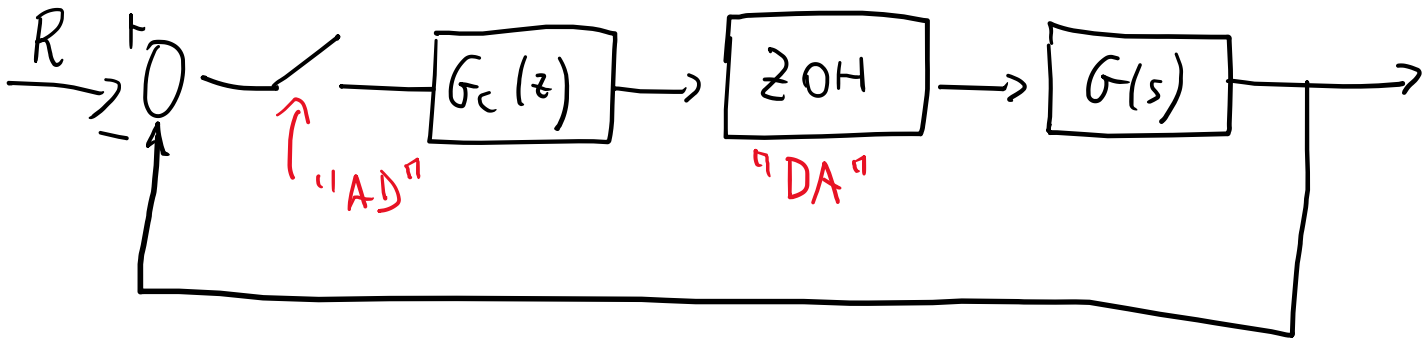
Escola Politécnica da Universidade de São Paulo
Departamento de Engenharia Mecatrônica e de Sistemas Mecânicos - PMR

Aula 8

Projeto de Controle – Modo indireto

Prof. Eduardo A. Tannuri

PMR 3409 – Controle II

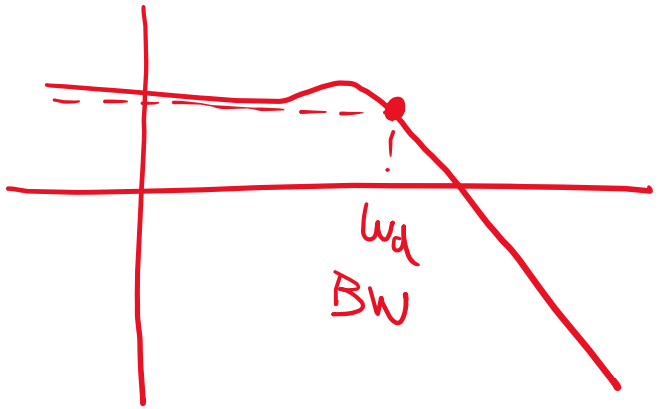


- TRANSFORMAR DINÂMICA P/ (S)
- PROJETAR $G_c(s)$ ⇒ CONTROLE Δ * ⇒ UTILIZANDO "PLANTA" $\frac{1}{T/2\,s+1} \cdot G(s)$
- $G_c(s) \rightsquigarrow G_c(z)$ → bilinear, backward, forward, MATCHED

ZOH → $\frac{1-e^{-Ts}}{s} \cong \frac{1}{\frac{T}{2}s+1}$ *

$e^{-sT} \cong \frac{1-T/2s}{1+T/2s}$; ganho 1

Ex) $G(s) = \frac{1}{s(s+2)}$



$M_p \leq 16\%$

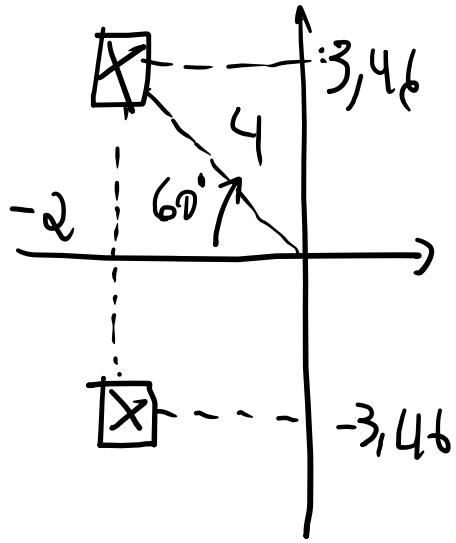
$t_s^{2\%} \leq 2s$

Tadequado

a) $t_s = \frac{4}{\zeta\omega_N} \Rightarrow \begin{cases} \omega_N = 2 \Rightarrow \frac{1}{\zeta\omega_N} = \frac{1}{\sigma} = \frac{1}{a} \end{cases}$

$M_p = 0,16 \Rightarrow \begin{cases} = 0,5 \Rightarrow \omega_N = 4 rad/s \end{cases}$

$\omega_d = 3,46 rad/s$

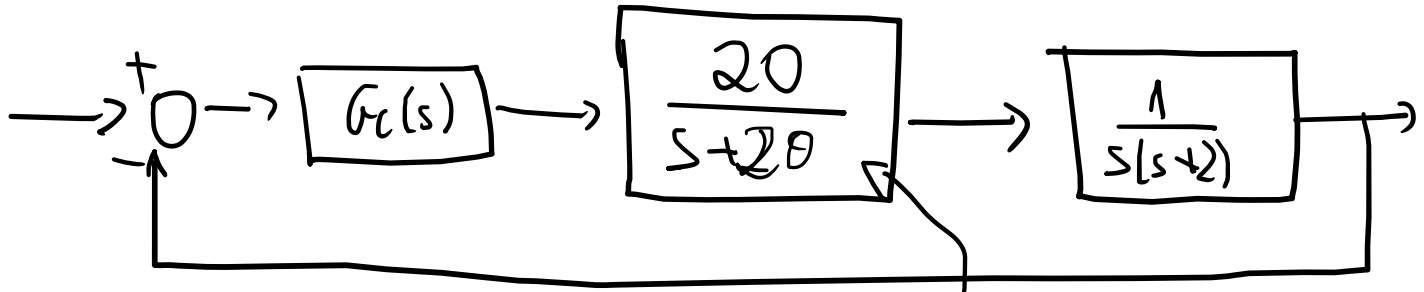


b) $T = ?$ $\quad \omega_s > 20 BW$

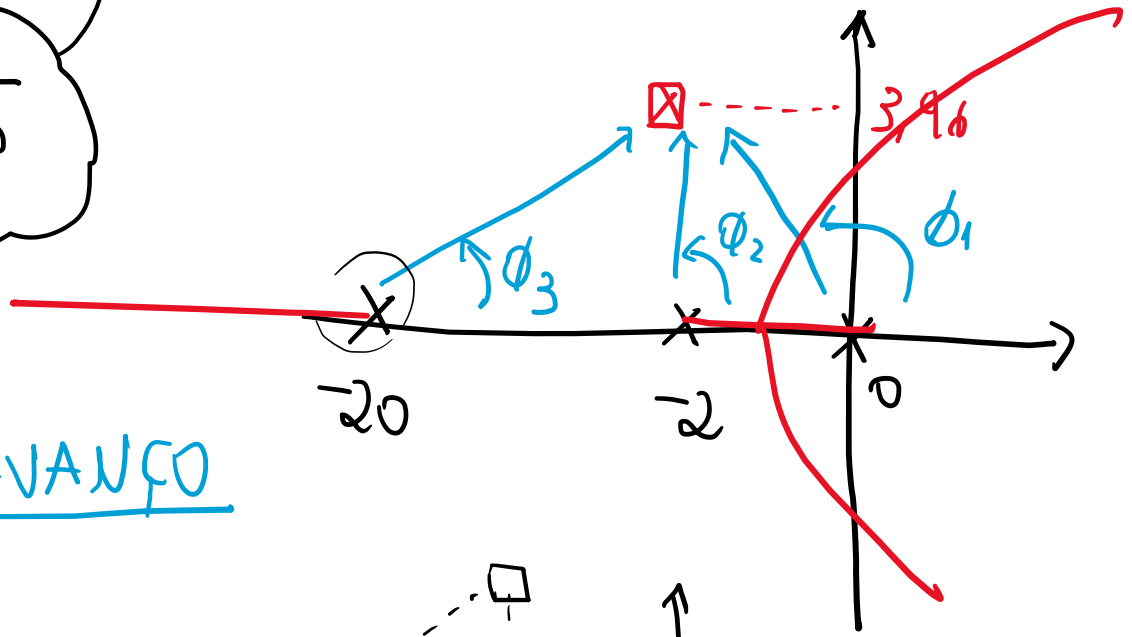
↳ LARGURA BANDA EM MALHA FECHADA

$BW \cong \omega_d = 3,96$

$\omega_s = \frac{2\pi}{T} = 20 \times 3,96 \Rightarrow \boxed{T \cong 0,1s}$



$$ZOH = \frac{1}{\frac{T}{2}s+1} = \frac{1}{0{,}05s+1} = \frac{20}{s+20}$$

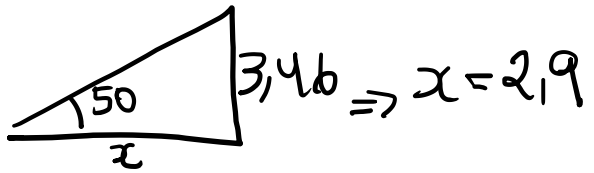


$$-\phi_1 - \phi_2 - \phi_3 = -220^\circ \Rightarrow \underline{40^\circ \text{ AVANÇO}}$$

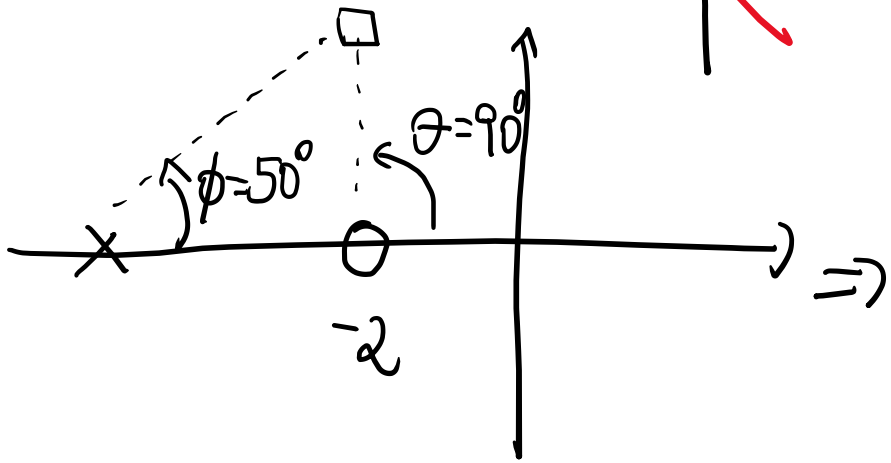
c) $$G_C = K_C \cdot \frac{s-z}{s-p}$$

$z = -2$

$p = -4{,}9$



$\Rightarrow x = 2{,}9$



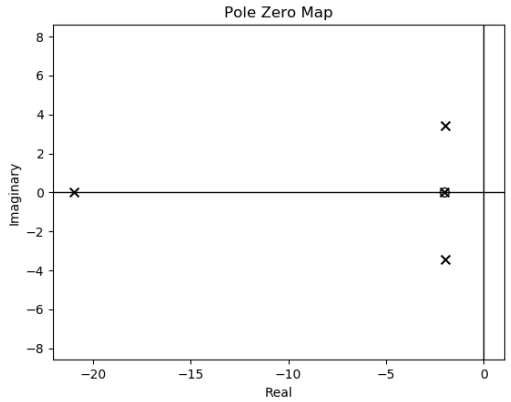
$$\Rightarrow G_C = K_C \cdot \frac{s+2}{s+4{,}9}$$

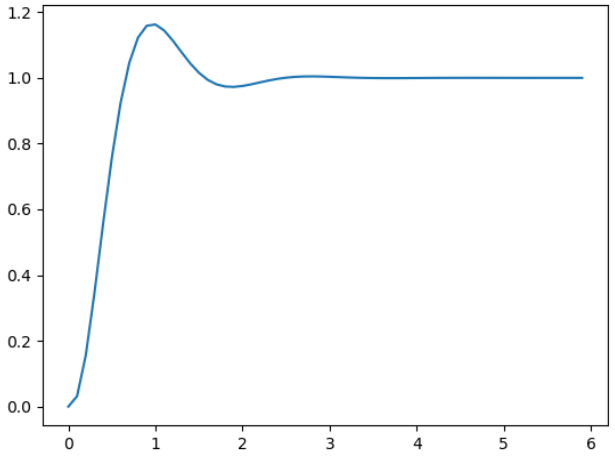
$$G_c(s) \cdot G(s) \cdot G_{ZOH}(s)\Big|_{s=-2\pm 3{,}46j} = 1 \Rightarrow$$

$$G_c = \frac{16{,}5\,s + 2}{s + 4{,}9}$$

$$k_c = 16{,}5$$

d)






```
stepinfo(Gmf)
Out[57]:
{'RiseTime': 0.4216744379163493,
 'SettlingTime': 2.083357604281624,
 'SettlingMin': 0.903326744866426,
 'SettlingMax': 1.1641701521913939,
 'Overshoot': 16.49360599565594,
 'Undershoot': 0.0,
 'Peak': 1.1641701521913939,
 'PeakTime': 0.9648482901475789,
 'SteadyStateValue': 0.9993425323573604}
```

FUNCIONAMENTO OK NO CONTÍNUO

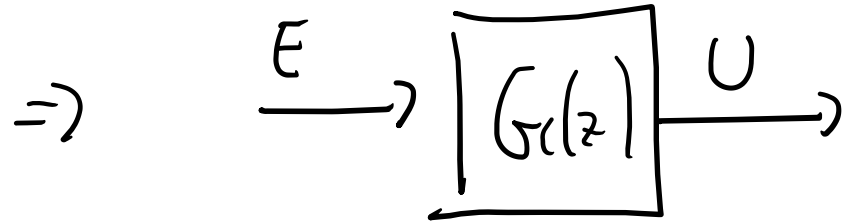
e) DISCRETIZAR $G_c(s) \rightsquigarrow G_c(z)$ ← bilinear

$$16\,\frac{\frac{2}{T}\frac{z-1}{z+1} + 2}{\frac{2}{T}\frac{z-1}{z+1} + 4{,}9} = G_c(z)$$

```
In [58]: Gcd = c2d(Gc,Ts,method='tustin')

In [59]: Gcd
Out[59]:
```

$$\frac{14.58z - 11.93}{z - 0.6064} \quad dt = 0.1$$

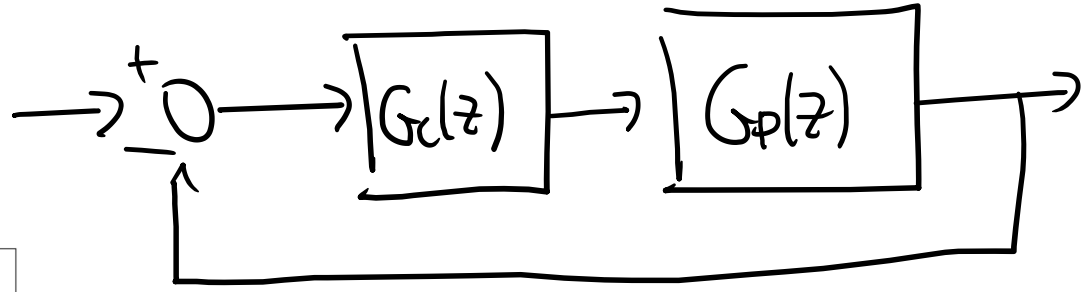
$\Rightarrow$ 

$$\frac{U(z)}{E(z)} = \frac{16z - 11}{z - 0,6} = \frac{16 - 11z^{-1}}{1 - 0,6z^{-1}}$$

$$u[k] = 0,6u[k-1] + 16e[k] - 11e[k-1]$$

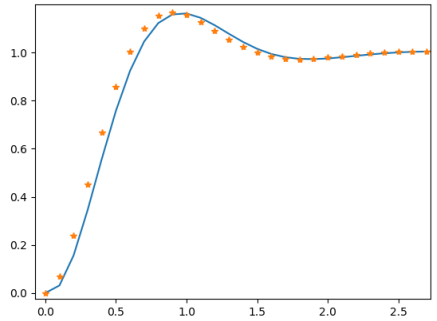
EQ DIFERENÇA

VERIFICAÇÃO NO ESPAÇO DISCRETO



$$G = \frac{z-1}{z} \cdot \mathcal{Z}\left\{\mathcal{L}^{-1}\left\{\frac{G(s)}{s}\right\}\right\}$$

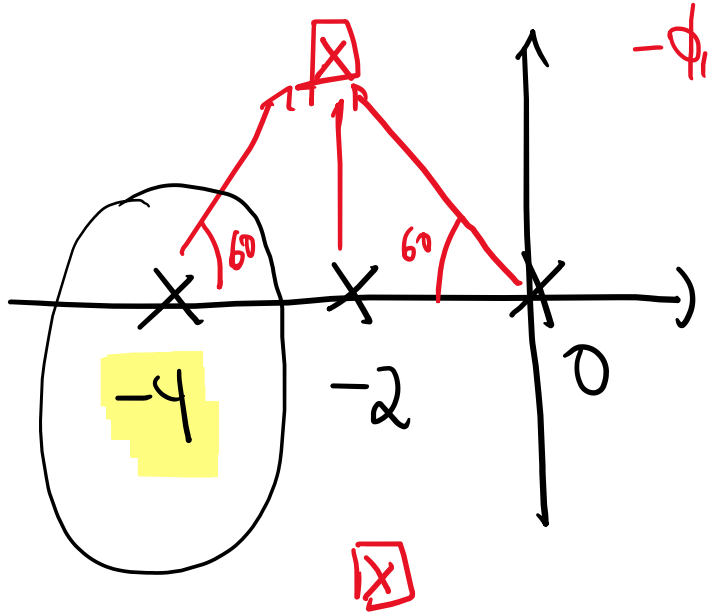
c2d('zoh')



REFAZER USANDO $\boxed{T = 0{,}5s}$

$$ZOH = \frac{1}{0{,}125s+1} = \frac{4}{s+4}$$

$$G_p = \frac{4}{s+4} \cdot \frac{1}{s(s+2)}$$



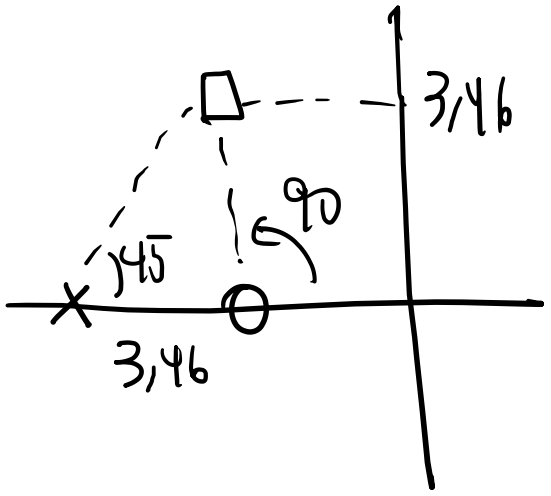
$-\phi_1 - \phi_2 - \phi_3 = -120 - 60 - 90 = -270$

$\Rightarrow +90^\circ$ AVANÇO

VAMOS CALCULAR 2 COMP. EM SÉRIE, CADA UM COM 45° AVANÇO

$$G_c(s) = K_c \cdot \left(\frac{s+2}{s+p}\right)^2$$

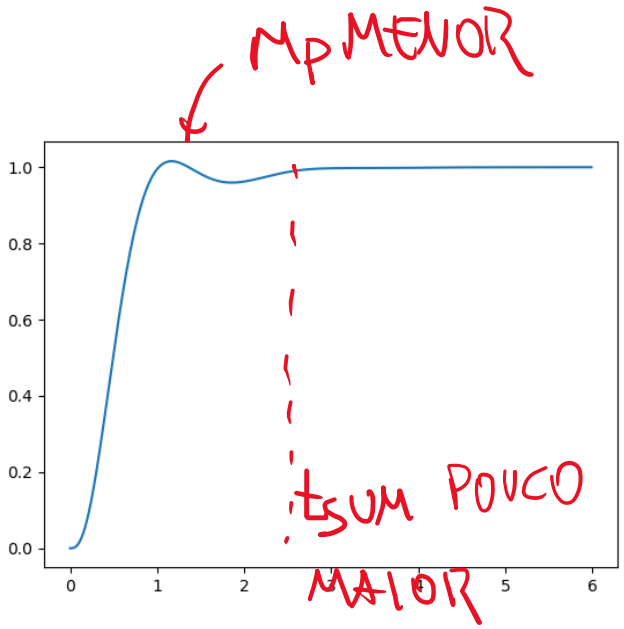
↳ $p = -5{,}46$



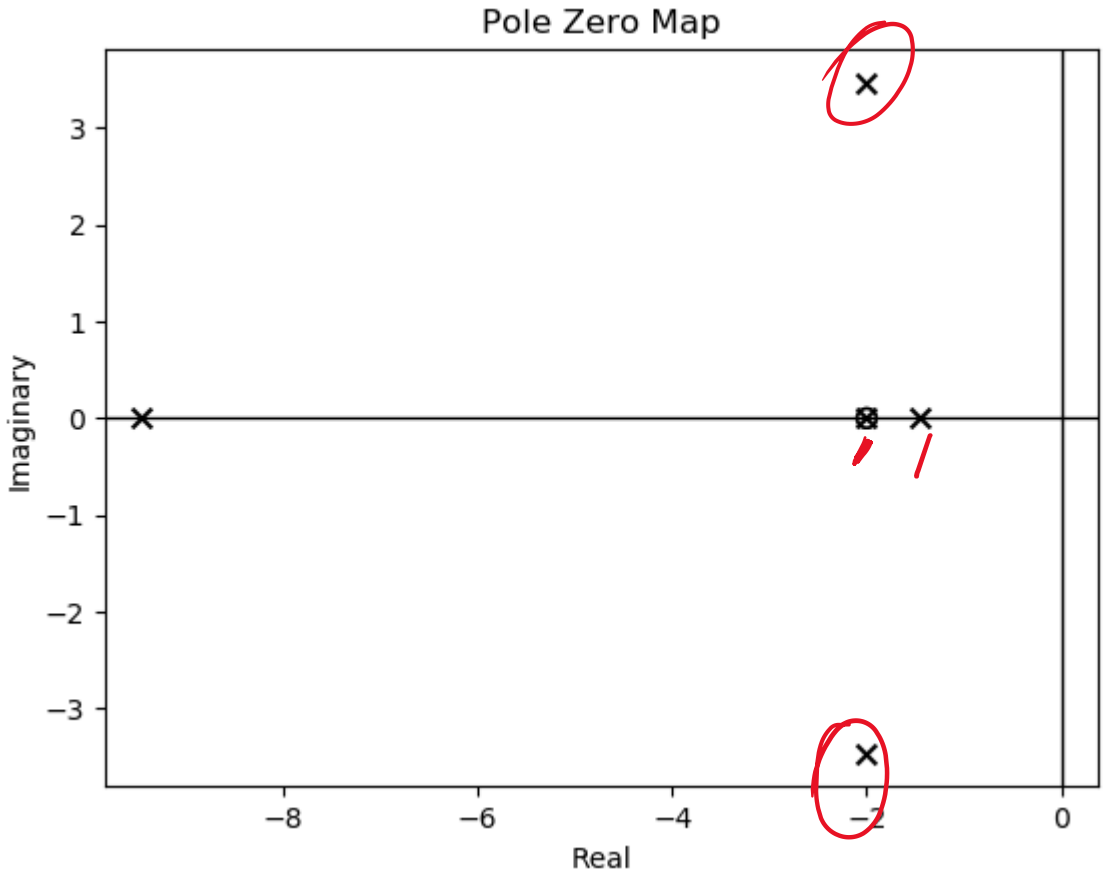
$$\Rightarrow G_c(s) = K_c \left(\frac{s+2}{s+5{,}46}\right)^2$$

PELA COND. MÓDULO $\Rightarrow$

$K_c = 27{,}6$

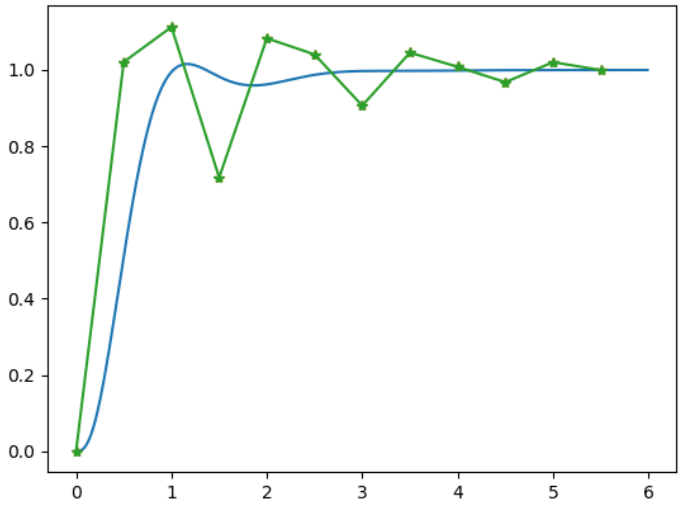


EM (3)




```
In [73]: pole(Gmf)
Out[73]:
array([-9.45474314+0.j        , -2.001191  +3.45821496j,
       -2.001191  -3.45821496j, -2.        +0.j        ,
       -1.46287486+0.j        ])


In [75]: zero(Gmf)
Out[75]: array([-2., -2.])
```



e) AO DISCRETIZAR C/

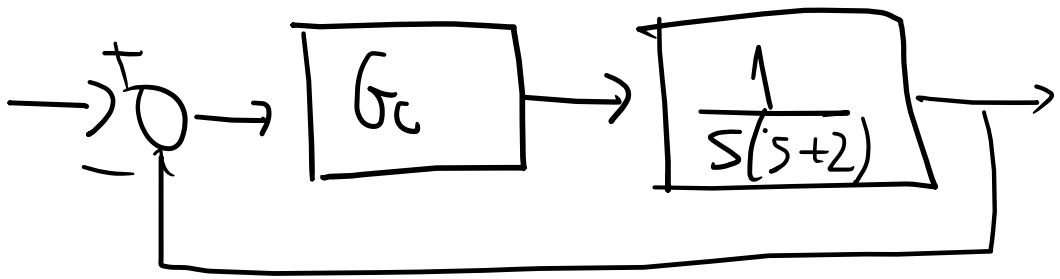
← TUSTIN

LEMBRE-SE QUE ESTAMOS COM

$\omega_s = 4 \times BW$ (BEM POR QUE O RECOMENDADO $20 \cdot BW$)

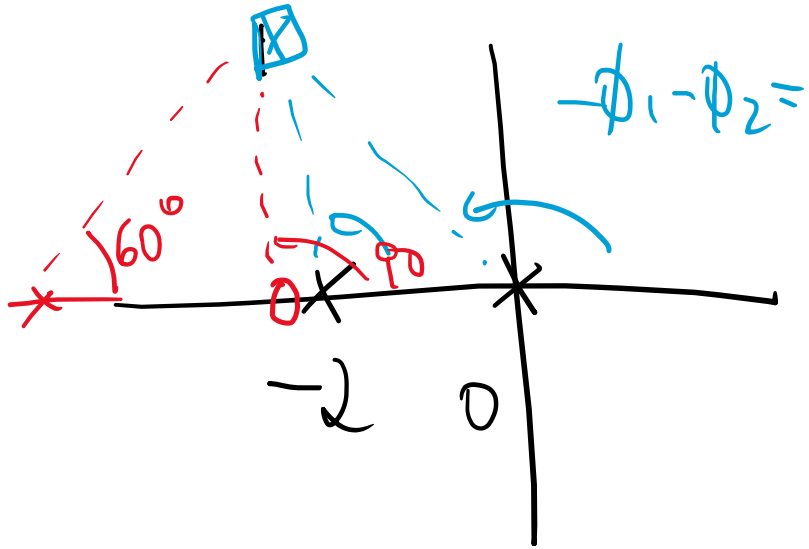
VAMOS REFAZER SEM LEVAR EM CONTA O ZOH NO PROJETO

$T = 0{,}1\,s$



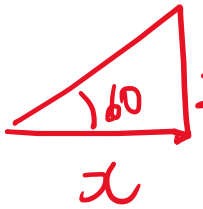
(PROJETO ERRADO! SEM LEVAR EM CONTA ZOH

$G_c(s)$



$-\phi_1 - \phi_2 = -120 - 90 = -210 \Rightarrow 30°$ AVANÇO

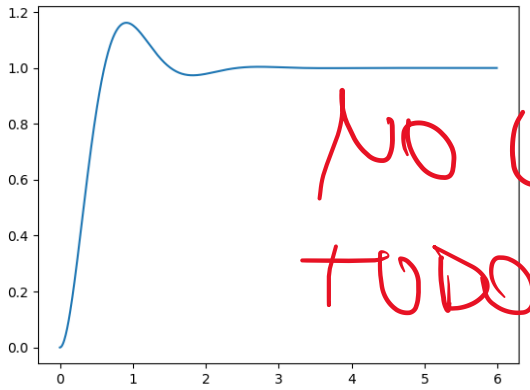
$G_c(s) = K_c \cdot \frac{s+2}{s-p} \Rightarrow K_c \cdot \frac{s+2}{s+4}$



$\Rightarrow x = 2$

PELA COND MODULO $K_c = 15{,}9$

$$G_c = 15{,}9 \cdot \frac{s+2}{s+4}$$

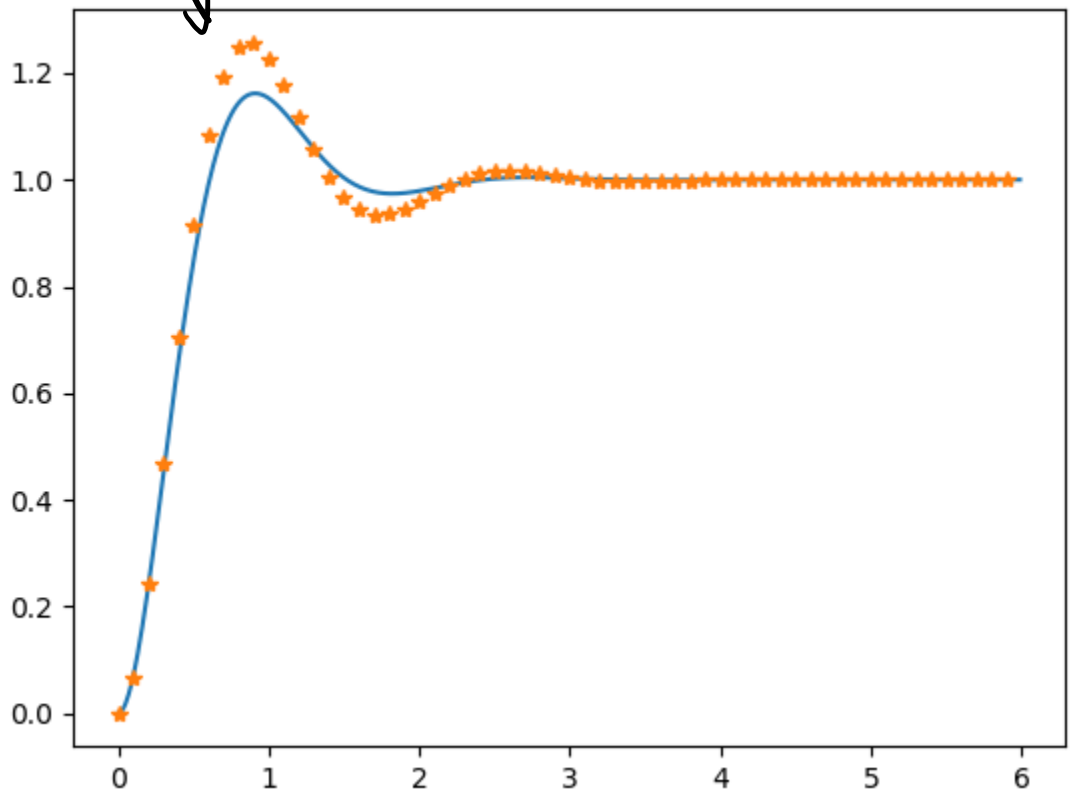


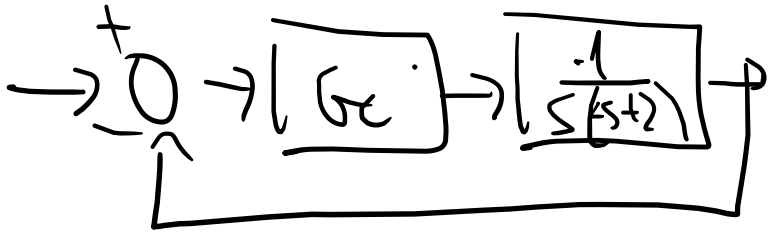
NO CONTÍNUO, TUDO OK!

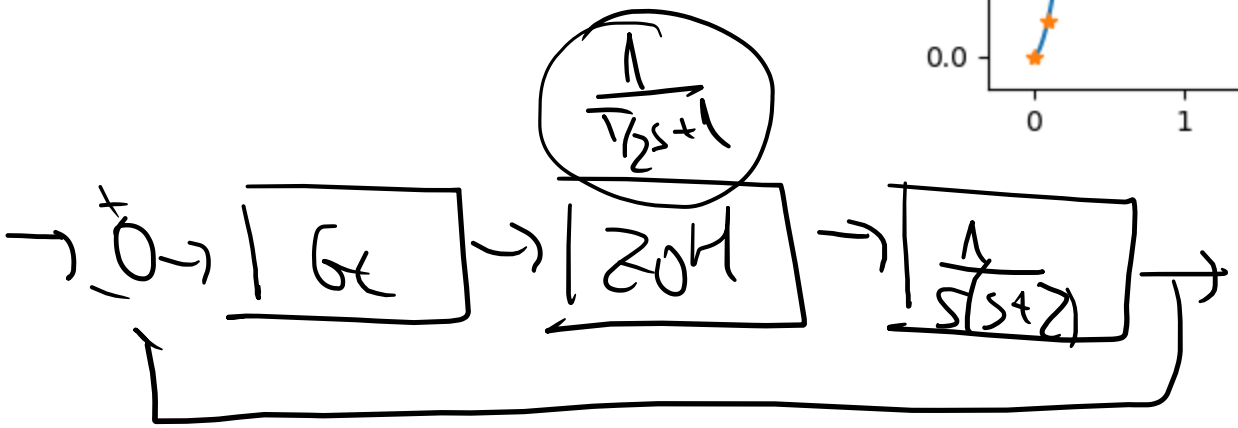
DISCRETIZANDO $T=0.1s$

$\Rightarrow G_c(z) =$ TUSTIN

DEGRADAÇÃO COMPARADO AO SLIDE 6 (PROJETO CORRETO)







DISCRETIZANDO $T=0,15$

$\Rightarrow G_c(z) =$