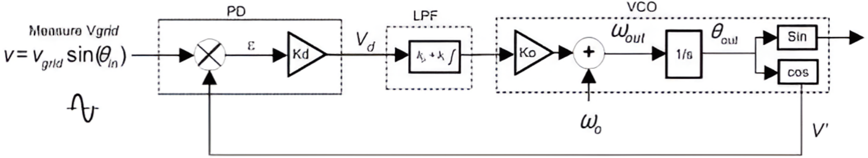
Introduction

- The phase angle of the utility grid is crucial for power devices like PV inverters to operate synchronously and efficiently.
- A Phase-Locked Loop (PLL) maintains a clean phase lock with the grid voltage using a Phase Detector (PD), Loop Filter (LPF), and a Voltage Controlled Oscillator (VCO).



PLL Phase Detector Equations

$$v = V_{\text{grid}} \sin(\theta_{\text{in}}) = V_{\text{grid}} \sin(\omega_{\text{grid}} t + \theta_{\text{grid}}) \tag{1}$$

$$V' = \cos(\theta_{\text{out}}) = \cos(\omega_{\text{PLL}} t + \theta_{\text{PLL}}) \tag{2}$$

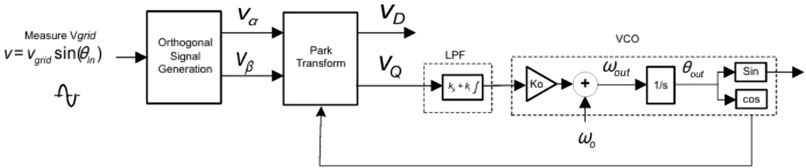
$$\begin{aligned} v_d = \frac{K_d V_{\text{grid}}}{2} \big[& \sin((\omega_{\text{grid}} - \omega_{\text{PLL}})t + (\theta_{\text{grid}} - \theta_{\text{PLL}})) \\ & + \sin((\omega_{\text{grid}} + \omega_{\text{PLL}})t + (\theta_{\text{grid}} + \theta_{\text{PLL}}))\big] \end{aligned} \tag{3}$$

$$v_d = \frac{K_d V_{\text{grid}}}{2} \sin((\omega_{\text{grid}} - \omega_{\text{PLL}})t + (\theta_{\text{grid}} - \theta_{\text{PLL}})) \tag{4}$$

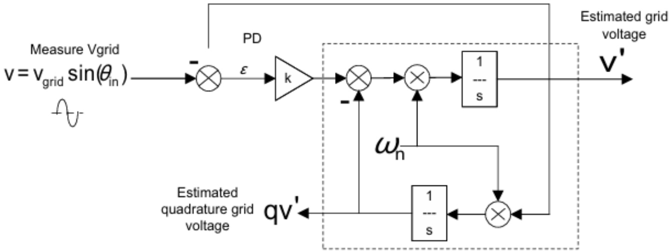
$$\text{err} = \frac{V_{\text{grid}}(\theta_{\text{grid}} - \theta_{\text{PLL}})}{2} \tag{5}$$

Orthogonal Signal Generator PLL

- Single-phase grid software PLL design is tricky because of the twice the grid frequency component present in the phase detect output.
- Use an orthogonal signal generator + Park transformation to linearize PD output.



Second Order Generalized Integrator (SOGI)



Second Order Generalized Integrator (SOGI) - Transfer Functions and Discretization

Closed-loop transfer functions:

$$H_d(s) = \frac{v'}{v}(s) = \frac{k\omega_n s}{s^2 + k\omega_n s + \omega_n^2}, \quad H_q(s) = \frac{qv'}{v}(s) = \frac{k\omega_n^2}{s^2 + k\omega_n s + \omega_n^2} \tag{10}$$

$$H_d(z) = \frac{\frac{2k\omega_n}{T_s} \cdot \frac{z-1}{z+1}}{\left(\frac{2}{T_s} \cdot \frac{z-1}{z+1}\right)^2 + k\omega_n \cdot \frac{2}{T_s} \cdot \frac{z-1}{z+1} + \omega_n^2} \tag{11}$$

Using $x = 2k\omega_n T_s, \quad y = (\omega_n T_s)^2$:

$$H_d(z) = \frac{\left(\frac{x}{x+y+4}\right) + \left(\frac{-x}{x+y+4}\right) z^{-2}}{1 - \left(\frac{2(4-y)}{x+y+4}\right) z^{-1} - \left(\frac{x-y-4}{x+y+4}\right) z^{-2}} = \frac{b_0 + b_2 z^{-2}}{1 - a_1 z^{-1} - a_2 z^{-2}} \tag{12}$$

Second Order Generalized Integrator (SOGI) - Further Discretization

Similarly,

$$H_q(z) = \frac{\left(\frac{ky}{x+y+4}\right) + 2\left(\frac{ky}{x+y+4}\right)z^{-1} + \left(\frac{ky}{x+y+4}\right)z^{-2}}{\left\{1 - \left(\frac{2(4-y)}{x+y+4}\right)z^{-1} - \left(\frac{x-y-4}{x+y+4}\right)z^{-2}\right\}}$$

$$= \frac{qb_0 + qb_1 z^{-1} + qb_2 z^{-2}}{1 - a_1 z^{-1} - a_2 z^{-2}} \tag{13}$$

Discrete Implementation of PI Controller

The PI controller is implemented digitally as:

$$y_{\mathrm{lf}}[n] = A_1 y_{\mathrm{lf}}[n-1] + B_0 y_{\mathrm{notch}}[n] + B_1 y_{\mathrm{notch}}[n-1] \tag{6}$$

Using Z-transform, Eq. (10) becomes:

$$\frac{Y_{\mathrm{lf}}(z)}{Y_{\mathrm{notch}}(z)} = \frac{B_0 + B_1 z^{-1}}{1 - z^{-1}} \tag{7}$$

The Laplace-domain form of a PI controller is:

$$\frac{Y_{\mathrm{lf}}(s)}{Y_{\mathrm{notch}}(s)} = K_p + \frac{K_i}{s} \tag{8}$$

Using bilinear transformation:

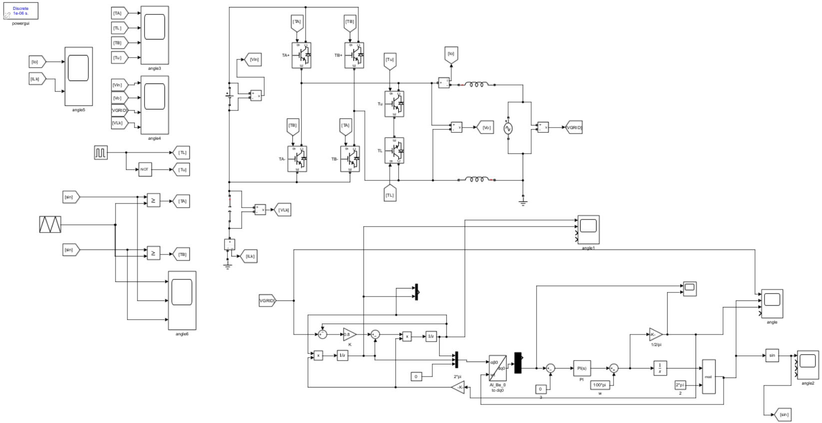
$$s = \frac{2}{T} \cdot \frac{z-1}{z+1}, \quad \text{where } T = \text{sampling time}$$

Discrete Implementation of PI Controller

Substitute into Eq. (8) to get discrete PI:

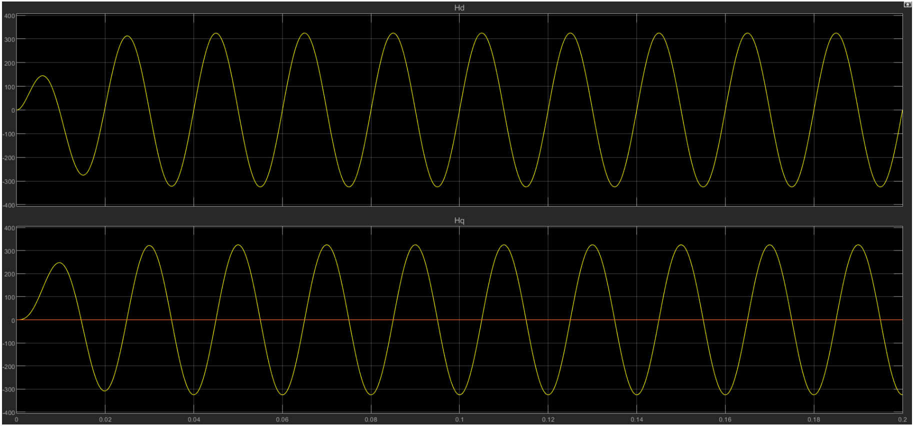
$$\frac{Y_{\mathrm{lf}}(z)}{Y_{\mathrm{notch}}(z)} = \frac{\left(\frac{2K_p + K_i T}{2}\right) + \left(\frac{2K_p - K_i T}{2}\right) z^{-1}}{1 - z^{-1}} \tag{9}$$

simulation



Discrete
1e-06 s.
powergui
[TA]
[TL]
[TB]
[Tu]
angle3
[Io]
[ILk]
angle5
[Vin]
[Vo]
VGRID
[VLk]
angle4
NOT
[sin]
angle6
TA+
TB+
TA-
TB-
Tu
TL
[Vin]
[VLk]
[ILk]
[Io]
[Vo]
VGRID
angle1
0.8
K
1/s
2*pi
Al_Be_0
to dq0
PI(s)
PI
100*pi
w
-K-
1/2/pi
2*pi
mod
sin
angle
angle2
[sin]

Hd and Hq components



Energy Stored in Inductor:

$$E = \frac{1}{2}LI^2 = \frac{1}{2} \times 120 \times 10^{-6} \times 13^2 = 0.01014 \text{ J}$$

General Formula:

$$A_p = \frac{2E}{K_c K_w B_m J}$$

Area Product (A_p) Calculation:

$$A_p = \frac{2 \times 0.01014}{1.3 \times 0.6 \times 5 \times 10^6 \times 0.25} = 20800 \text{ mm}^4$$

Inductor Design

Core Selected: EE 42/21/15

Permeance Calculation:

$$\text{Permeance} = \frac{\mu_0 \mu_r A_c \times 10^{-6}}{(l_m \times 10^{-3}) + (\mu_r \times l_g \times 10^{-3})}$$
$$= 1.1076 \ \frac{\text{H}}{\text{turn}^2}$$

Number of Turns:

$$N = \sqrt{\frac{120 \times 10^{-6}}{1.1076}} \approx 33$$

Wire Used: SWG 20 // 3 wire

Inductor


IM3536 LCR METER
HIOKI
152.656μH
1.53456 Ω
89.083 °
Vac 689.5mV
Iac 7.190mA
FREQ 100.00kHz
V 1.000V
LIMIT OFF
RANGE AUTO 1kΩ
LOW Z OFF
J SYNC OFF
JUDGE OFF
SPEED MED
AVG OFF
DELAY 0.0000s
SYNC OFF
DCBIAS OFF
CABLE 0m
OPEN OFF
SHORT OFF
LOAD OFF
SCALE OFF
MEAS
COMP/BIN
IN
OUT
UNKNOWN

code link:

Click here to visit the repository

FUTURE WORK

- Inductor design
- Hardware (soldering)
- Testing
- Microcontroller code development and testing

Reference

Manish Bhardwaj,
Software Phase Locked Loop Design Using C2000™ Microcontrollers for Single Phase Grid Connected Inverter,
Application Report SPRABT3A, Texas Instruments, July 2013 (Revised July 2017).
https://www.ti.com/lit/pdf/sprabt3a