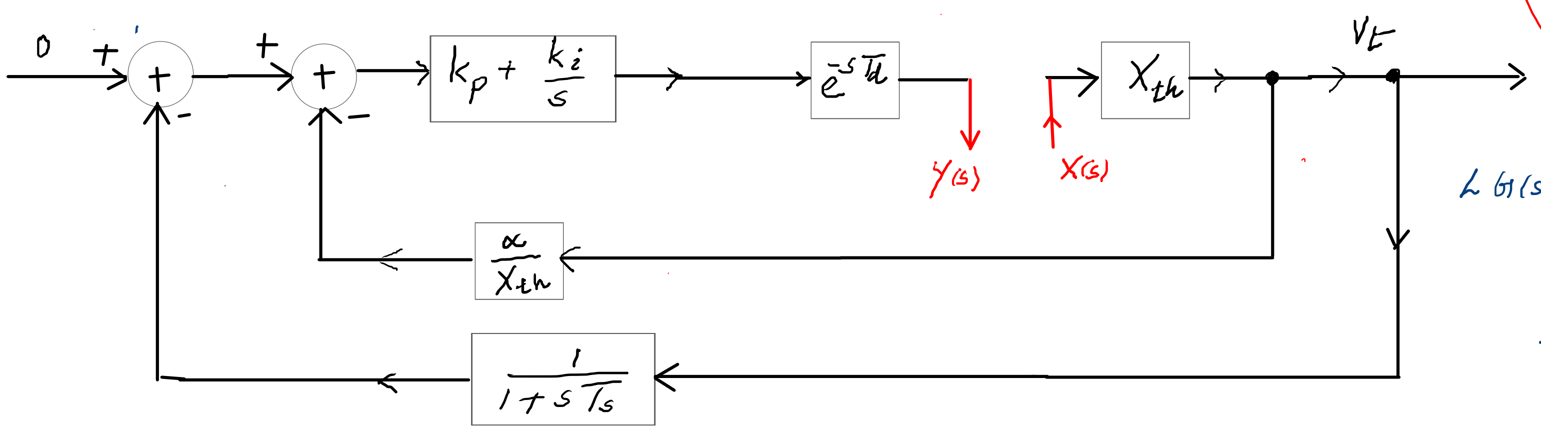
$\therefore$ SVC Rating $= (-0.35\,pu$ to $1.263\,pu)$.

SVC Control

Designing the Closed Loop SVC Control with Regulation Droop for a Given Phase Margin



1. How does the rating of SVC affect this design?
2. Where is the rating accounted for?
3. How does X_{th} value affect the design?



$$\angle G(s) = -X_{th}\,\frac{\alpha + X_{th} + s\alpha T_s}{X_{th}(1+sT_s)}\;\frac{k_i(1+s\tau_i)}{s}\,e^{-sT_d}$$

$$= -(\alpha + X_{th})\,k_i\left(\frac{1+s\tau_i}{s}\right)\left(\frac{1+s\,\frac{\alpha T_s}{\alpha + X_{th}}}{1+sT_s}\right)e^{-sT_d}$$

SVC Control

Choose f_{co} (and ω_{co}).

Delay Angle of $\angle G(j\omega_{co})$ is given by

$$180^\circ + 90^\circ + \omega_{co} T_d \frac{180}{\pi} - \tan^{-1} \omega_{co} \tau_i - \tan^{-1} \frac{\omega_{co} \alpha T_s}{\alpha + X_{th}} + \tan^{-1} \omega_{co} T_s$$

This must be $= 360^\circ - \phi$ where ϕ is the specified phase margin.

$\omega_{co} \tau_i$ can be found from this and so τ_i can be found. Then applying loop gain cross over condition,

$$k_i (\alpha + X_{th}) \frac{\sqrt{1 + (\omega_{co}\tau_i)^2}}{\omega_{co}} \frac{\sqrt{1 + \left(\frac{\omega_{co} \alpha T_s}{\alpha + X_{th}}\right)^2}}{\sqrt{1 + (\omega_{co} T_s)^2}} = 1$$

k_i can be found.

$\tau_i = \frac{k_p}{k_i}$, so k_p can be found.

Example: $X_{th} = 0.1$ pu $\quad \alpha = 0.04 \quad T_d = \frac{T}{6} = 3.33$ ms

$T_s = 5.3$ ms $\quad \phi = 45^\circ$.

Choose $f_{co} = 30$ Hz.

$$180^\circ + 90^\circ + 60\pi \times 3.33 \times 10^{-3} \times \frac{180}{\pi} - \tan^{-1} \omega_{co} \tau_i - \tan^{-1} \frac{60\pi \times 0.04 \times 5.3 \times 10^{-3}}{0.14} + \tan^{-1} 60\pi \times 5.3 \times 10^{-3} = 360 - 45$$

$$36^\circ - \tan^{-1} \omega_{co} \tau_i - 15.93^\circ + 45^\circ = 45^\circ$$

$$\therefore \tan^{-1} \omega_{co} \tau_i = 20.07^\circ$$

$$\therefore \omega_{co} \tau_i = 0.3653$$

$$\text{So } \tau_i = 0.00194$$

$$k_i \times 0.14 \times \frac{\sqrt{1 + 0.3653^2}}{60\pi} \frac{\sqrt{1 + \left(\frac{60\pi \times 5.33 \times 10^{-3} \times 0.04}{0.14}\right)^2}}{\sqrt{1 + (60\pi \times 5.33 \times 10^{-3})^2}} = 1$$

So $k_i = 1717.6$

and $\frac{k_p}{k_i} = 0.00194$, $\quad k_p = k_i \tau_i = 3.33$

So $k_p = 3.33$ & $k_i = 1717.6$ for Phase Margin of 45°.

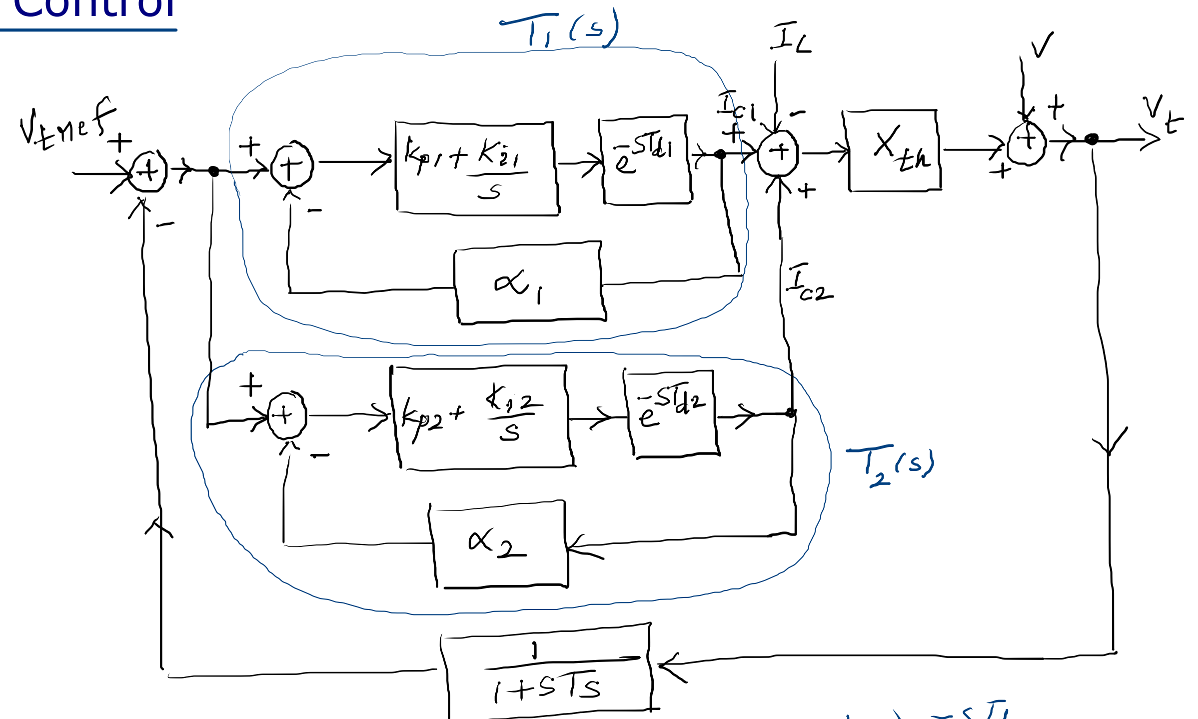
SVC Control

Designing the Closed Loop SVC Control with Regulation Droop for a Given Phase Margin for Parallel Connected SVC Units

Consider a case where two SVC units of ratings R_1, R_2 are in $\parallel^{el}$ at a bus.

Step 1 : Decide α value based on total rating $R = R_1 + R_2$, range of V_g variation, range of I_L variation and allowed range of variation for V_t.

Step 2 : Design k_p & k_i values with this value of α and relevant X_{th} treating the two units as a single unit of rating $R = R_1 + R_2$.



Let $\beta \triangleq \dfrac{R_1}{R_1+R_2}$; $1-\beta = \dfrac{R_2}{R_1+R_2}$

Then use

$$k_{p1} = \beta k_p, \quad k_{i1} = \beta k_i, \quad \alpha_1 = \frac{\alpha}{\beta}$$

$$k_{p2} = (1-\beta) k_p, \quad k_{i2} = (1-\beta) k_i, \quad \alpha_2 = \frac{\alpha}{1-\beta}$$

in the Controllers for two units.

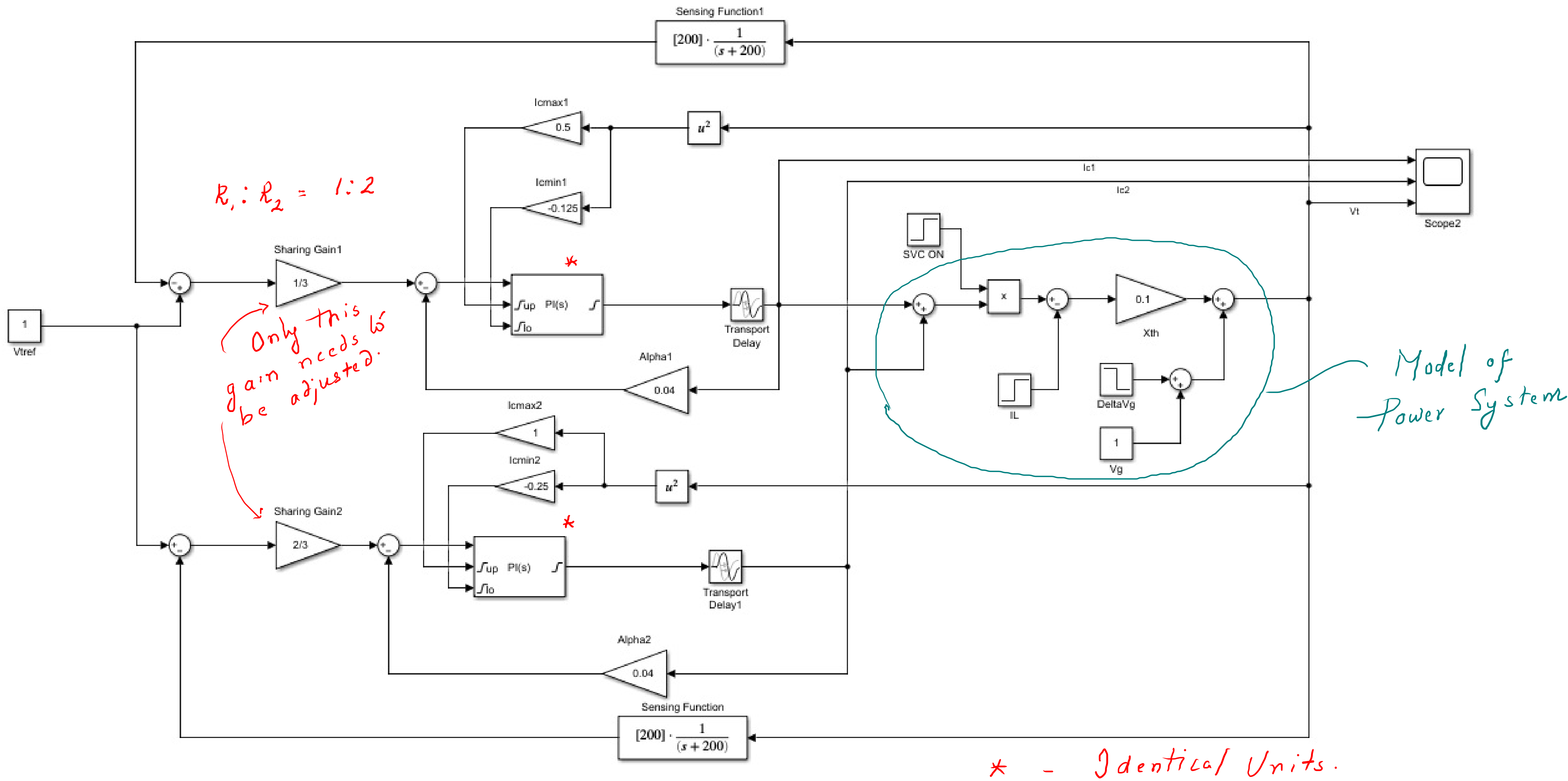
$$T_1(s) = \frac{\left(\beta k_p + \beta \frac{k_i}{s}\right) e^{-sT_d}}{1 + \alpha \left(k_p + \frac{k_i}{s}\right) e^{-sT_d}} = \frac{\beta \left(k_p + \frac{k_i}{s}\right) e^{-sT_d}}{1 + \alpha \left(k_p + \frac{k_i}{s}\right) e^{-sT_d}}$$

$$T_2(s) = \frac{\left[(1-\beta) k_p + (1-\beta) \frac{k_i}{s}\right] e^{-sT_d}}{1 + \alpha \left(k_p + \frac{k_i}{s}\right) e^{-sT_d}} = \frac{(1-\beta)\left(k_p + \frac{k_i}{s}\right) e^{-sT_d}}{1 + \alpha \left(k_p + \frac{k_i}{s}\right) e^{-sT_d}}.$$

$$T_1(s) + T_2(s) = \frac{\left(k_p + \frac{k_i}{s}\right) e^{-sT_d}}{1 + \alpha \left(k_p + \frac{k_i}{s}\right) e^{-sT_d}} = \text{Same as in total system}$$

$$\frac{I_{c1}(s)}{I_{c2}(s)} = \frac{T_1(s)}{T_2(s)} = \frac{\beta}{1-\beta} = \frac{R_1}{R_2}$$; in the rating ratio always.

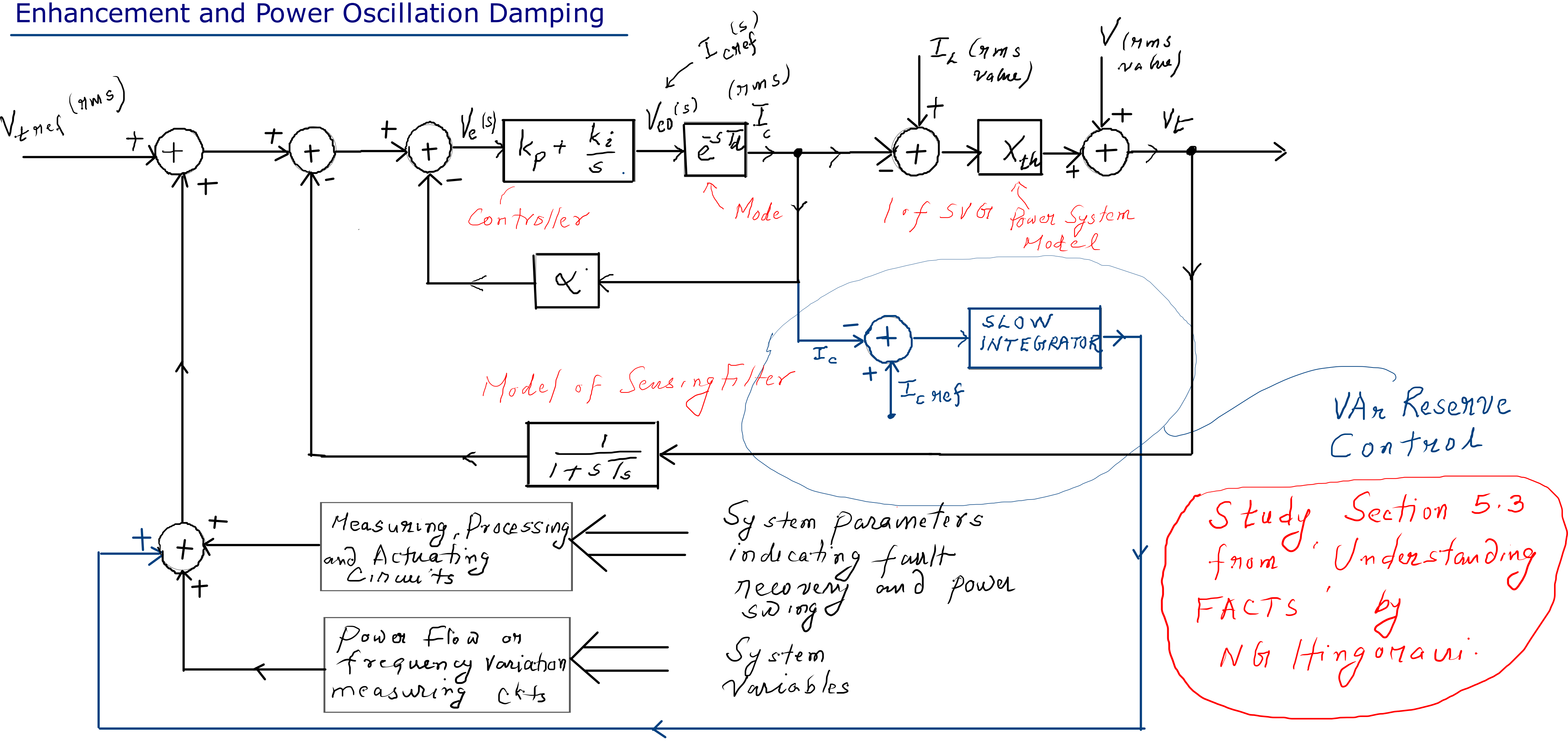
SVC Control



Sensing Function1
[200] · 1/(s + 200)
Icmax1
0.5
u^2
Icmin1
-0.125
$R_1 : R_2 = 1:2$
Sharing Gain1
1/3
PI(s)
*
Transport Delay
Ic1
Ic2
Vt
Scope2
SVC ON
x
0.1
Xth
IL
DeltaVg
1
Vg
Vtref
Only this gain needs to be adjusted.
Alpha1
0.04
Model of Power System
Icmax2
1
Icmin2
-0.25
Sharing Gain2
2/3
Transport Delay1
Alpha2
0.04
Sensing Function
[200] · 1/(s + 200)
* - Identical Units.

SVC Control

Supplementary Controls for Transient Stability Enhancement and Power Oscillation Damping



Study Section 5.3 from 'Understanding FACTS' by N G Hingorani.