Internal Control of STATCOM

Internal Control Objective

External Control loop of STATCOM sets the reference for reactive current to be drawn by the Inverter inside the STATCOM. This will be in the form of a dc voltage representing the desired reactive current rms value to be drawn by STATCOM. We assume that a +ve value indicates that STATCOM has to draw capacitive reactive current and a −ve value indicates that STATCOM has to draw inductive reactive current.

Internal Control makes the reactive current drawn by STATCOM Inverter equal to reference value as fast as possible with good dynamic response.

Internal Control strategy depends on the Type of Inverter used inside STATCOM.

Types of STATCOM

Type I STATCOM: is a STATCOM that has an inverter that is capable of varying the amplitude of output sinusoidal voltage by means of some modulation strategy with DC side voltage maintained constant.
Eg: PWM Converter, Multi-Level Converters, Multi-pulse Converters with PHE etc

Type II STATCOM: is a STATCOM that has an inverter with amplitude of output rigidly fixed by dc side voltage with no modulation strategy available. DC side voltage has to be varied to change the a.c output amplitude. eg: Multi-pulse Converter without PHE

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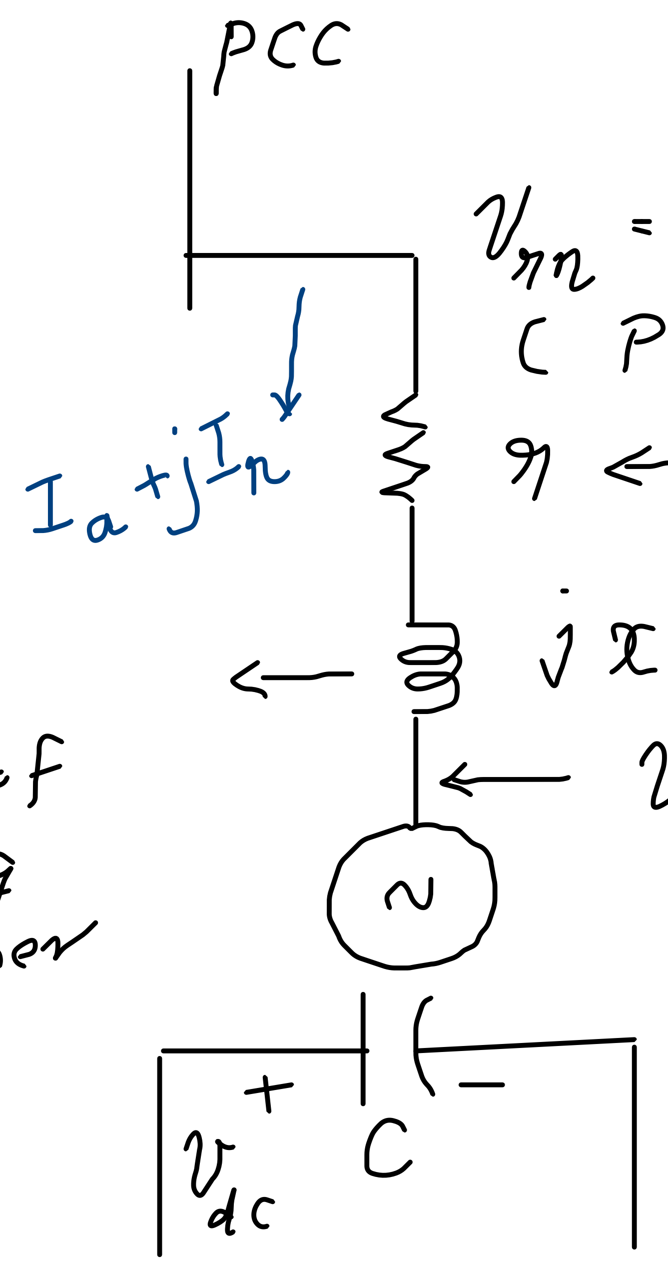
Internal Control of Type 2 STATCOM



$v_{rn} = \sqrt{2} V \sin \omega t$; $V\angle 0$
(phase voltage)

r ← includes transformer + inverter loss resistances

leakage reactance of interfacing transformer

$v_{inv} = \sqrt{2}\, k\, V_{dc} \sin(\omega t - \Delta\alpha)$
(r-phase voltage)
$k V_{dc} \angle -\Delta\alpha$

Assumptions :
1) Harmonics in v_{in} are neglected in analysis
2) α is adjusted only once in a cycle
3) α is adjusted in small steps.
4) Capacitor is loss-free

* For approximate modeling and analysis we neglect r and take it as 0.

We express v_{dc} as $V_{dc} + \Delta V_{dc}$ where V_{dc} is the DC side voltage when STATCOM is delivering zero reactive current. Under that condition

$V_{dc} = V/k$ and $\Delta\alpha = 0$

Now, if we want STATCOM to draw capacitive current of value ΔI_{cref} (rms) inverter output voltage should increase by $x\, \Delta I_{cref}$ (rms value) and so dc voltage across capacitor has to increase by $\Delta v_{dc} = \dfrac{x\, \Delta I_{cref}}{k}$

Similarly if we want STATCOM to draw inductive current of value $-\Delta I_{cref}$ (where ΔI_{cref} is +ve), capacitor voltage has to decrease by $\Delta v_{dc} = -\dfrac{x\, \Delta I_{cref}}{k}$

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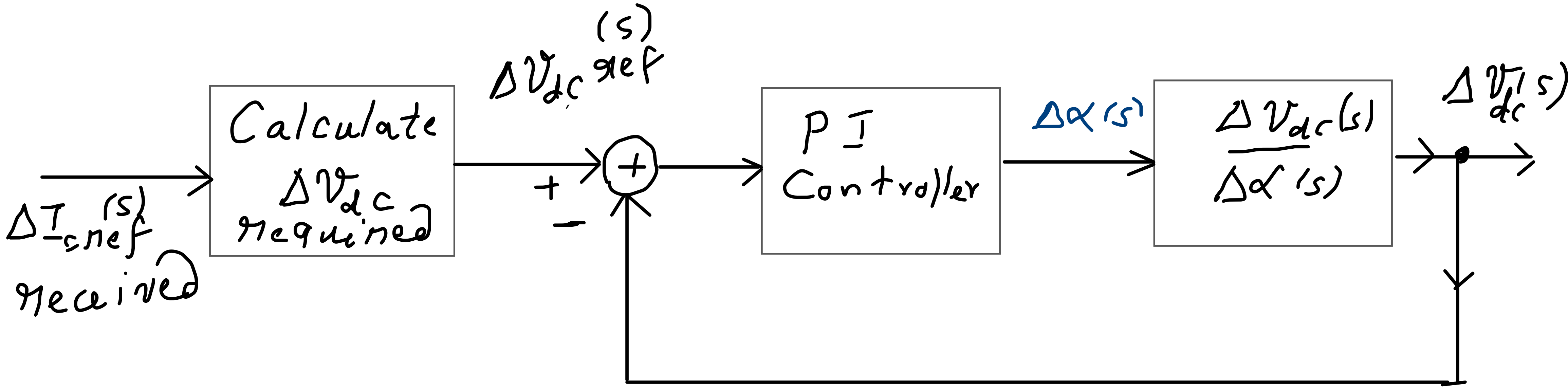
Thus, for capacitive compensation v_{dc} has to increase above V_{dc} $(= V/k)$ and for inductive compensation v_{dc} has to decrease below V_{dc}.

Increase or decrease in v_{dc} is possible only by drawing / delivering active power. And that is possible iff $\Delta\alpha \neq 0$.

So to increase V_{dc} we have to increase $\Delta\alpha$ from 0 temporarily, let inverter draw active power and charge up capacitor to the correct of v_{dc} which is $V_{dc} + \frac{x}{k}\Delta I_{cref}$

and to decrease V_{dc} we have to make $\Delta\alpha$ −ve temporarily, let the inverter deliver active power and thereby discharge the capacitor to $V_{dc} - \frac{x}{k}\Delta I_{cref}$

So $\Delta\alpha$ is the control variable.



We need the transfer fn $\frac{\Delta V_{dc}(s)}{\Delta\alpha(s)}$ to design the PI Controller.

Active power drawn when phase angle is changed from 0 to $\Delta\alpha$

$$= \frac{3Vk(V_{dc}+\Delta V_{dc})}{x}\sin\Delta\alpha$$

$$\simeq \frac{3VkV_{dc}}{x}\Delta\alpha = \frac{3V^2}{x}\Delta\alpha$$

Energy balance over Δt is

$$\left(\frac{3V^2}{x}\Delta\alpha\right)\Delta t = \frac{1}{2}C(V_{dc}+\Delta V_{dc})^2 - \frac{1}{2}CV_{dc}^2$$

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i.e $C V_{dc} \, \Delta v_{dc} = \frac{3V^2}{x} \Delta\alpha \cdot \Delta t$

$$\therefore \frac{\Delta v_{dc}}{\Delta t} = \frac{3V^2}{C V_{dc} x} \Delta\alpha = \frac{3V^2}{C \frac{V}{k} x} \Delta\alpha$$

$$= \frac{3kV}{Cx} \Delta\alpha.$$

Taking $Lt \; \Delta t \to 0$,

$$\frac{d \, \Delta v_{dc}}{dt} = \frac{3kV}{Cx} \Delta\alpha$$

$$\therefore \frac{\Delta V_{dc}(s)}{\Delta\alpha(s)} = \left(\frac{3kV}{Cx}\right) \frac{1}{s} = \frac{\beta}{s}$$

Now the PI controller can be designed.

$$\frac{\Delta V_{dc}(s)}{\Delta V_{dcref}(s)} = \frac{\left(K_p + \frac{k_i}{s}\right) \frac{\beta}{s}}{1 + \left(K_p + \frac{k_i}{s}\right) \frac{\beta}{s}}$$

$$= \frac{(k_p s + k_i)\beta}{s^2 + (k_p s + k_i)\beta} = \frac{\beta k_p \left(s + \frac{k_i}{k_p}\right)}{s^2 + k_p \beta s + k_i \beta}$$

Make one of the factors of denominator same as $s + \frac{k_i}{k_p}$.

i.e $\left(s + \frac{k_i}{k_p}\right)(s + \alpha) = s^2 + k_p \beta s + k_i \beta$

$$\therefore \frac{k_i}{k_p} + \alpha = k_p \beta \quad \& \quad \frac{\alpha k_i}{k_p} = k_i \beta$$

Then $\frac{\Delta V_{dc}(s)}{\Delta V_{dcref}(s)} = \frac{\beta k_p}{s + \beta k_p}$

The rise time will be $\frac{2.2}{\beta k_p}$ seconds.

We have assumed that the system is in a continued sinusoidal steady-state even when $\Delta\alpha$ is varying. That is why we used phasor theory. This is valid iff $\Delta\alpha$ is varying slowly.

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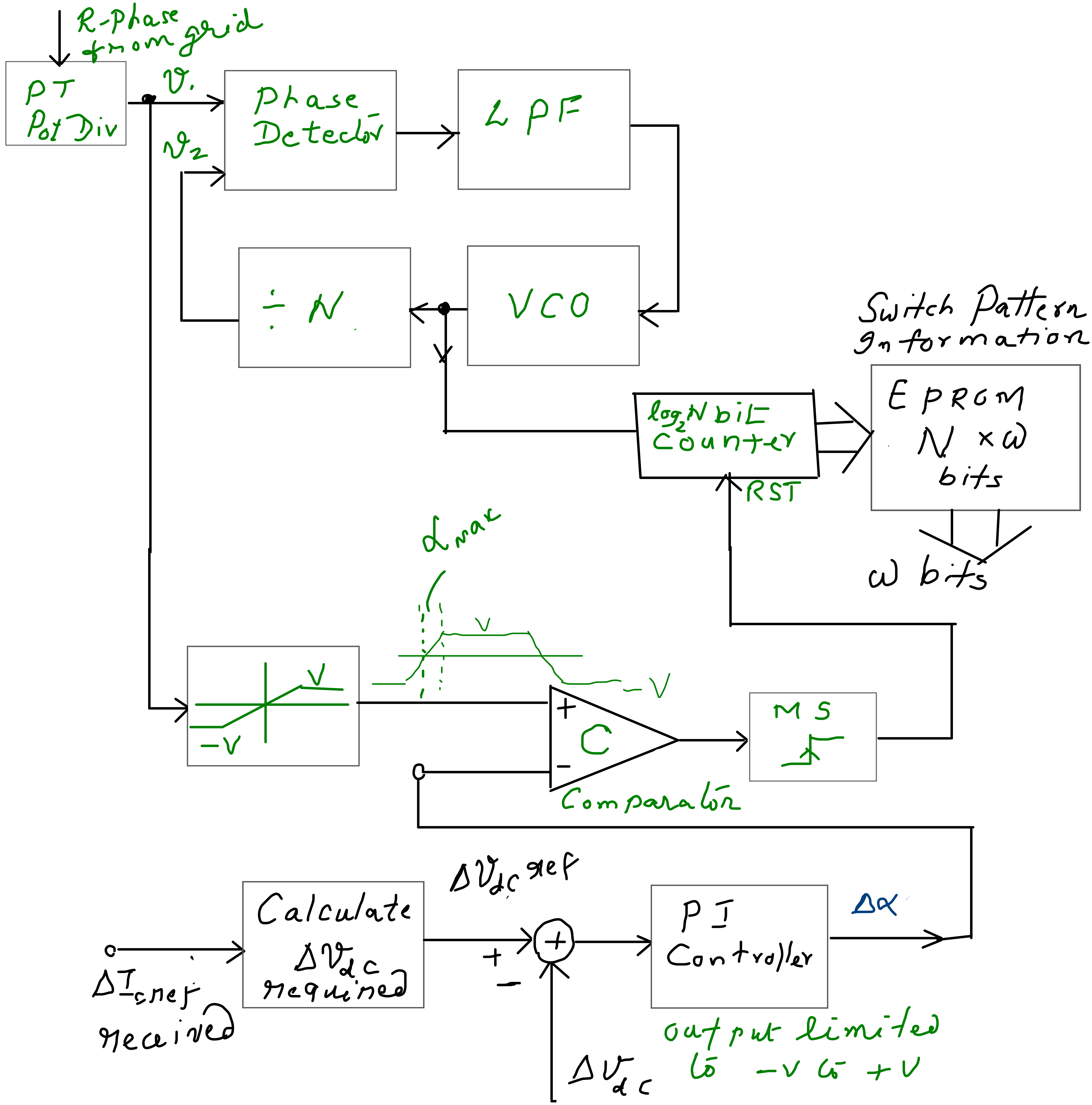
So rise time has to be much more than 20 ms. Choose a rise time between 100 ms – 200 ms. Then k_p can be found. k_i will be 0 and a simple proportional controller is enough.

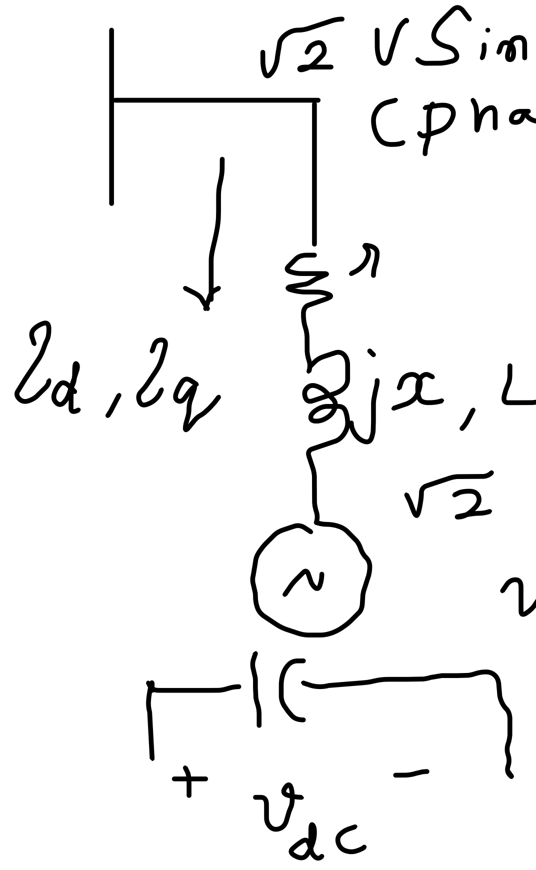
However if dielectric losses in C is considered, we will need a PI controller.



Internal Control of STATCOM

DQ Modeling of Type 2 STATCOM

Objective – Obtain a more accurate $\frac{\Delta V_{dc}(s)}{\Delta\alpha(s)}$



$v_d = V, \; v_q = 0$

$\sqrt{2}\, k V_{dc} \sin(\omega t - \Delta\alpha)$

$v_d = k V_{dc} \cos\Delta\alpha \simeq k V_{dc}$

$v_q = -k V_{dc} \sin\Delta\alpha \simeq -k V_{dc}\,\Delta\alpha$

Initial Operating Point is assumed to be zero – i.e zero shunt inverter current.

$\therefore \; k V_{dc} = V \; ; \; V_{dc} = V/k$

$i_d = i_q = 0, \quad \alpha = 0$

Now α is increased to $\Delta\alpha$ leading to ΔV_{dc}, Δi_d, Δi_q, Δv_d & Δv_q in inverter

$\Delta v_d = k(V_{dc} + \Delta V_{dc}) - k V_{dc} = k\,\Delta V_{dc}$

$\Delta v_q = -k(V_{dc} + \Delta V_{dc})\Delta\alpha - 0 \simeq -k V_{dc}\,\Delta\alpha = -V\Delta\alpha$

ΔP = Change in active power drawn by inverter

$= 3(V_{dc} + \Delta V_{dc})\,\Delta i_d + 3(0 + \Delta v_q)\,\Delta i_q$

$\simeq 3 V_{dc}\,\Delta i_d$

$r\,\Delta i_d + \frac{x}{\omega}\frac{d}{dt}\Delta i_d - x\,\Delta i_q = -\Delta v_d = -k\,\Delta V_{dc}$ (1)

$r\,\Delta i_q + \frac{x}{\omega}\frac{d}{dt}\Delta i_q + x\,\Delta i_d = -\Delta v_q = V\Delta\alpha$ (2)

$\Delta P \times \Delta t = \frac{1}{2}C(V_{dc} + \Delta V_{dc})^2 - \frac{1}{2}C V_{dc}^2$

$\therefore \; \frac{d\,\Delta V_{dc}}{dt} = \frac{3\,\Delta i_d}{C}$ (3)

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Laplace transforming (1), (2), (3)

$$\left(r + \frac{sx}{\omega}\right)\Delta i_d(s) - x\,\Delta i_q(s) = -k\,\Delta v_{dc}(s) \quad (4)$$

$$\left(r + \frac{sx}{\omega}\right)\Delta i_q(s) + x\,\Delta i_d(s) = V\,\Delta\alpha(s) \quad (5)$$

$$\Delta v_{dc}(s) = \frac{3}{sC}\,\Delta i_d(s) \quad (6)$$

From (5) $\Delta i_q(s) = \dfrac{-x}{r + \frac{sx}{\omega}}\Delta i_d(s) + \dfrac{V}{r+\frac{sx}{\omega}}\Delta\alpha(s)$ (7)

Putting (6) & (7) in (4)

$$\left(r + \frac{sx}{\omega} + \frac{x^2}{r+\frac{sx}{\omega}} + \frac{3}{sC}\right)\Delta i_d(s) = \frac{xV}{r+\frac{sx}{\omega}}\Delta\alpha(s)$$

$$\therefore \frac{\Delta i_d(s)}{\Delta\alpha(s)} = \frac{sCxV}{s\frac{C}{3}\left(r+\frac{sx}{\omega}\right)^2 + s\frac{x^2C}{3} + k\left(r+\frac{sx}{\omega}\right)}$$

$$= \frac{sCxV/3}{s^3\frac{x^2C}{\omega^2 3} + s^2\frac{2xrC}{\omega\, 3} + s\left(\frac{r^2C}{3} + \frac{x^2C}{3} + \frac{kx}{\omega}\right) + kr}$$

$$\therefore \frac{\Delta V_{dc}(s)}{\Delta\alpha(s)} = \frac{xV}{s^3\frac{x^2C}{3\omega^2} + s^2\frac{2xrC}{\omega 3} + s\left(\frac{r^2C}{3} + \frac{x^2C}{3} + \frac{kx}{\omega}\right) + kr}$$

$$= \frac{3\omega^2V/xC}{s^3 + \frac{2\omega r}{x}s^2 + s\left(\omega^2 + \frac{r^2}{x^2}\omega^2 + \frac{3\omega k}{xC}\right) + \frac{3kr\omega^2}{x^2C}}$$

But $x = \omega L$

$$\therefore \frac{\Delta v_{dc}(s)}{\Delta\alpha(s)} = \frac{3\omega V/LC}{s^3 + \frac{2r}{L}s^2 + s\left(\omega^2 + \frac{r^2}{L^2} + \frac{3k}{LC}\right) + \frac{3k}{LC}\frac{r}{L}}$$

It is a 3^{rd} order transfer function.

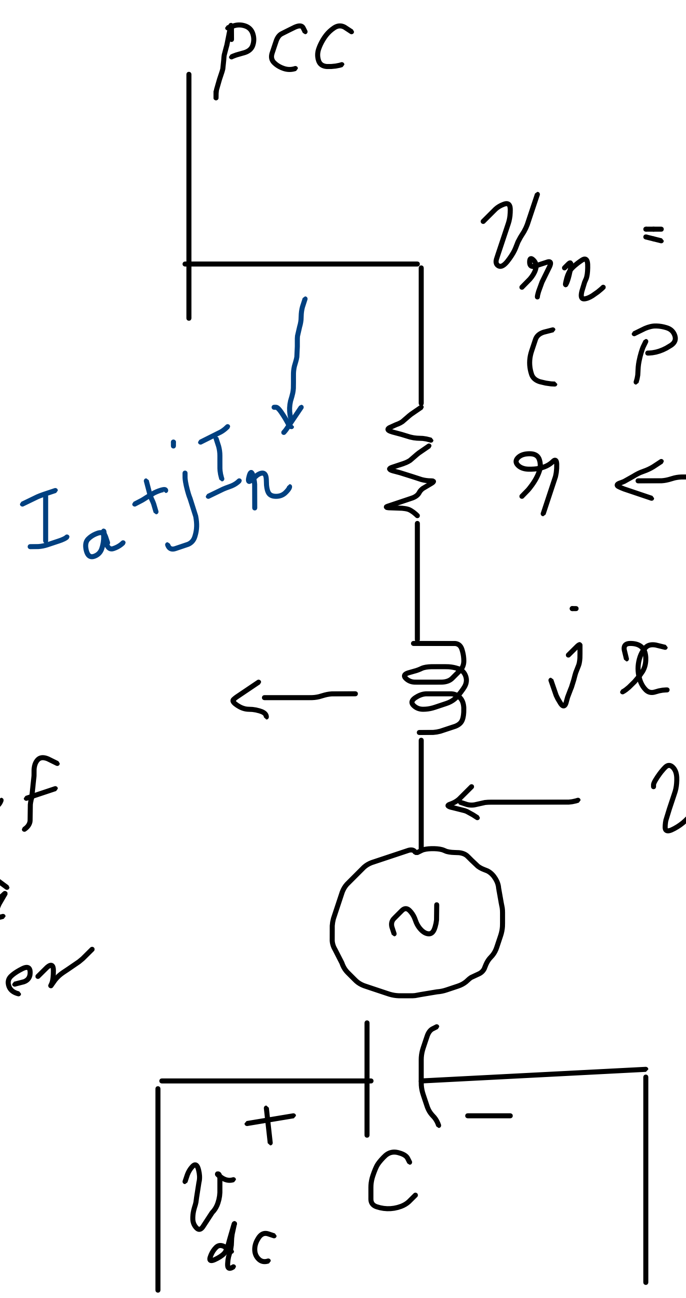
If r is neglected

$$\frac{\Delta v_{dc}(s)}{\Delta\alpha(s)} = \frac{3\omega V/LC}{s\left(s^2 + \omega^2 + \frac{3k}{LC}\right)}$$

We will need a compensator of lead-lag type along with proportional control for this kind of a 3^{rd} order TF.

Internal Control of Type 1 STATCOM

α Control for Vdc and Modulation Control for ΔIcref



$V_{rn} = \sqrt{2}V\sin\omega t$; $V\angle 0$
(phase voltage)

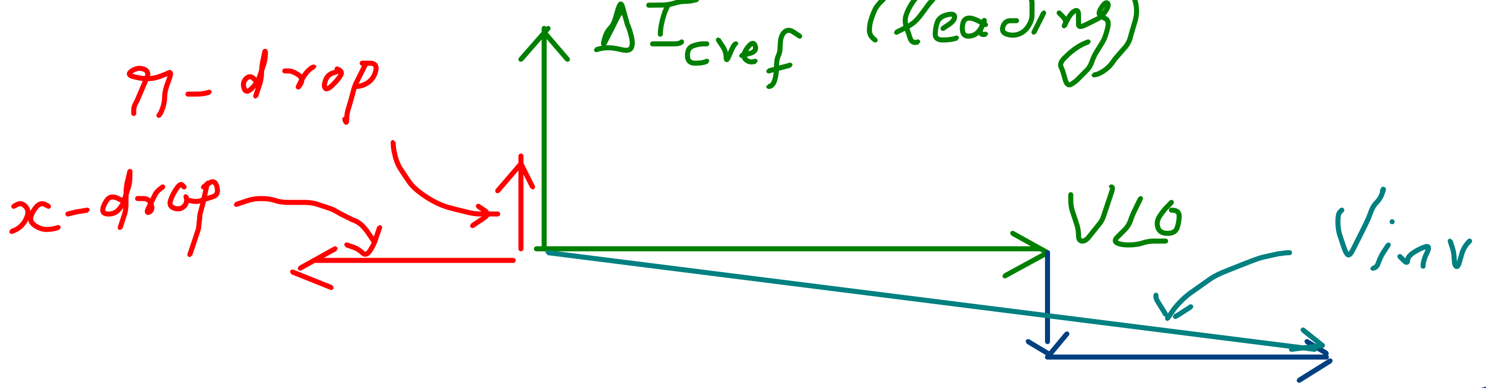
r ← includes transformer + inverter loss resistances

leakage reactance of interfacing transformer

$V_{inv} = \sqrt{2}\,k\,V_{dc}\,\sin(\omega t - \Delta\alpha)$
(r-phase voltage)
$kV_{dc}\angle -\Delta\alpha$

- V_{dc} is maintained at a reference value V_{dcref} by $\Delta\alpha$ control.
- Reactive current is controlled by calculating required amplitude of inverter voltage and making the inverter deliver it.

Calculation of V_{inv} amplitude when ΔI_{cref} is received



$\therefore$ V_{inv} amplitude $= \sqrt{2}\sqrt{(V + x\,\Delta I_{cref})^2 + (r\,\Delta I_{cref})^2}$

r, x must be known.

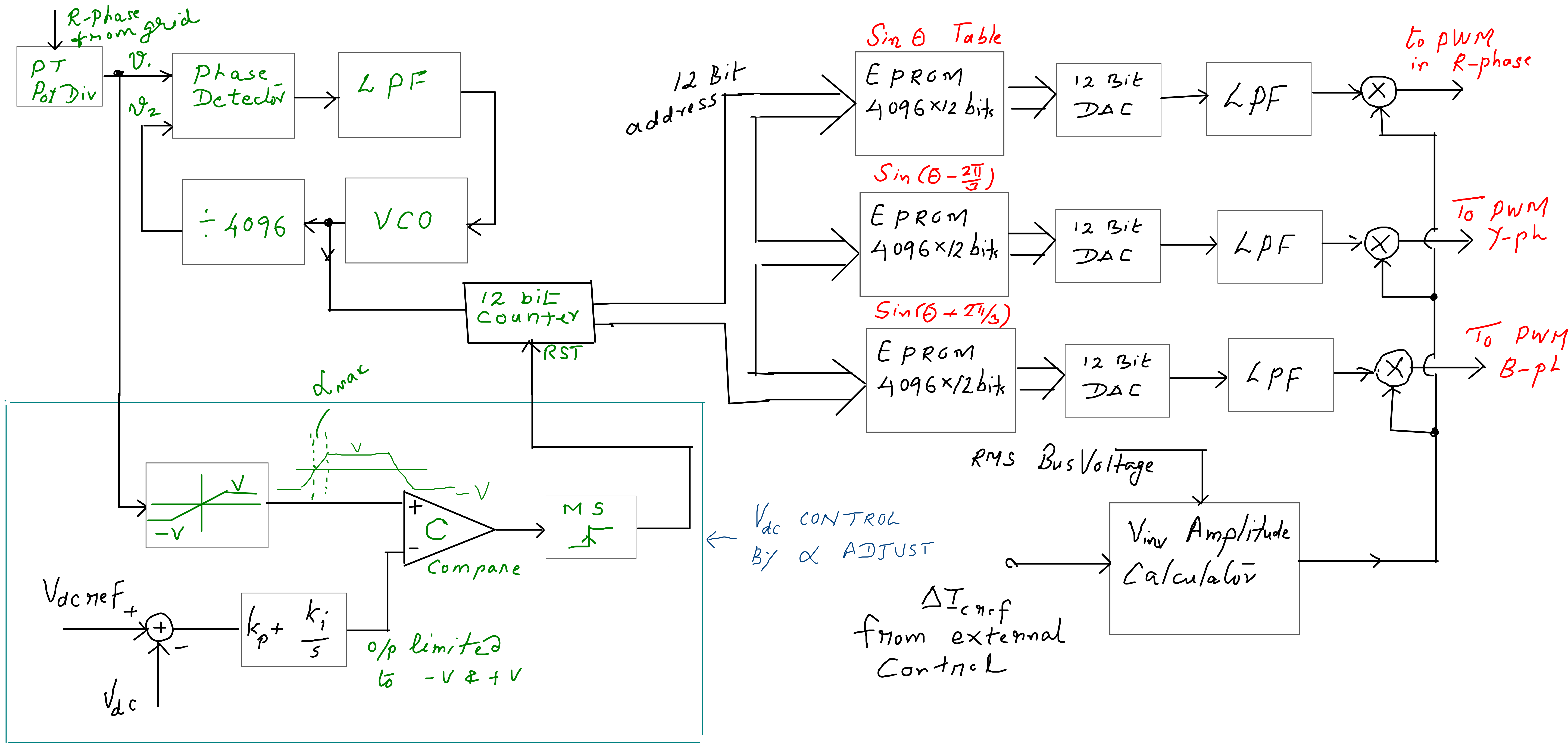
We consider two cases for the Type I Inverter.

Case 1 – 3ϕ PWM Inverter using Δ wave for PWM.

Case 2 – Multi-pulse Inverter with PHE.

Internal Control of Type 1 STATCOM

Case 1 - PWM Inverter



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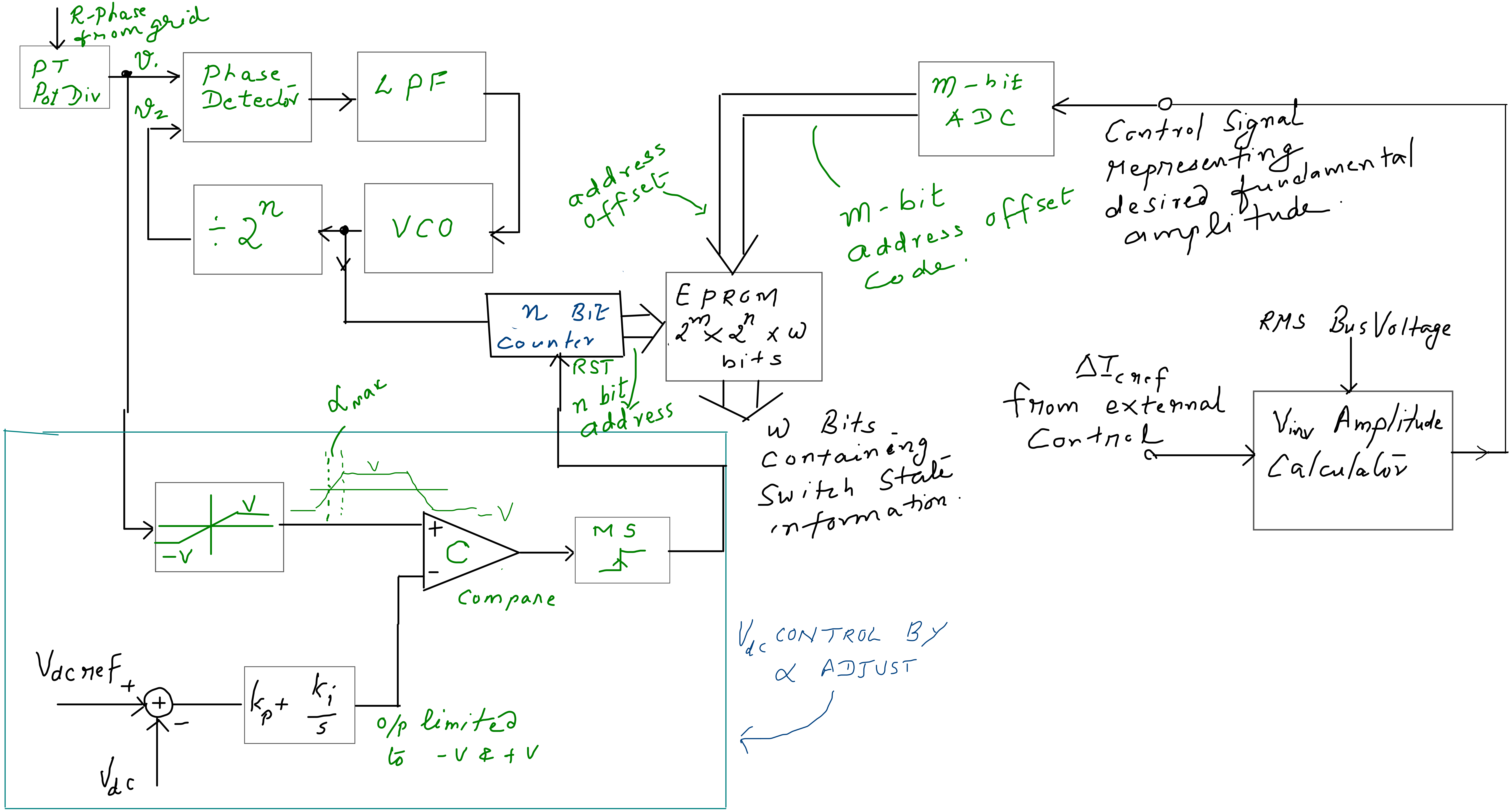
Case 2 - Multi-Pulse Inverter with PHE



Internal Control of Type 1 STATCOM

Feed Forward Control for a Type 1 STATCOM with PWM Inverter