

# Estado da arte do sistema de controle de aerogeradores

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Laboratório de Redes Elétricas Avançadas

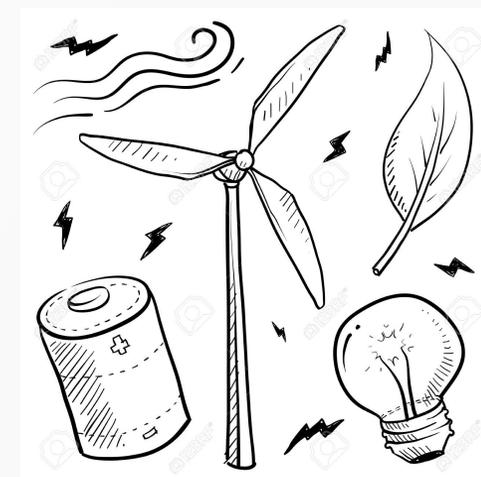
Departamento de Engenharia de Energia e Automação Elétricas

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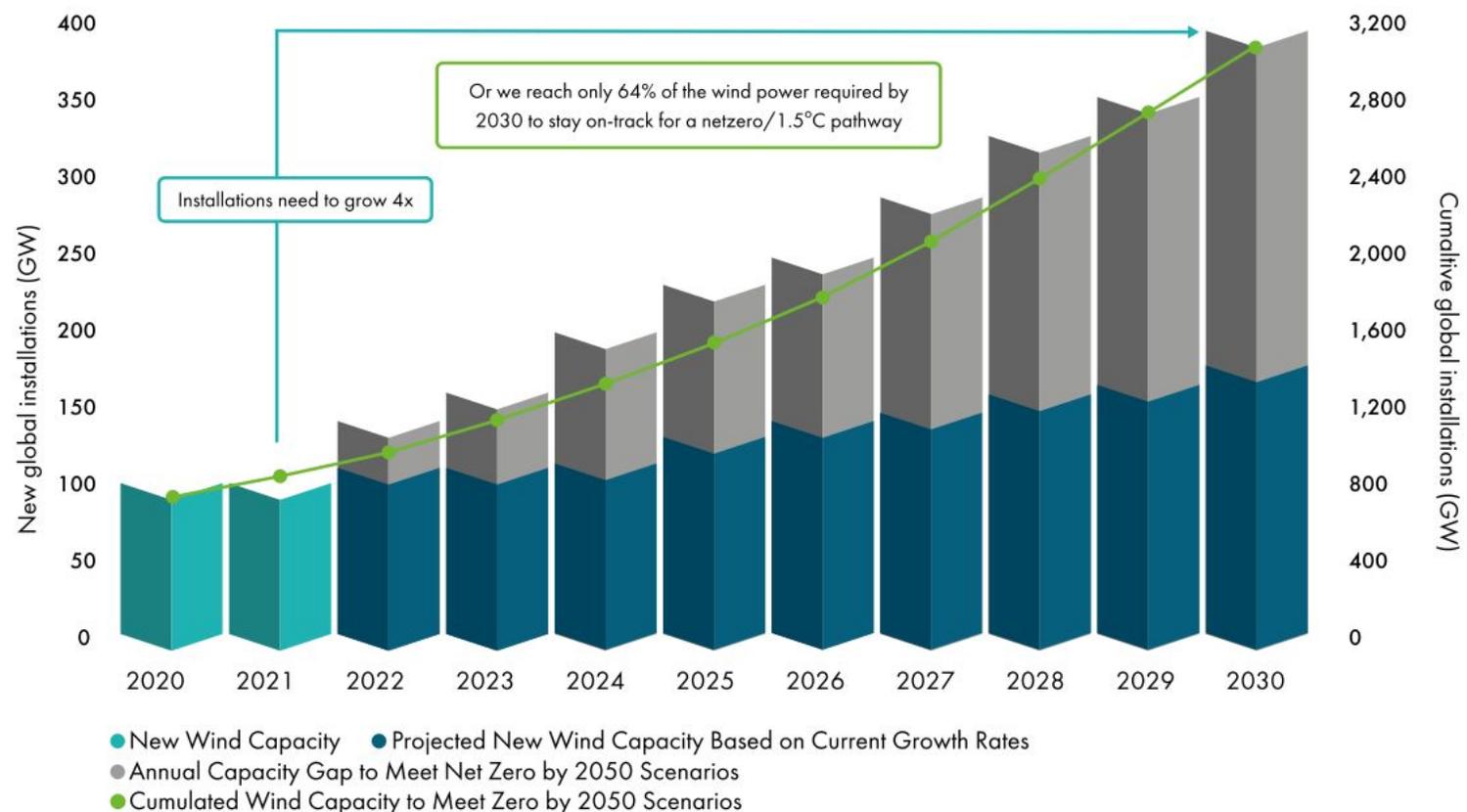
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## Desafio e oportunidade

### Energia Eólica no Brasil:

- 25,63GW (Atual)<sup>1</sup>;
- 13,33% da matriz elétrica<sup>1</sup>;
- 44,78GW (Projeção 2028)<sup>2</sup>;
- 5 maior produtor do mundo<sup>2</sup>;

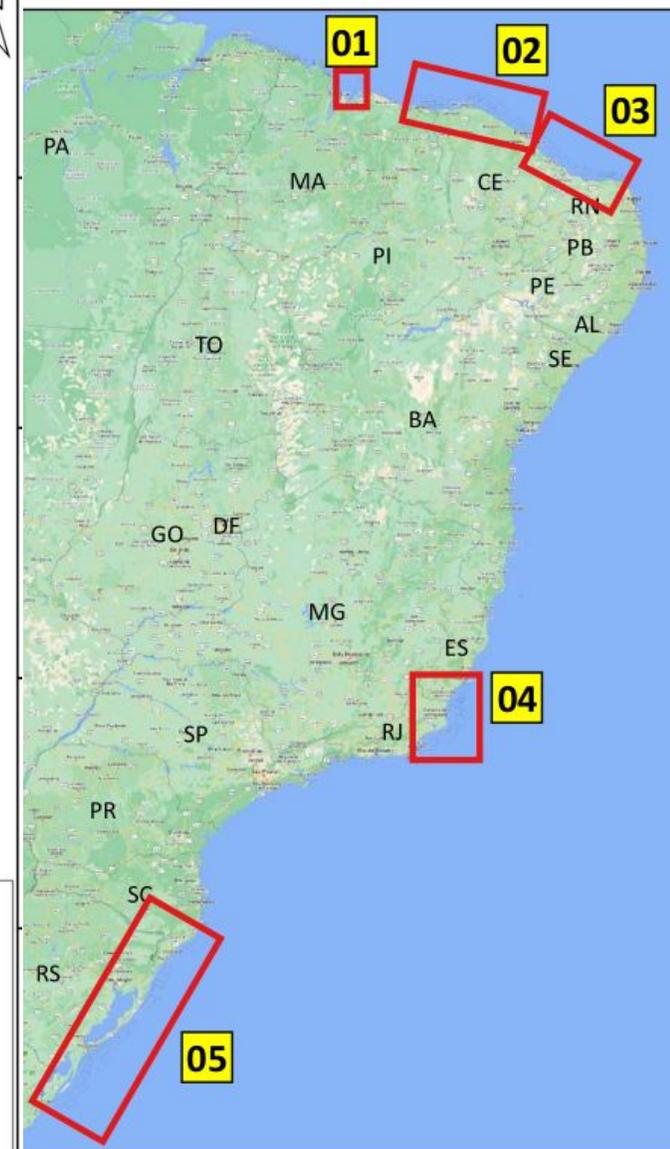
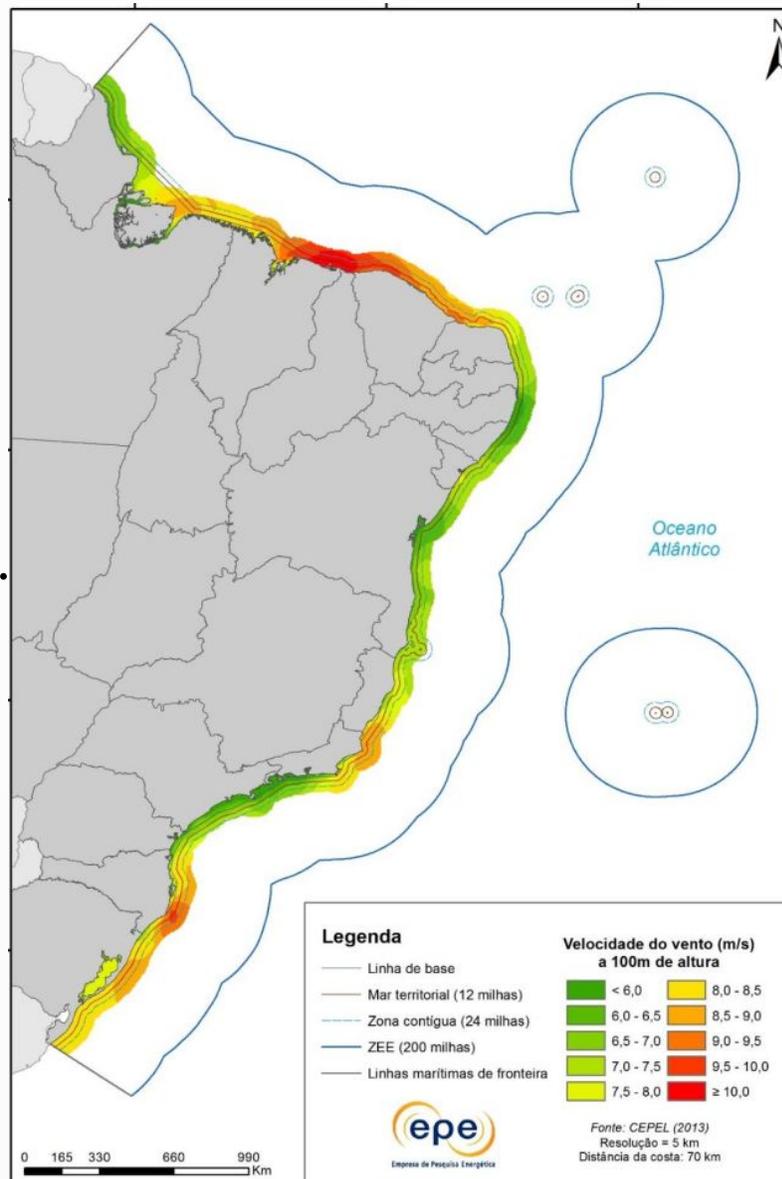


1-Sistema de Informações de Geração da ANEEL (SIGA)

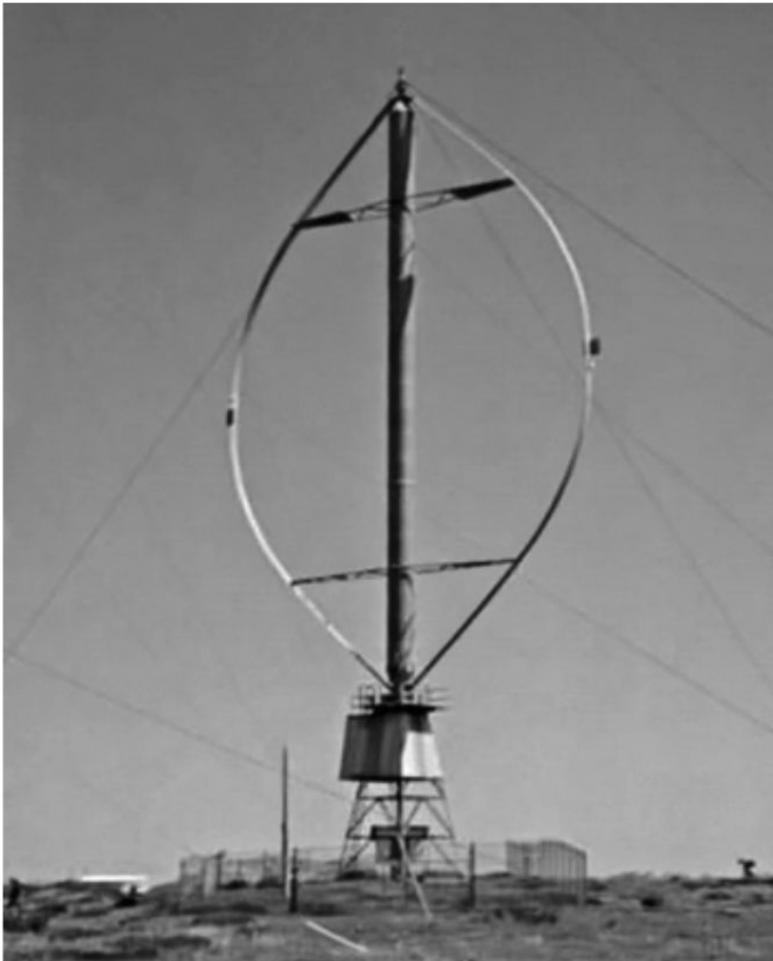
2-ABEEÓLICA

Geração eólica no Brasil:

- 700 GW de potencial
  - até 50 m de profundidade;
- ~183 GW
  - com pedido de licenciamento.



# Turbinas de eixo vertical e de eixo horizontal

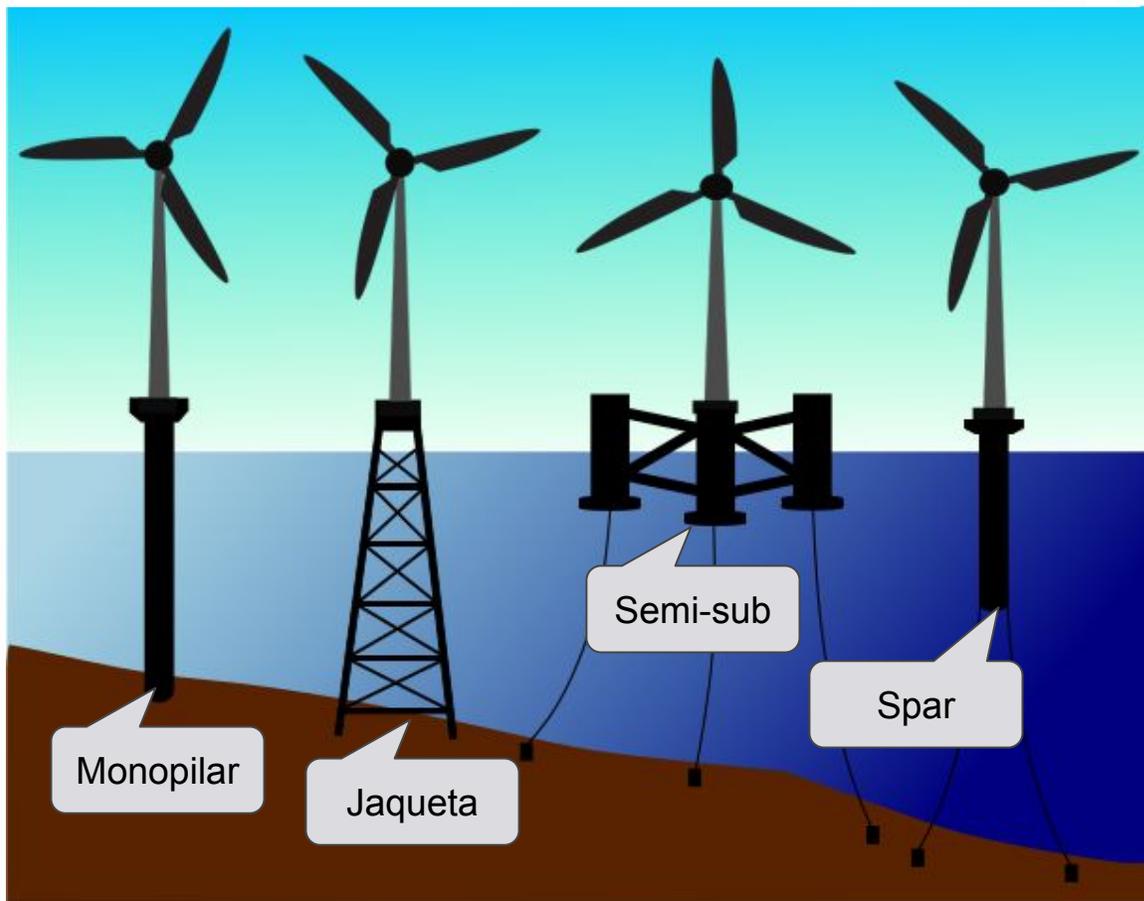


Fonte: (ALI, 2012)



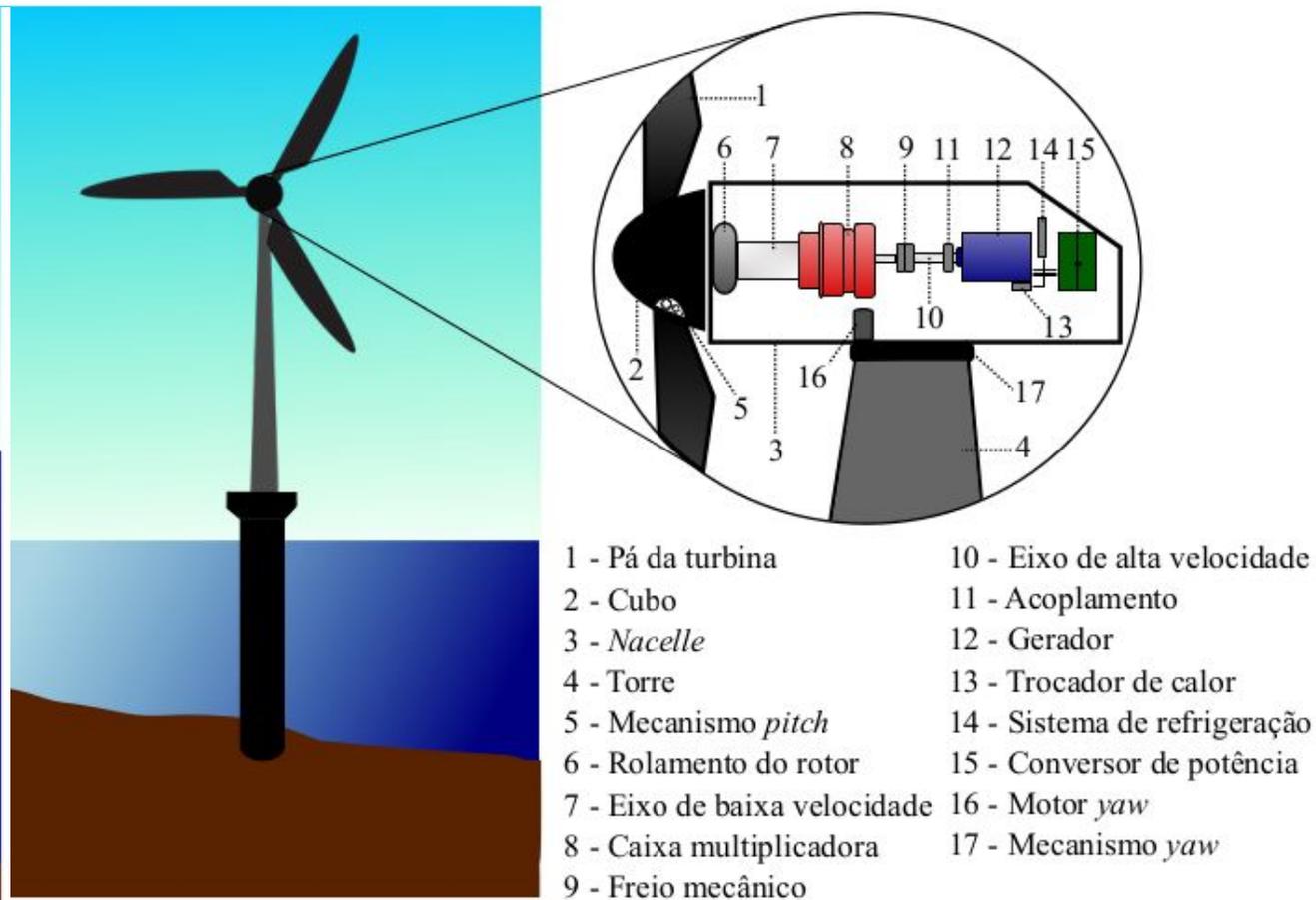
Fonte: (ALI, 2012)

# Partes do aerogerador



Tecnologias de estruturas de turbinas eólicas

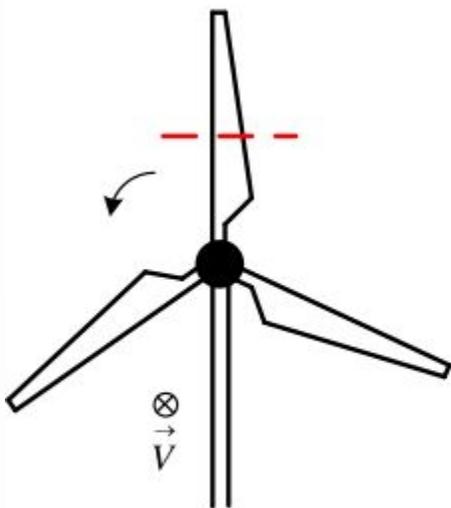
Fonte: Baseado em Anaya-Lara et al. (2018).



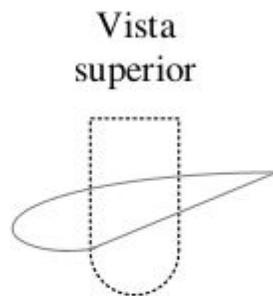
Representação de uma turbina eólica e principais componentes associados

Fonte: Adaptado de Bhattacharya (2019).

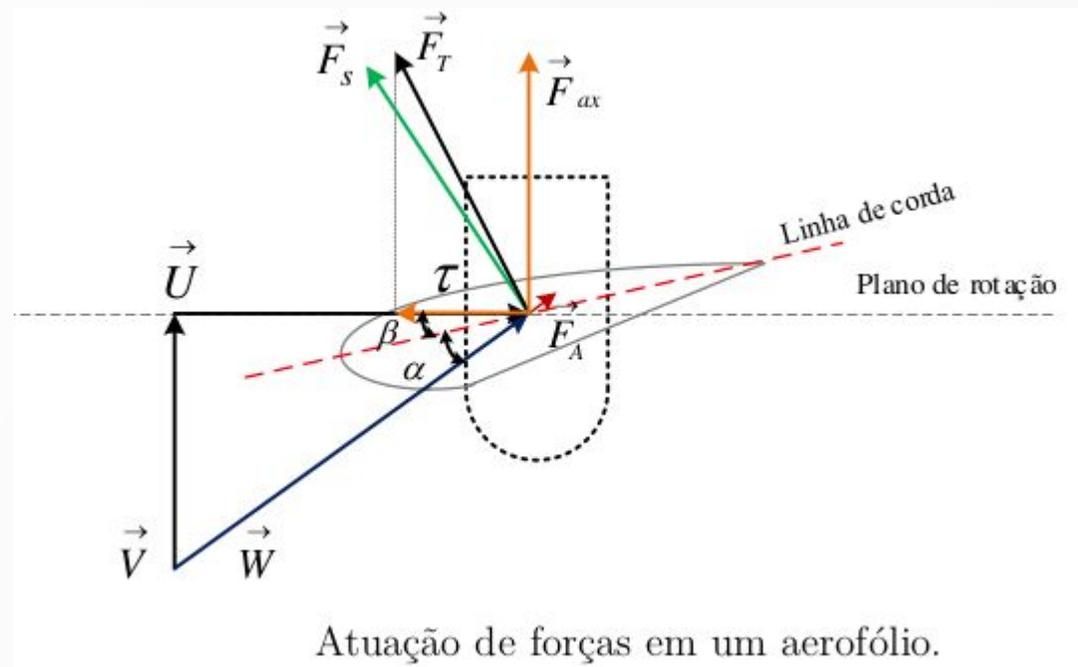
# Princípio aerodinâmico



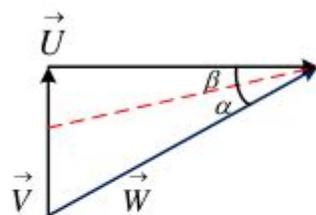
(a) Vista frontal.



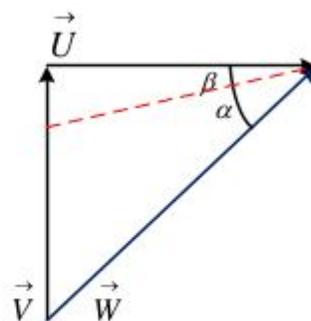
(b) Vista superior da seção transversal da pá.



Atuação de forças em um aerofólio.



(a) Baixa velocidade do vento incidente.



(b) Alta velocidade do vento incidente.

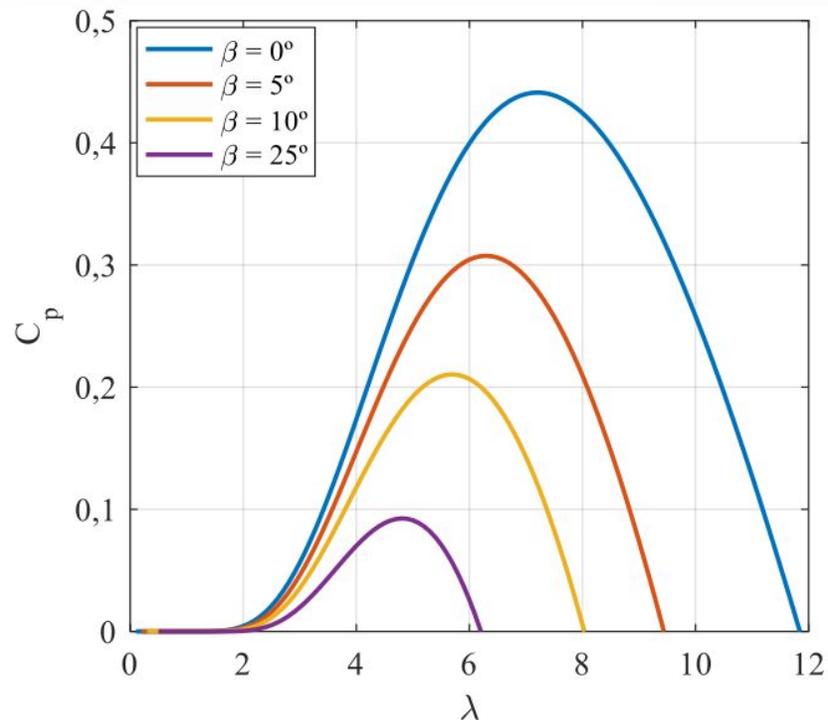
Duas variáveis de controle:

- Ângulo pitch das pás;
- Velocidade de rotação.

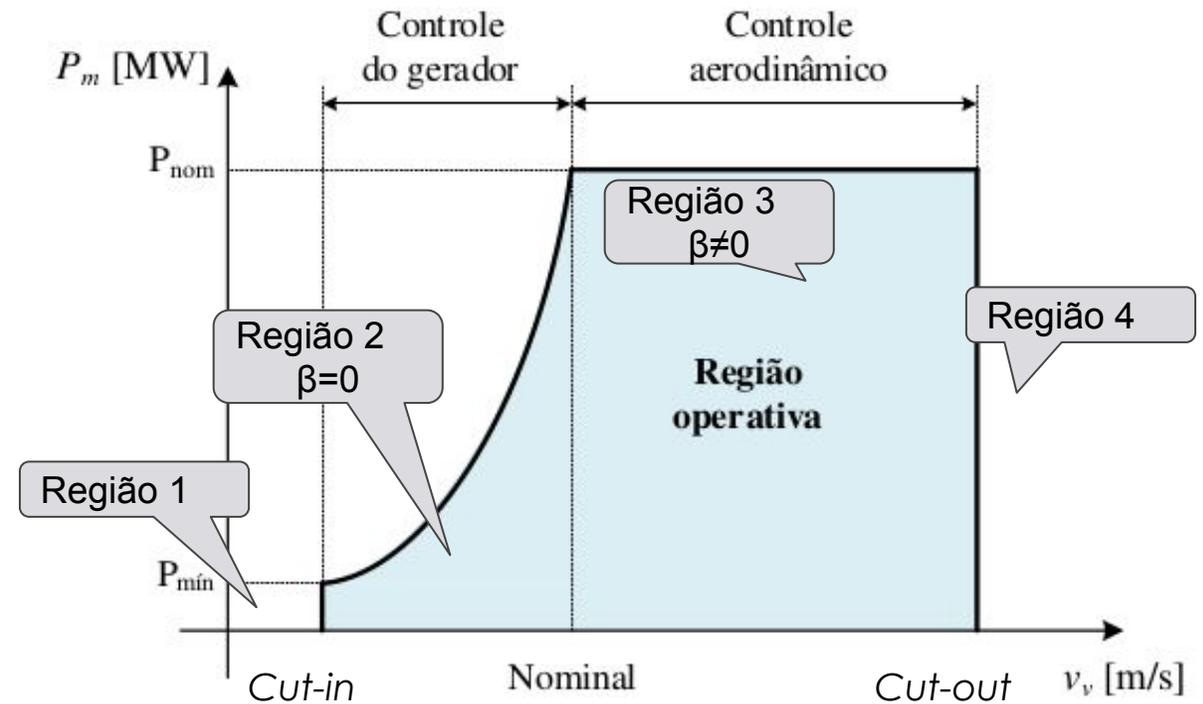
# Curva Cp

$$P_M = \frac{1}{2} \rho A v_v^3 C_p (\lambda, \beta)$$

$$\lambda = \frac{\omega_m r}{v_v}$$

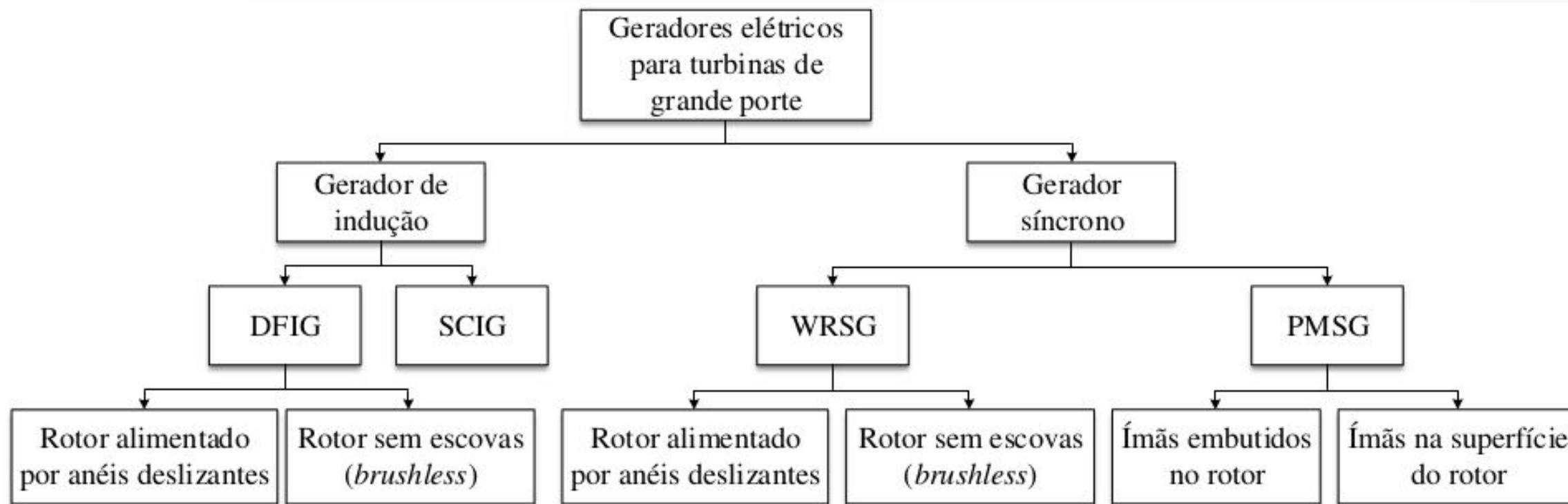


Curvas  $C_p$  para distintos valores de ângulo de passo.



Curva de potência de uma turbina eólica hipotética.  
Fonte: Baseado em Wu et al. (2011).

# Máquinas Eléctricas empregadas em Geradores Eólicos



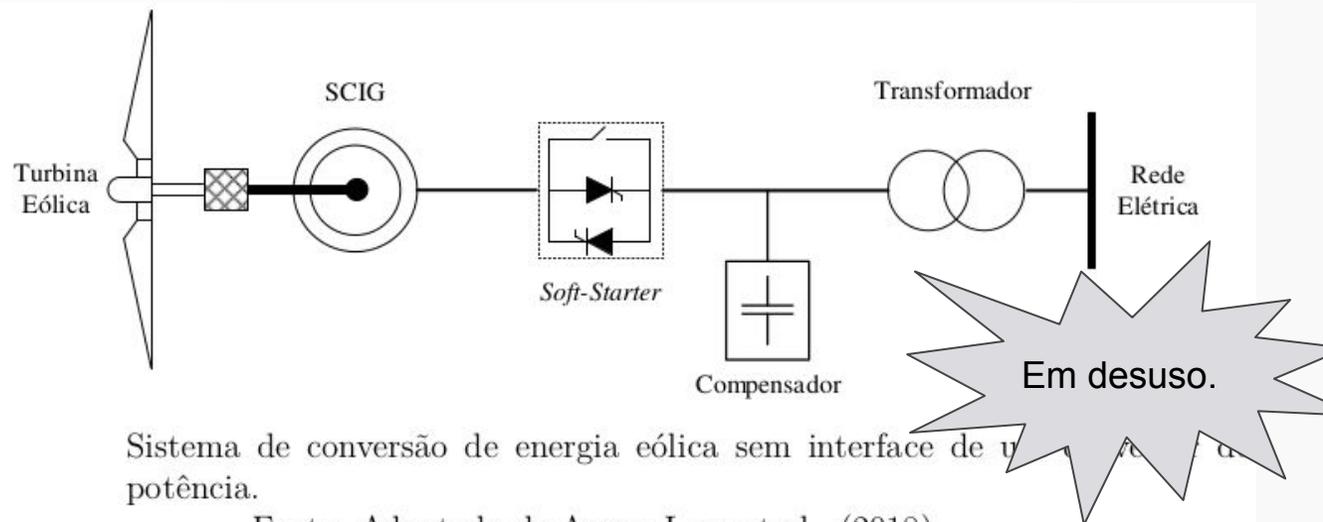
Classificação dos geradores eléctricos comumente empregados em turbinas eólicas de grande porte.

Fonte: Traduzido de Wu et al. (2011).

# Aplicação das máquinas elétricas

## Aerogerador Tipo 1:

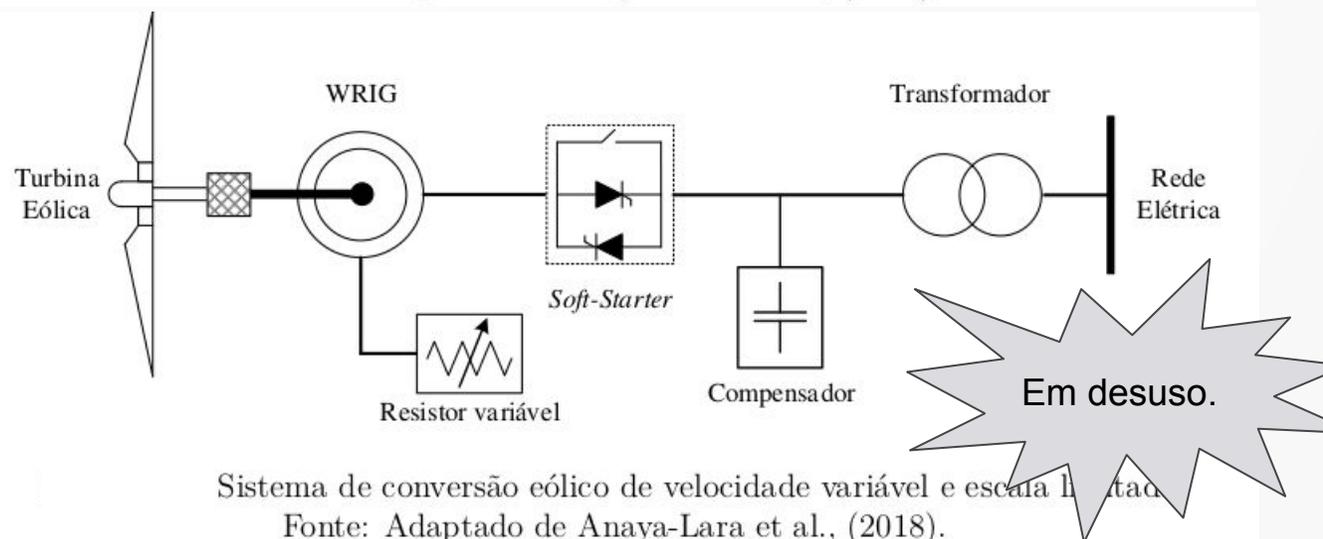
- Velocidade Fixa;
- Gerador de Indução Gaiola de Esquilo;



Fonte: Adaptado de Anaya-Lara et al., (2018).

## Aerogerador Tipo 2:

- Velocidade Variável Limitada;
- Gerador de Indução Rotor Bobinado;
- Resistor variável (muda torque elétrico).

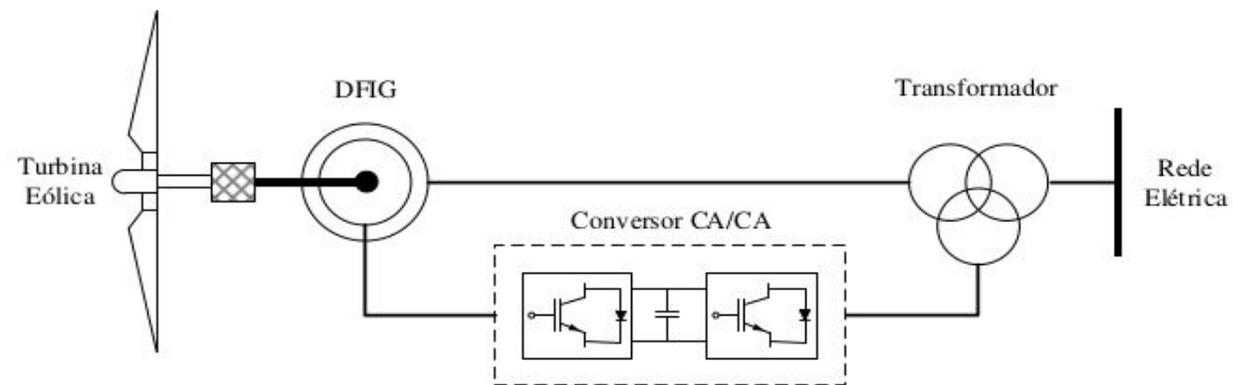


Fonte: Adaptado de Anaya-Lara et al., (2018).

# Máquinas controladas por conversores de potência

## Aerogerador Tipo 3:

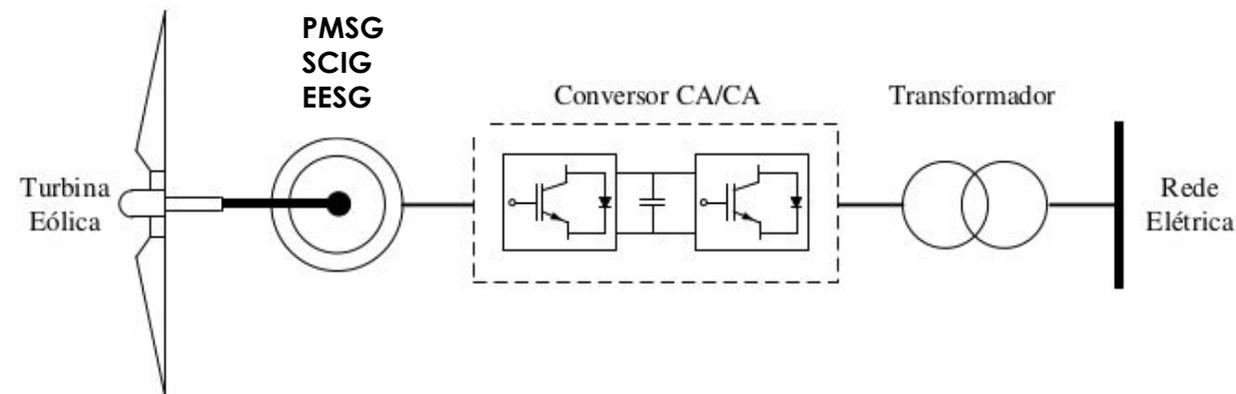
- Velocidade Variável;
- Gerador de Indução Rotor Bobinado;
- Gerador duplamente alimentado (DFIG);
- Conversor de escala parcial (33%).



Sistema de conversão eólico de velocidade variável e escala parcial.  
Fonte: Adaptado de Anaya-Lara et al., (2018).

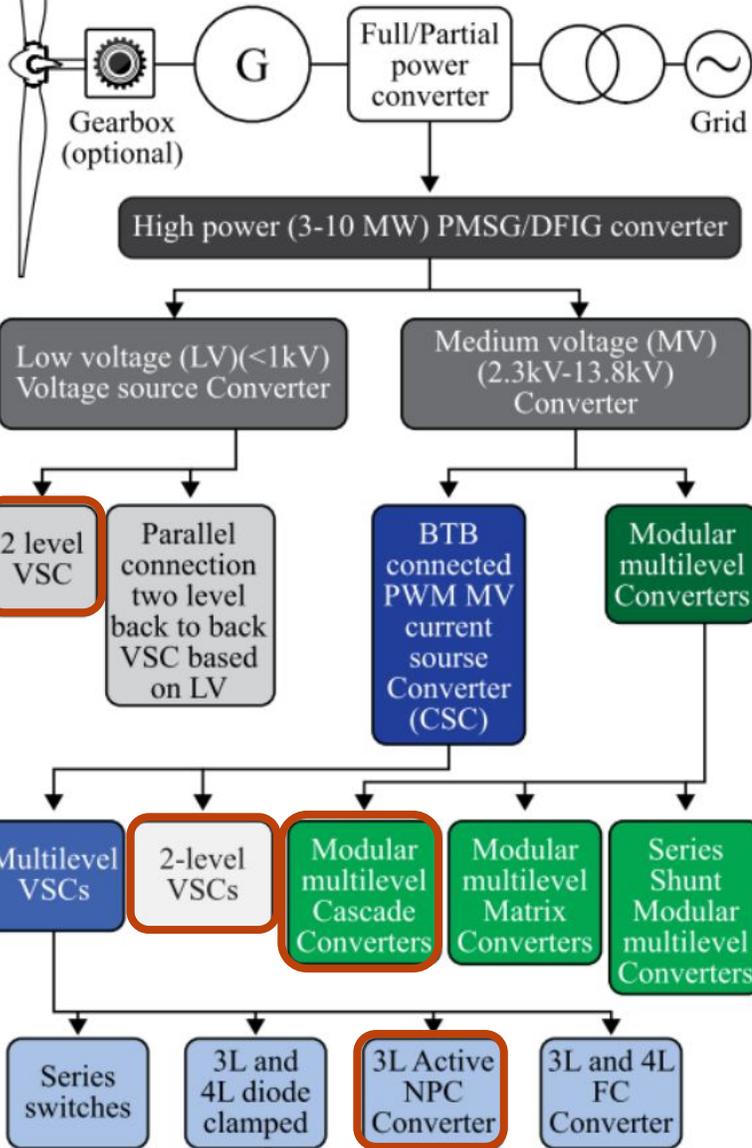
## Aerogerador Tipo 4:

- Velocidade Variável;
- Gerador de Indução Gaiola de Esquilo
- Gerador Síncrono Eletricamente Excitado;
- Gerador Síncrono de Imã Permanente;
- Conversor de escala completa (100%).



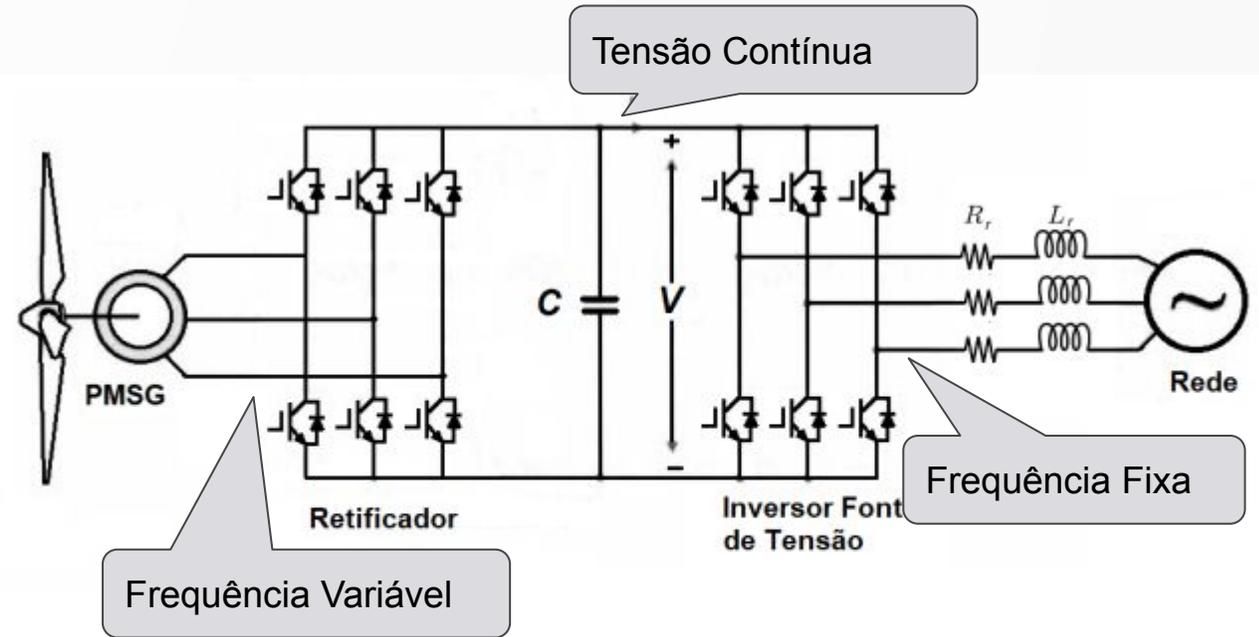
Sistema de conversão eólico de velocidade variável e escala completa.  
Fonte: Adaptado de Anaya-Lara et al., (2018).

# Tipos de conversores



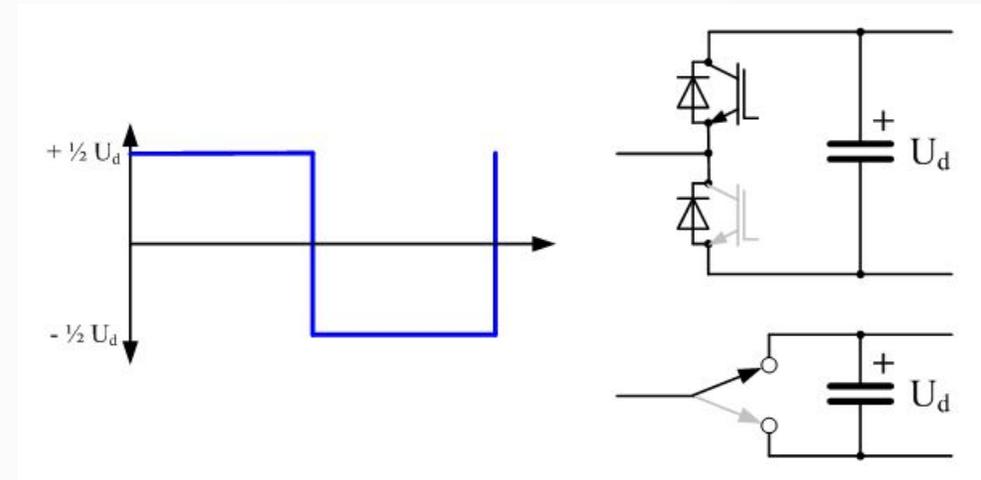
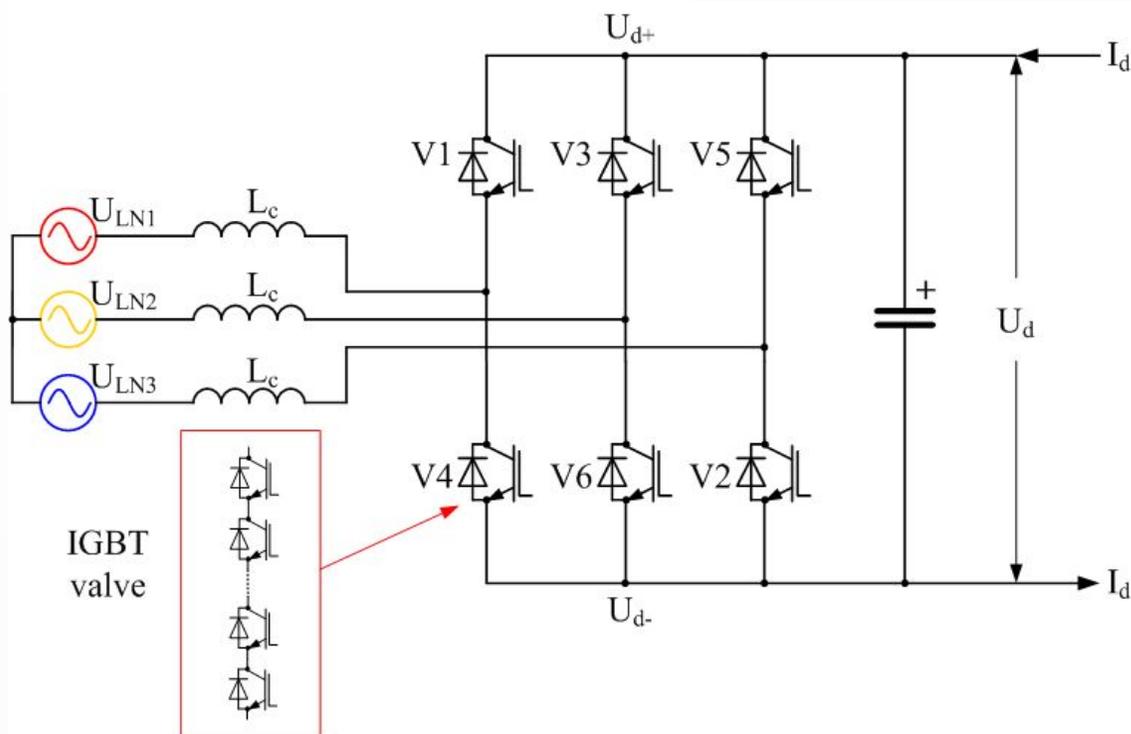
Fonte: adaptada de (RAJENDRAN et al., 2022)

## Configuração Back-Back

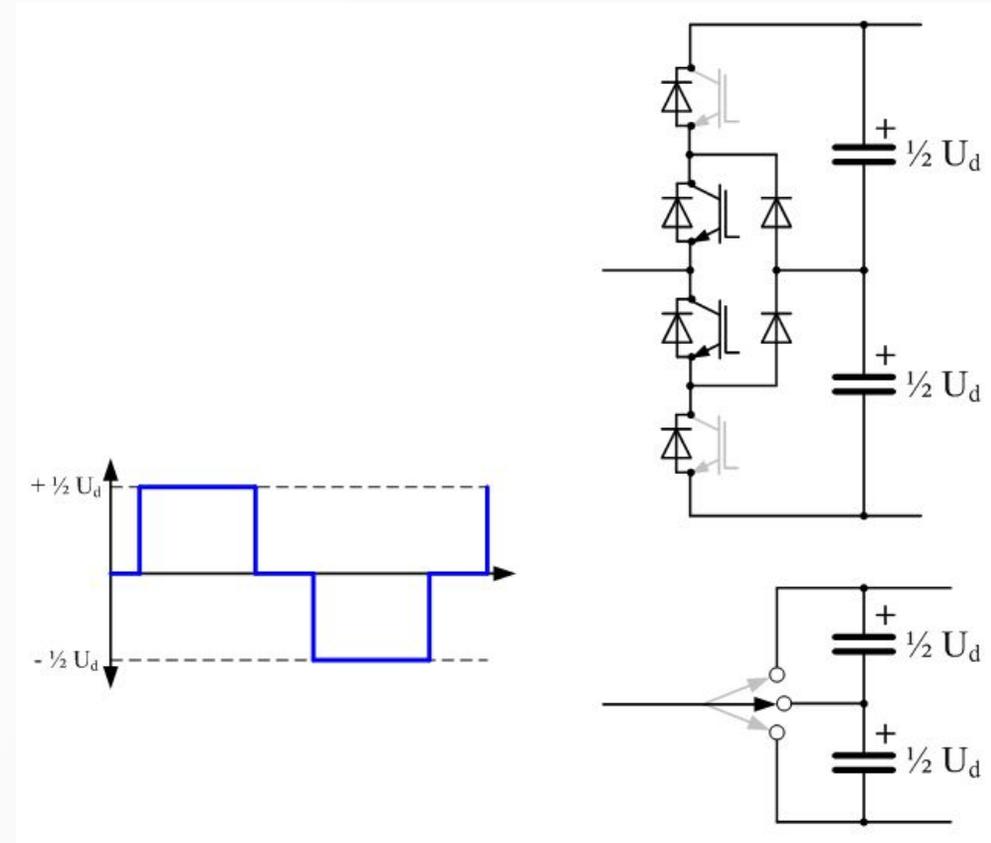
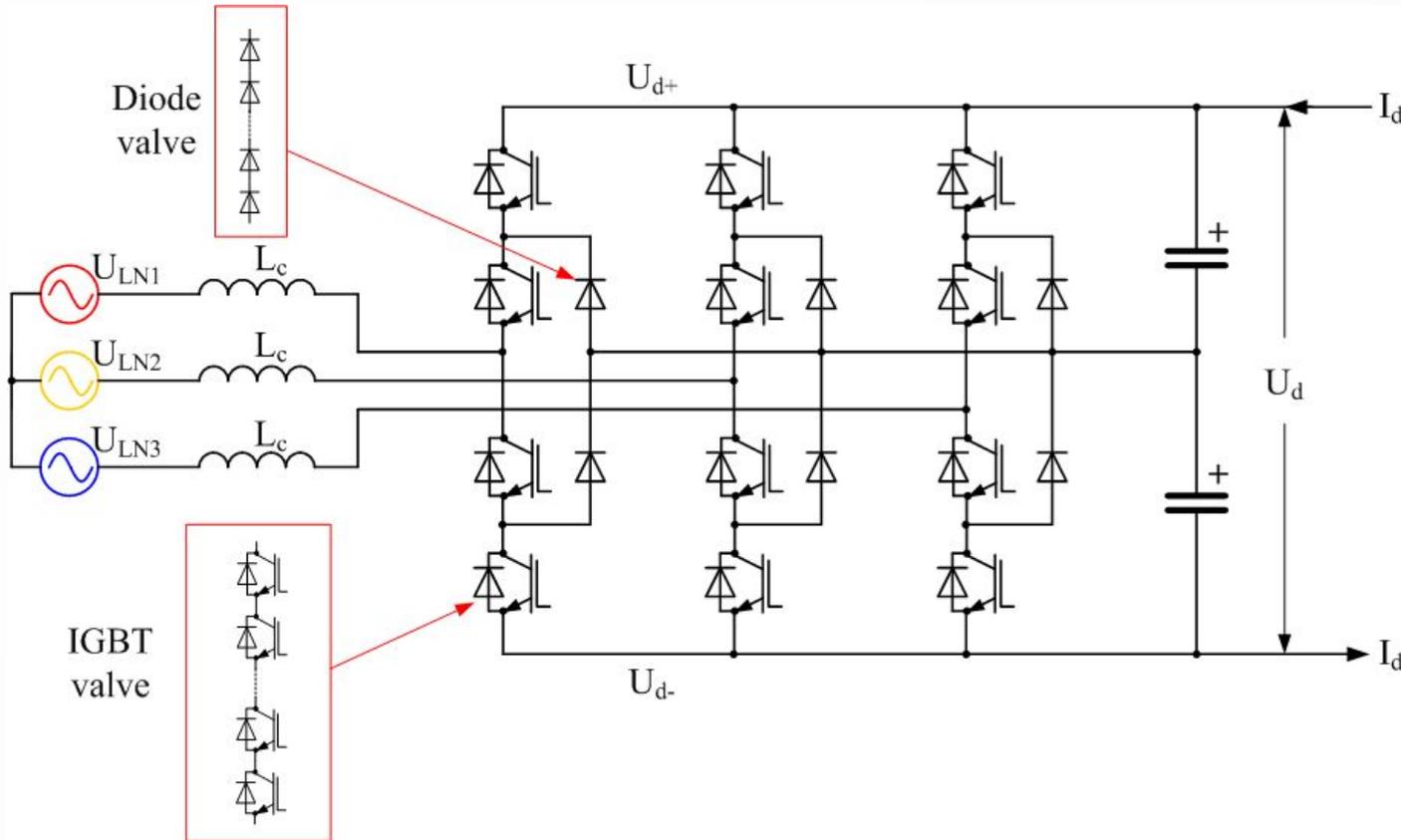


Fonte: adaptada de (WU et al., 2011)

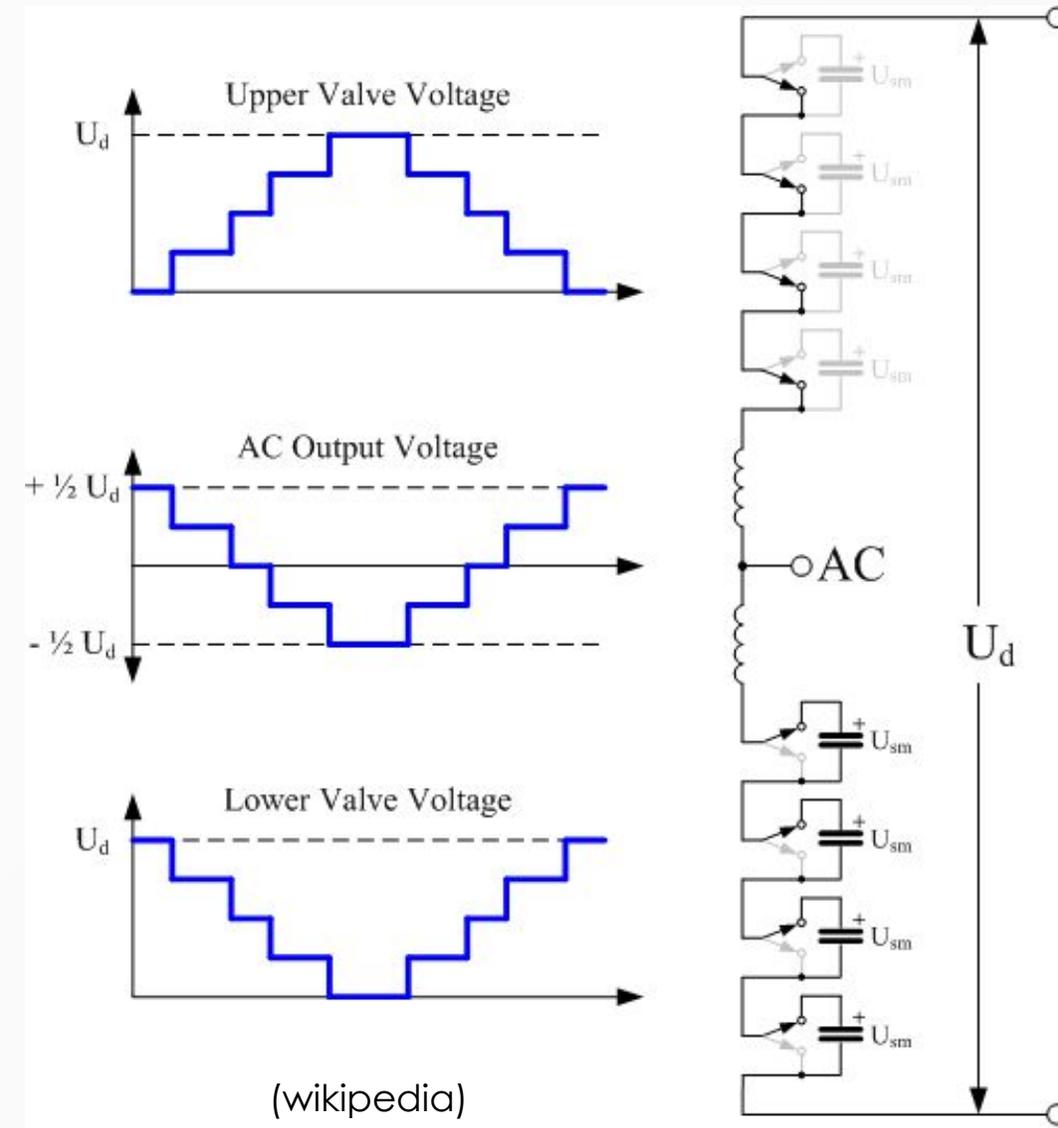
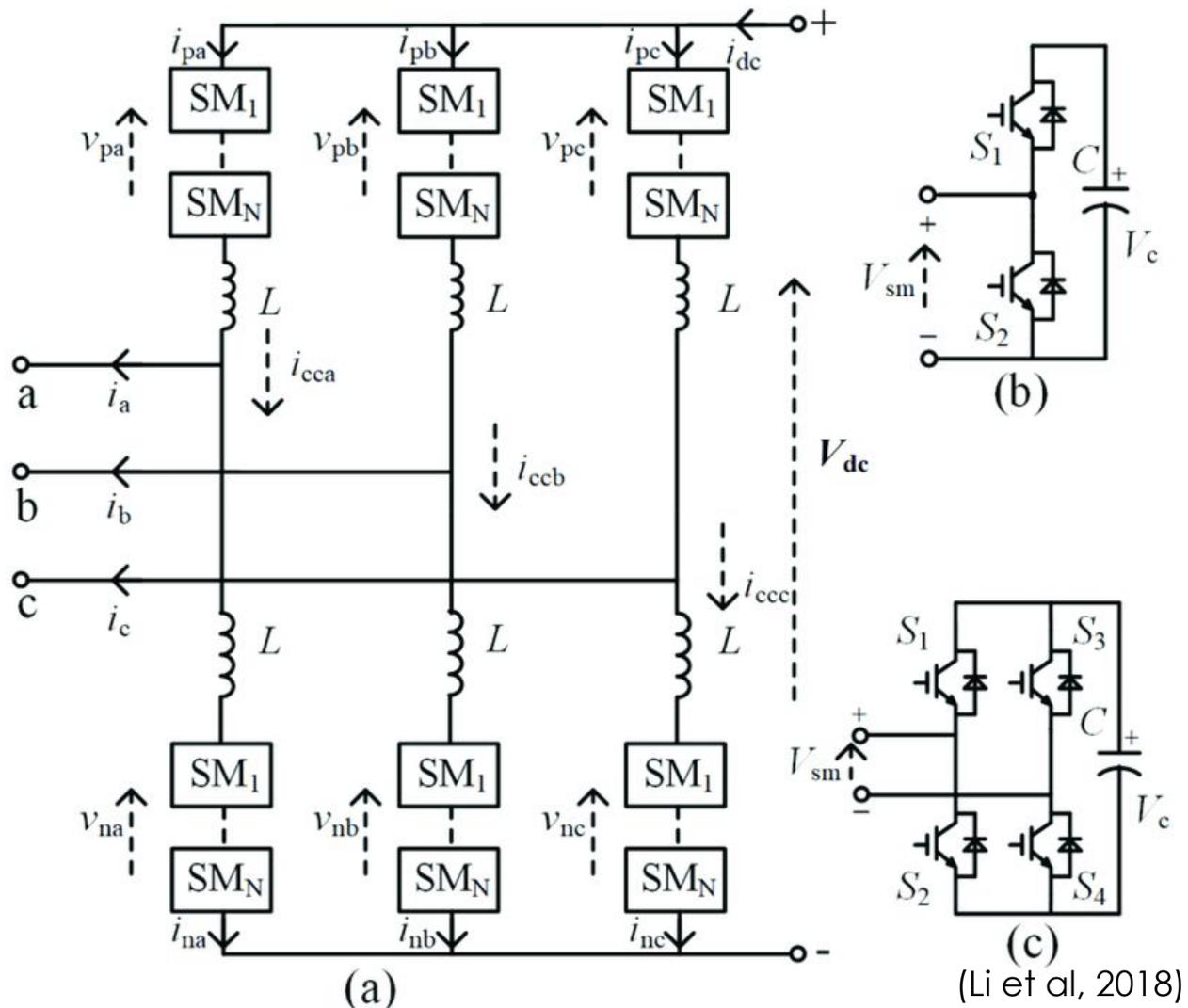
## Conversor 2 níveis



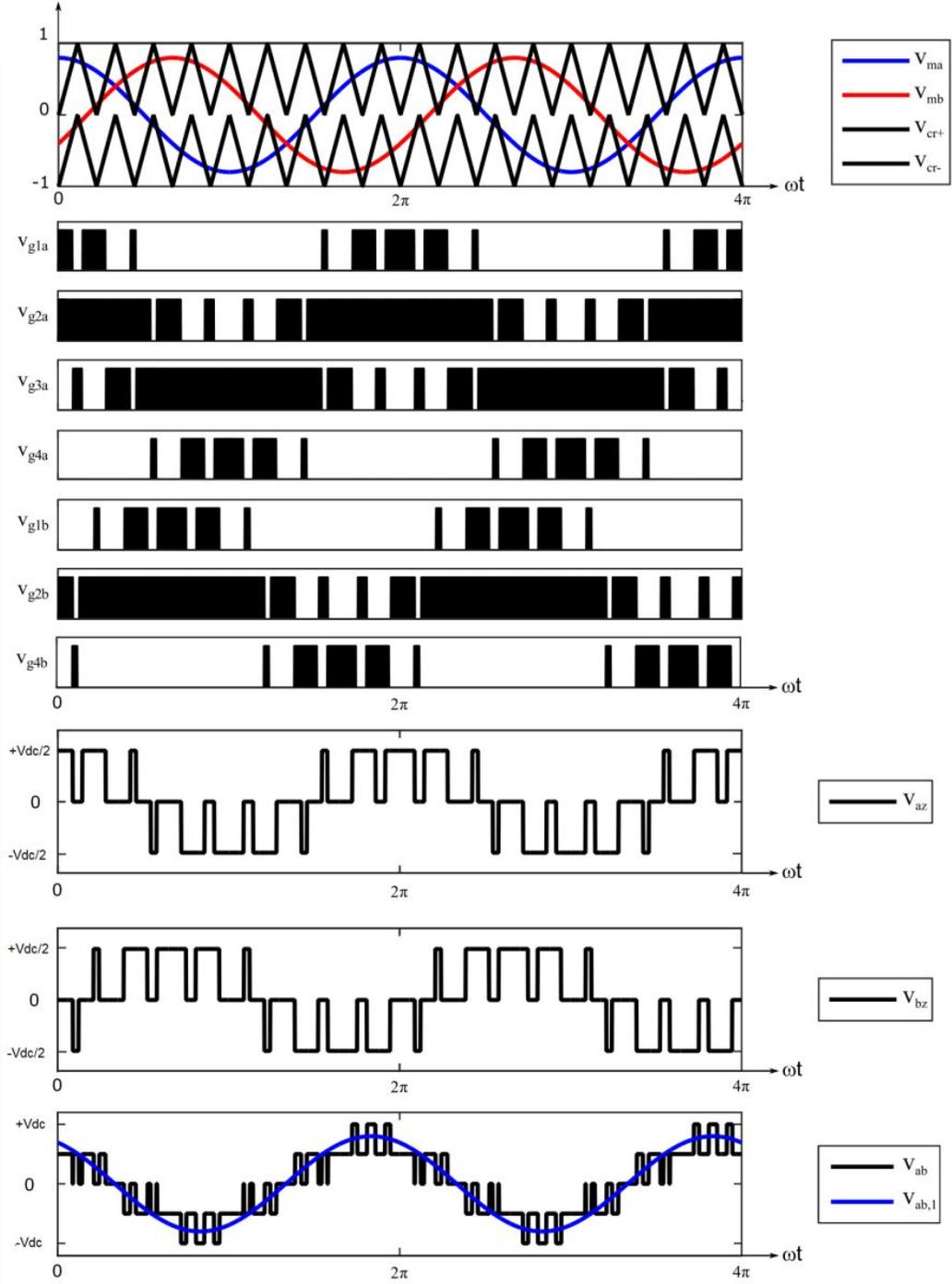
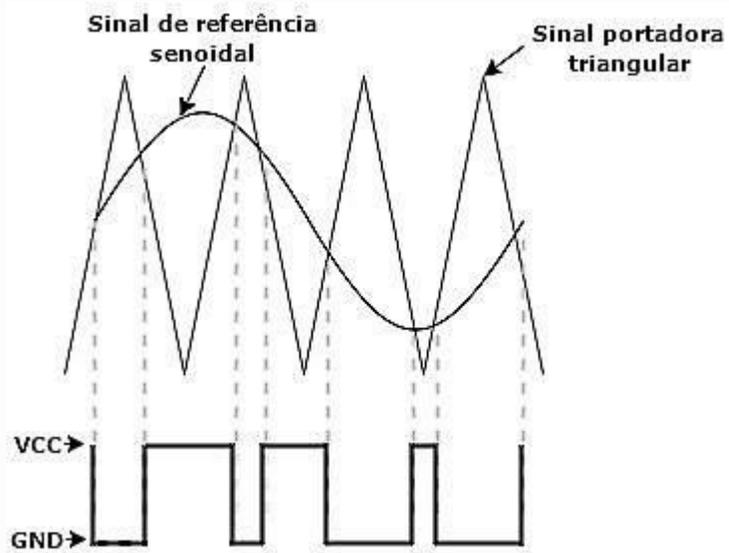
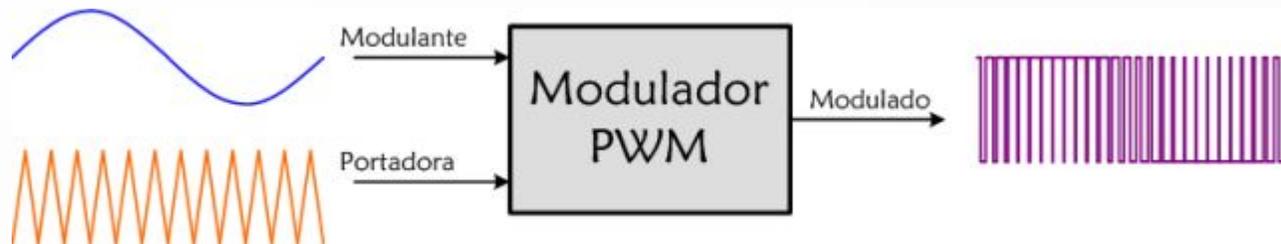
## Conversor 3 níveis



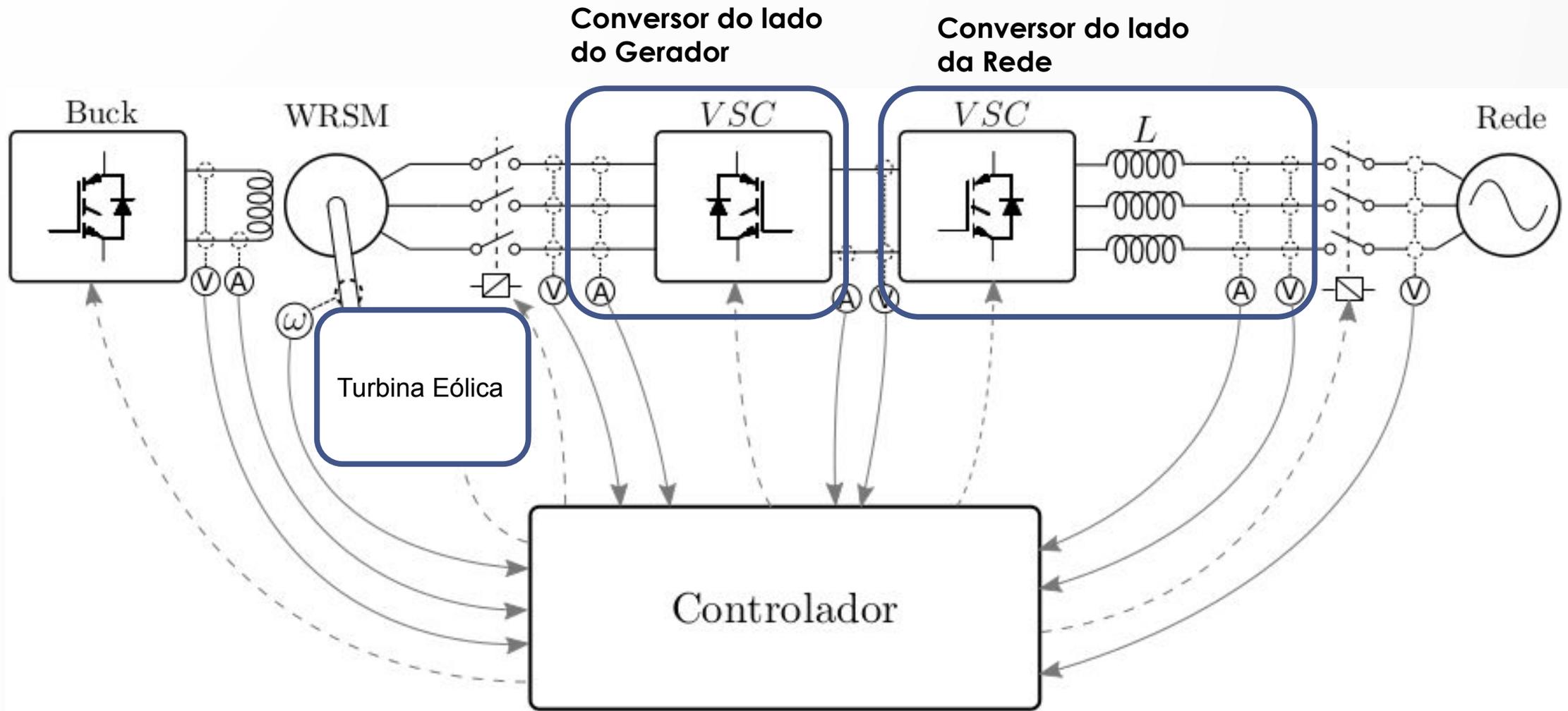
# Conversor Modular Multinível



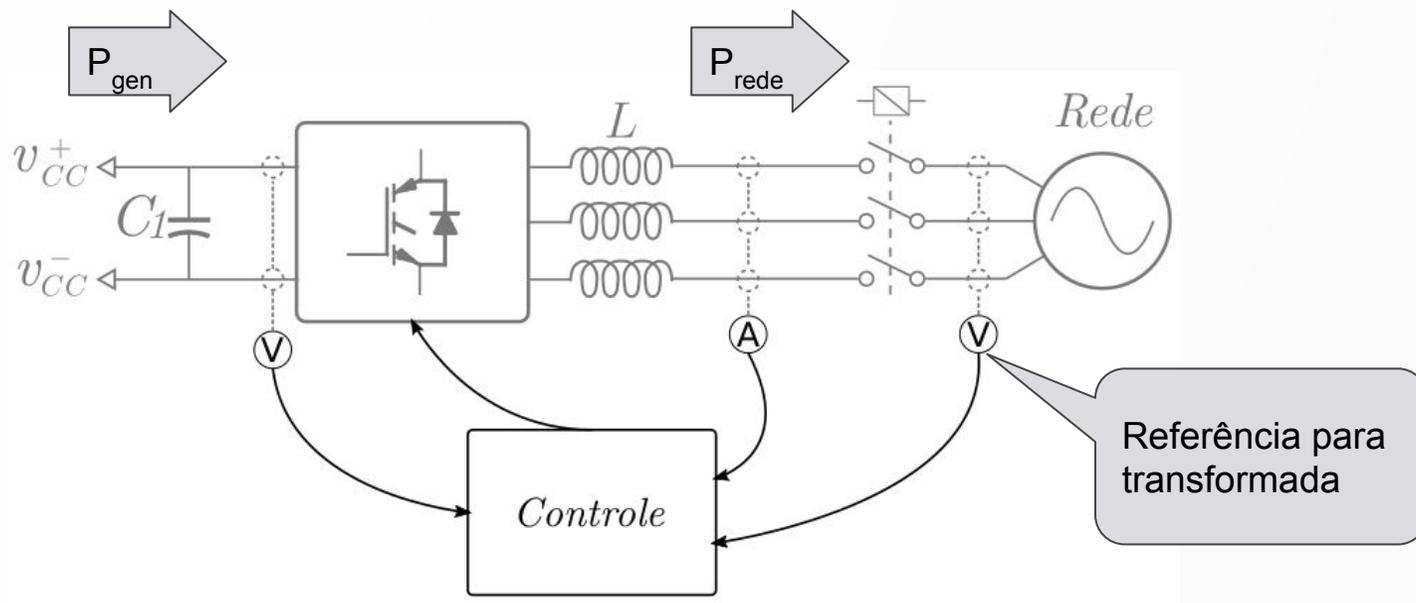
## Acionamento das chaves dos conversores



# Controle dos conversores Back-back



# Controle Conversor do Lado da Rede



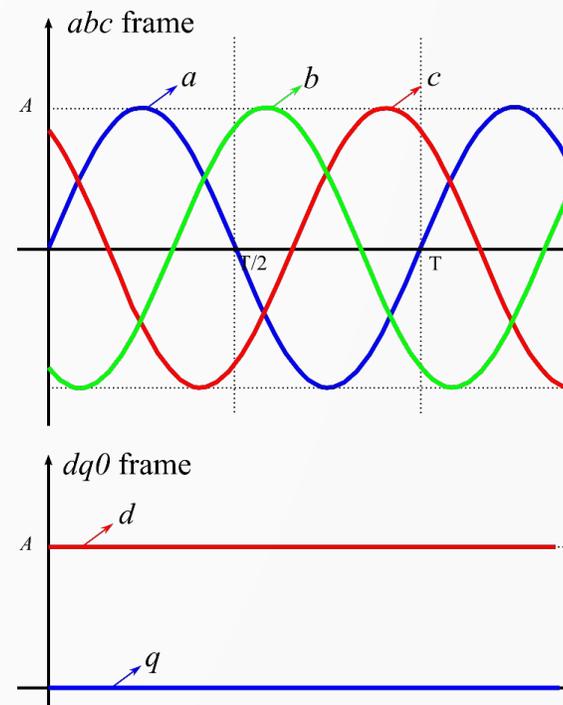
- Se  $P_{gen} > P_{rede}$  → Energia em  $C_1$  aumenta ( $V_{cc}$  aumenta)
- Se  $P_{gen} < P_{rede}$  → Energia em  $C_1$  diminui ( $V_{cc}$  diminui)

$$P_{rede} = V_a^{rede} I_a^{rede} + V_b^{rede} I_b^{rede} + V_c^{rede} I_c^{rede}$$

$$P_{rede} = V_d^{rede} I_d^{rede} + V_q^{rede} I_q^{rede} = V_d^{rede} I_d^{rede}$$

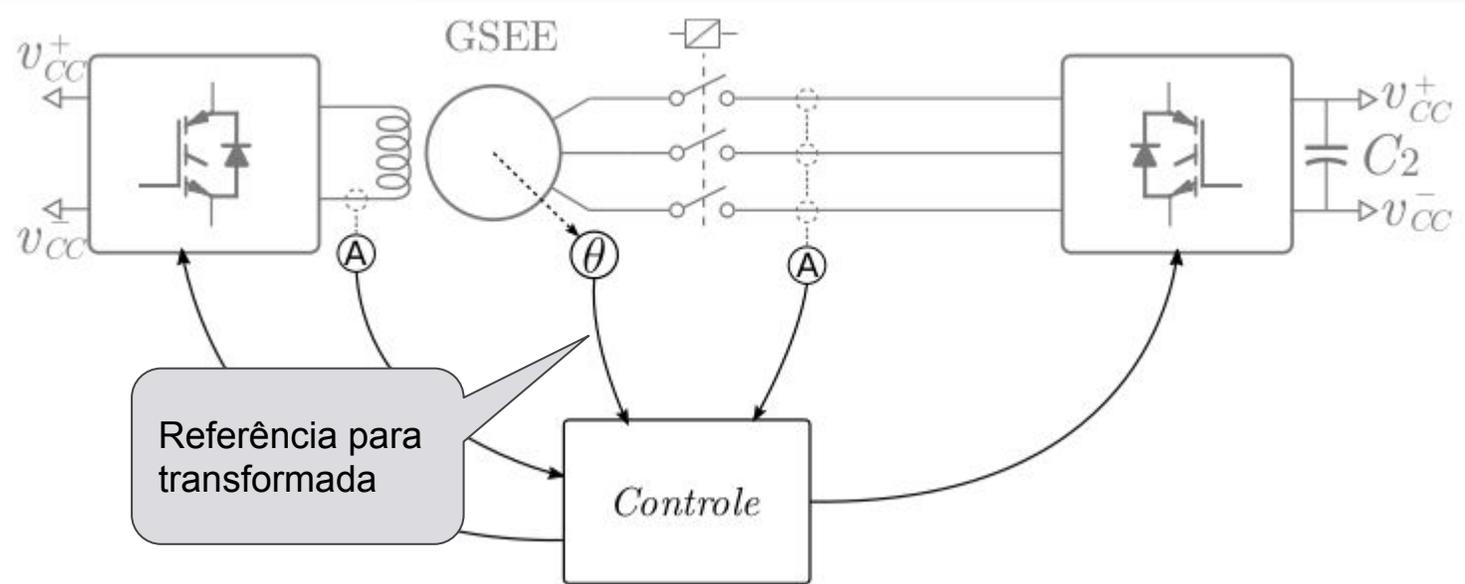
$$V_{dc} C \frac{dV_{dc}}{dt} = -\frac{3}{2} V_d^{rede} I_d^{rede} - P_{gen}$$

Transformada Vetorial ABC-DQ0





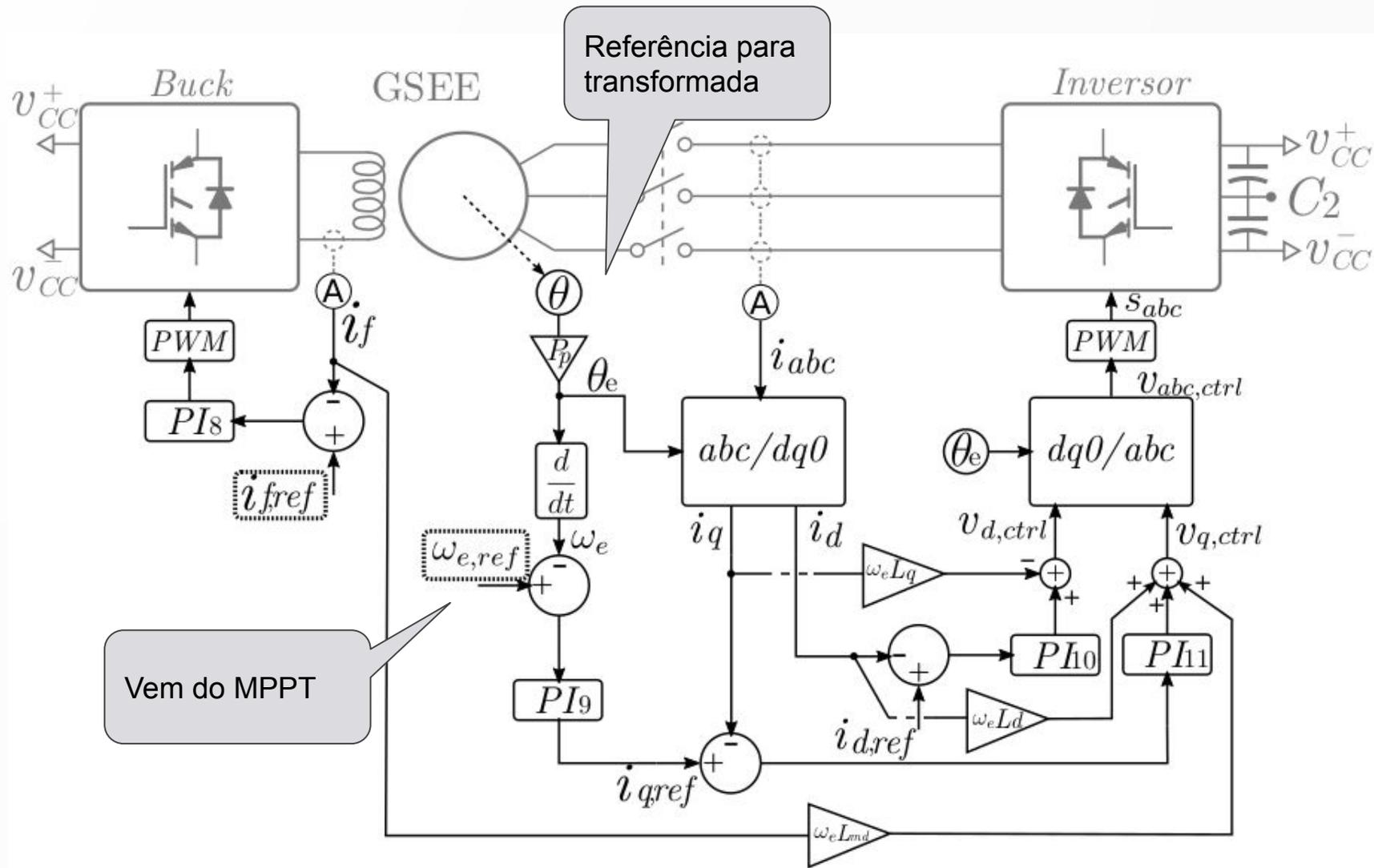
# Controle Conversor do Lado do Gerador



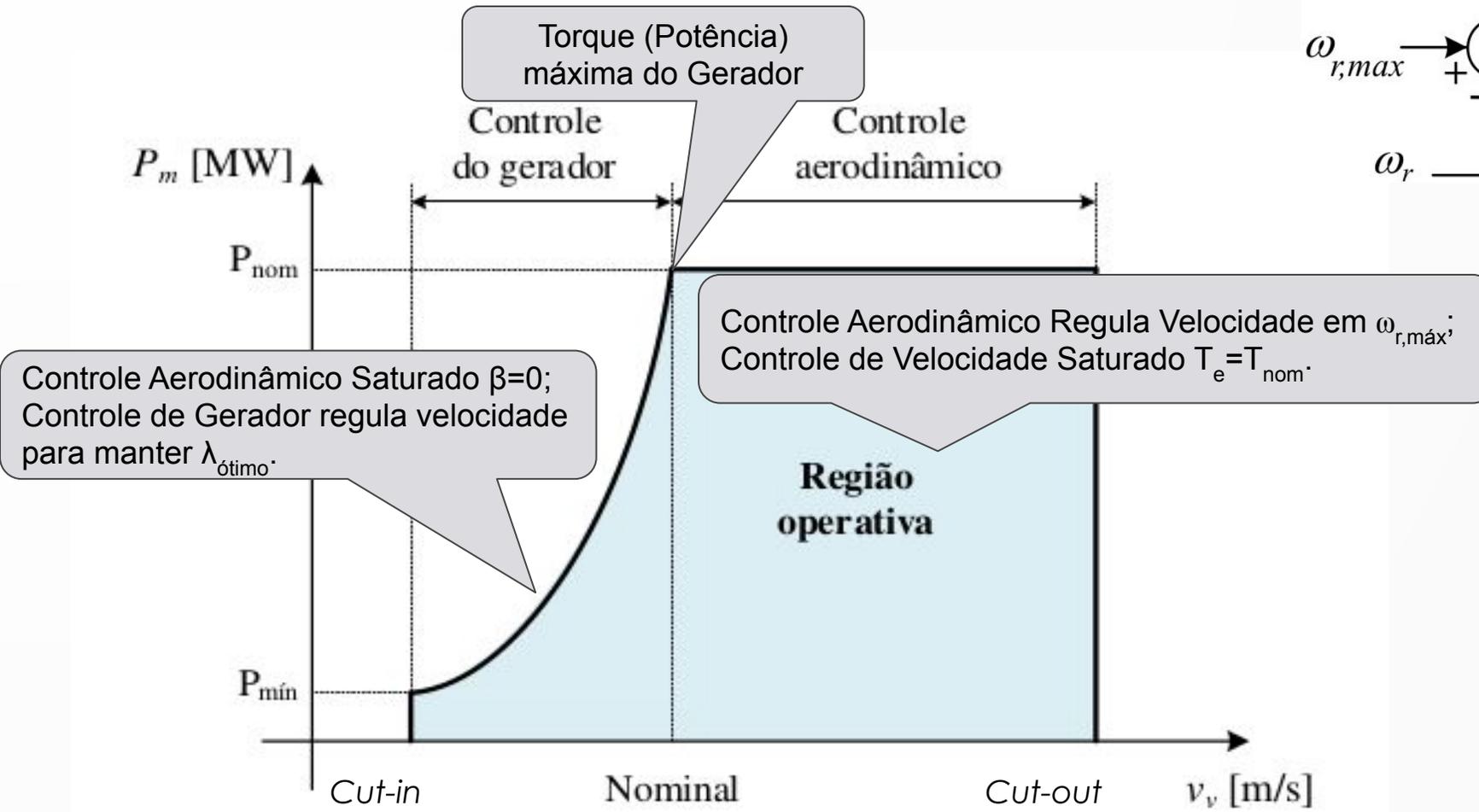
$$J \frac{d\omega_r}{dt} = T_m(\lambda(\omega_r, v_v), \beta) - T_e(I_d^{ger}, I_q^{ger}, I_f^{ger})$$

$$T_e = \frac{3P}{2} [-L_{md} I_f^{ger} I_q^{ger} + (L_{mq} - L_{md}) I_d^{ger} I_q^{ger}]$$

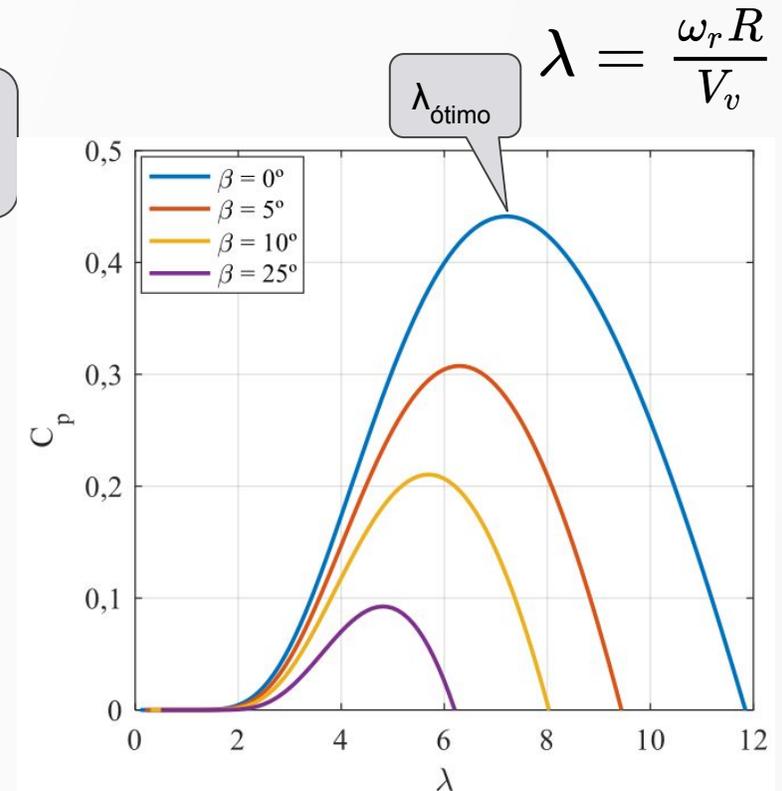
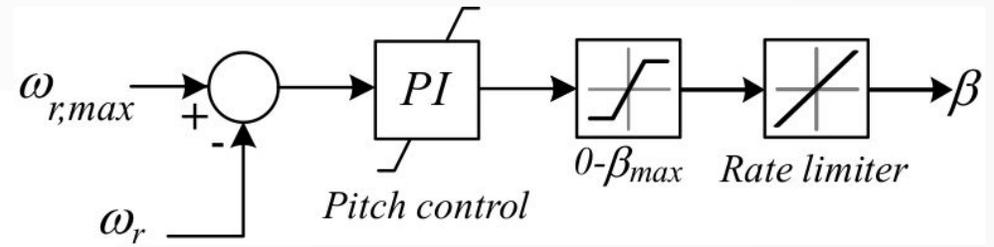
# Controle Conversor do Lado do Gerador



# Juntando tudo...

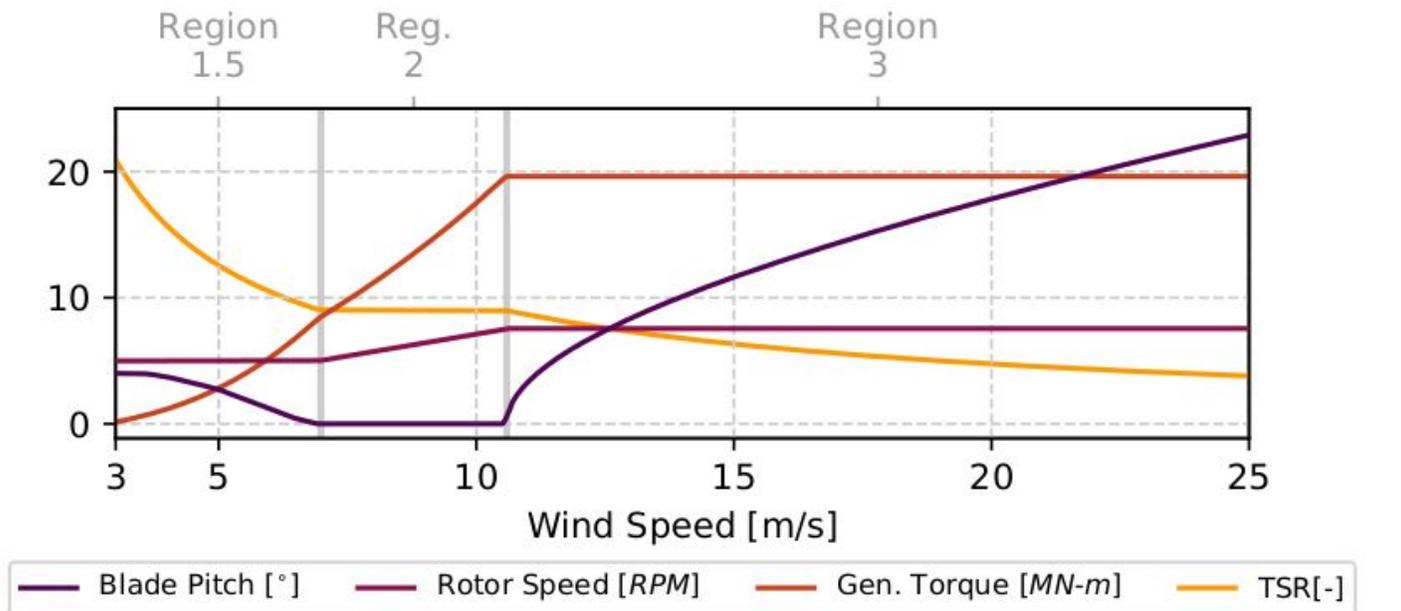
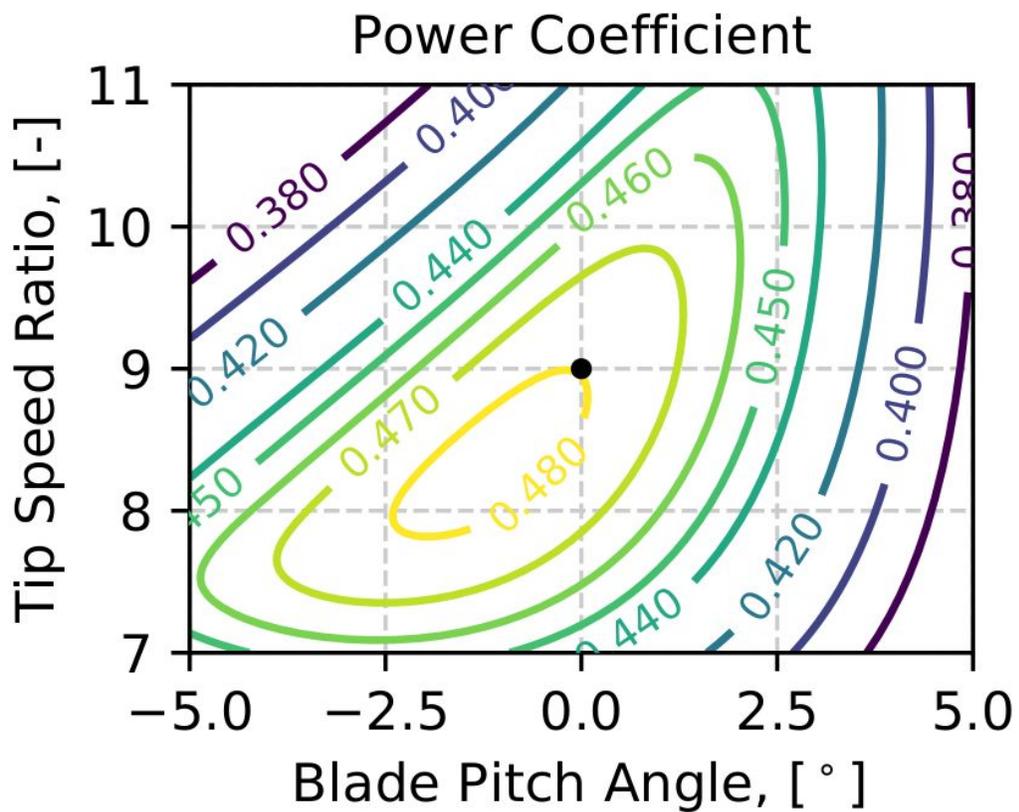


Controle Aerodinâmico

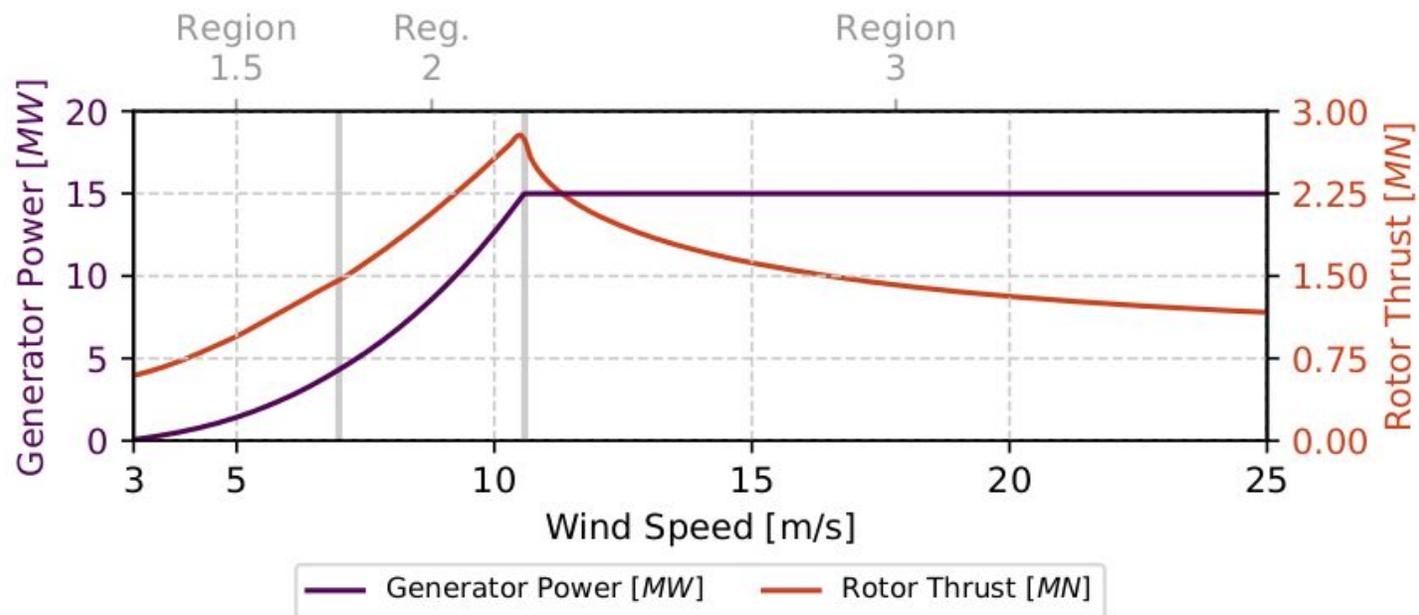




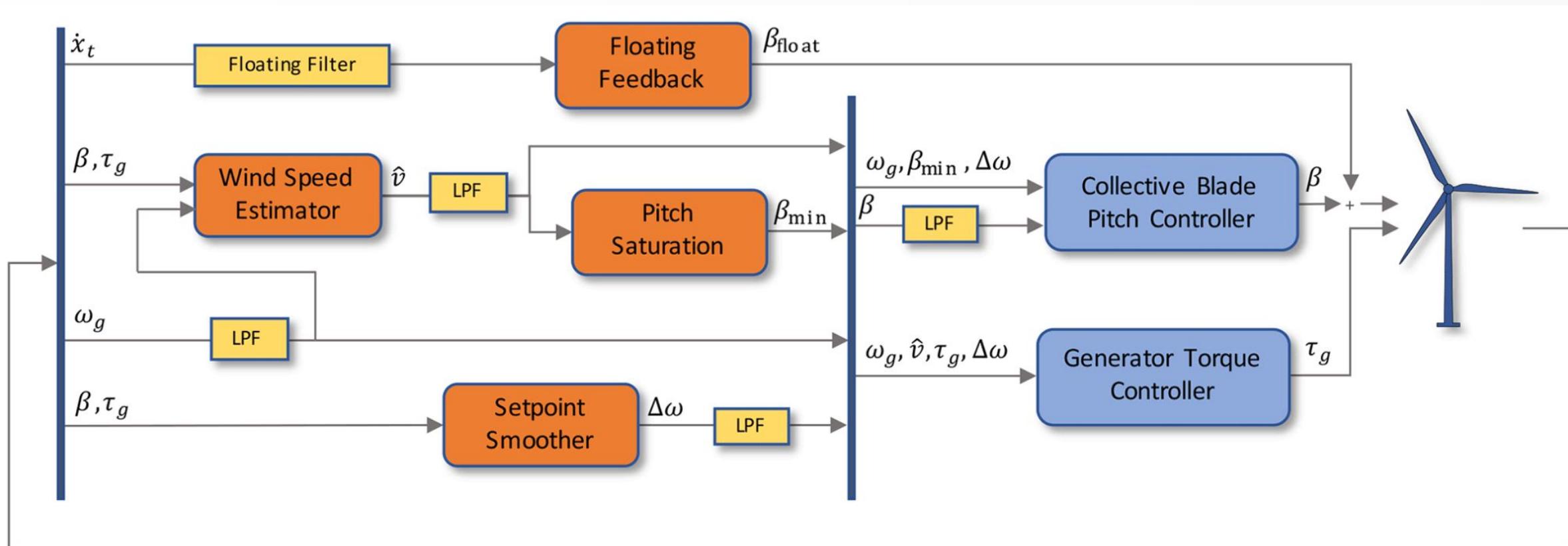
## NREL-IEA 15MW



(a) Controller regulation trajectory

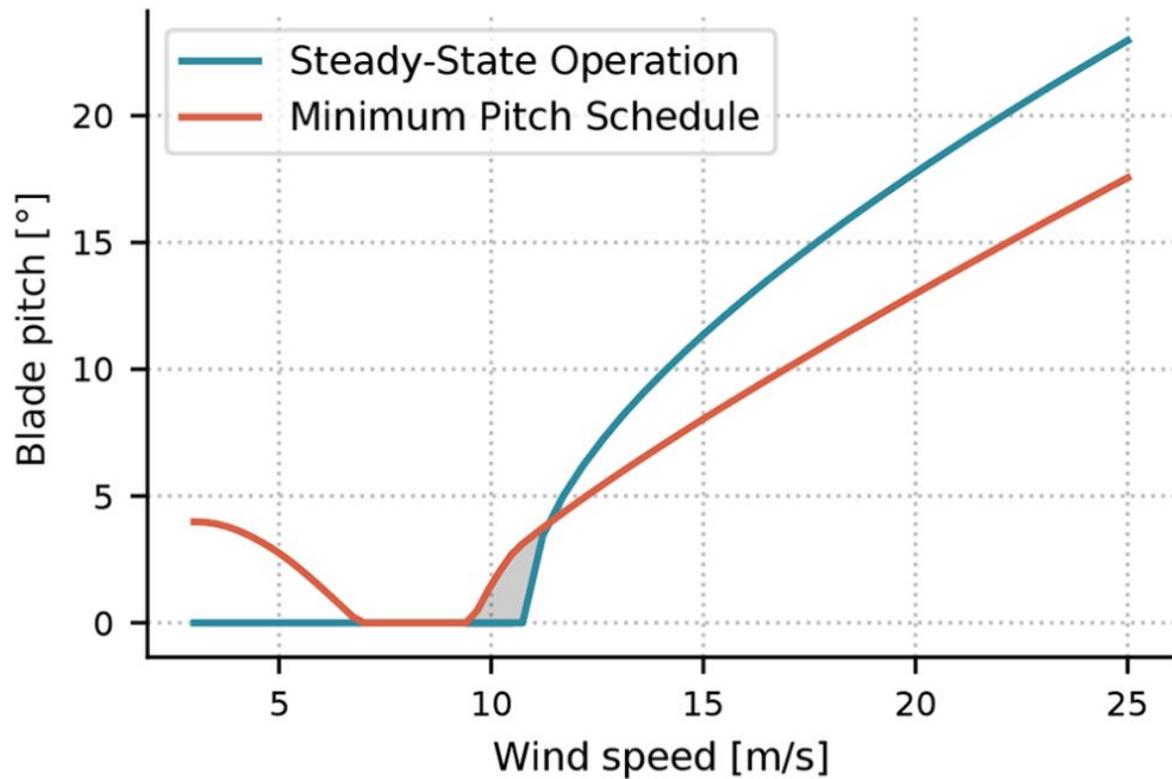


(b) Power and thrust curve

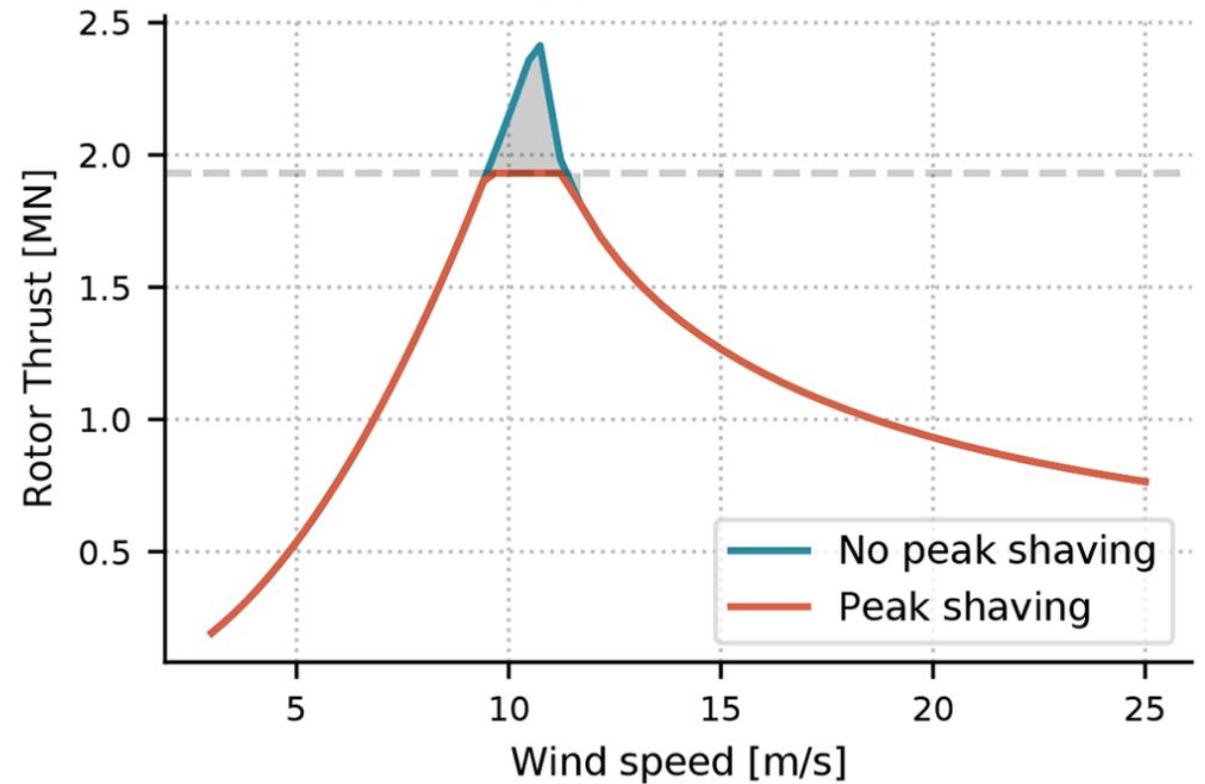


## NREL-IEA 15MW

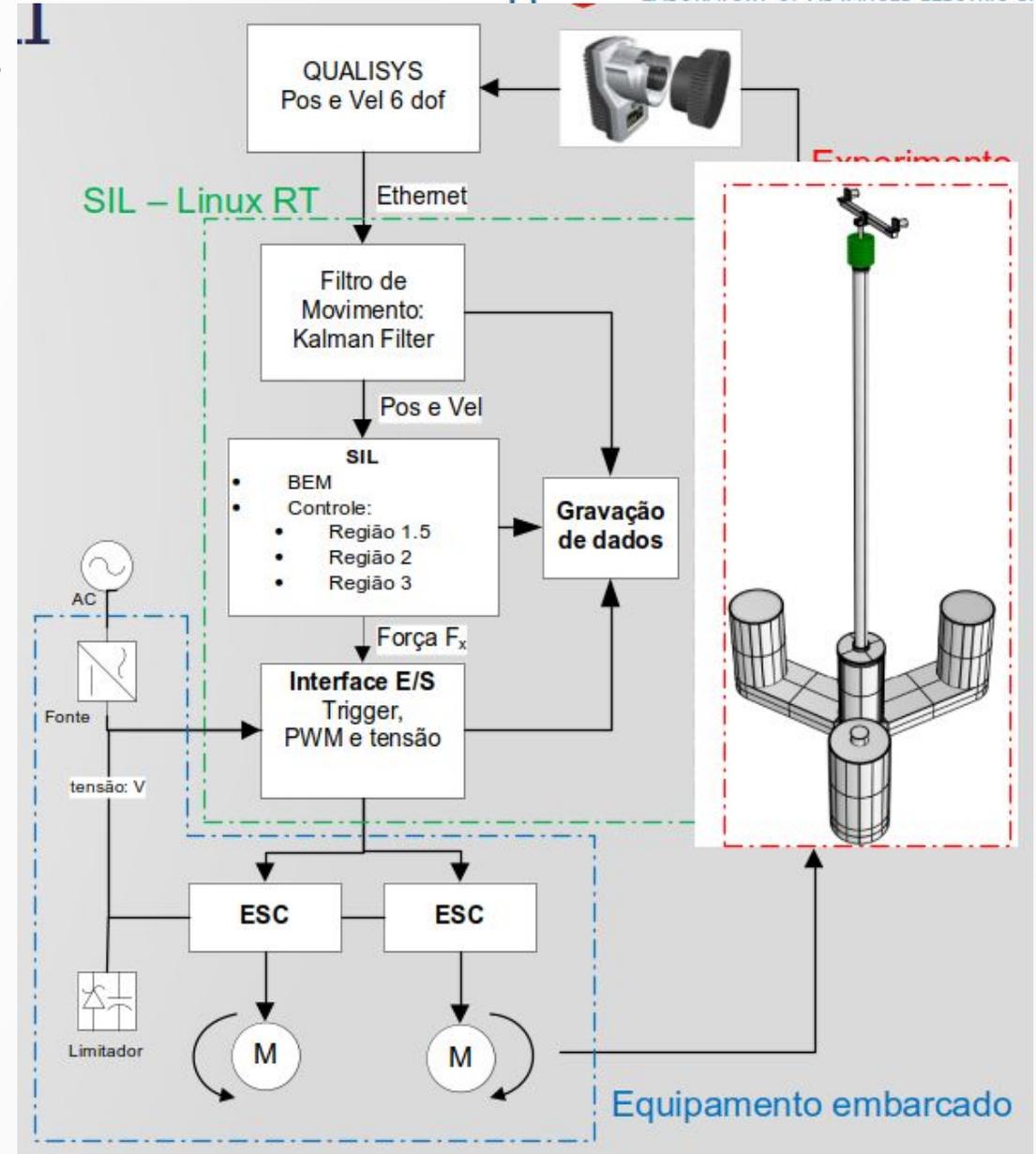
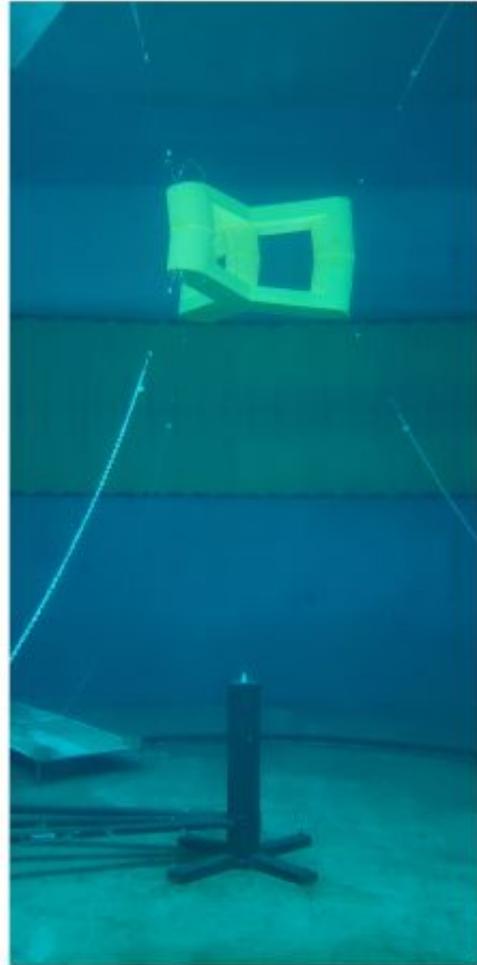
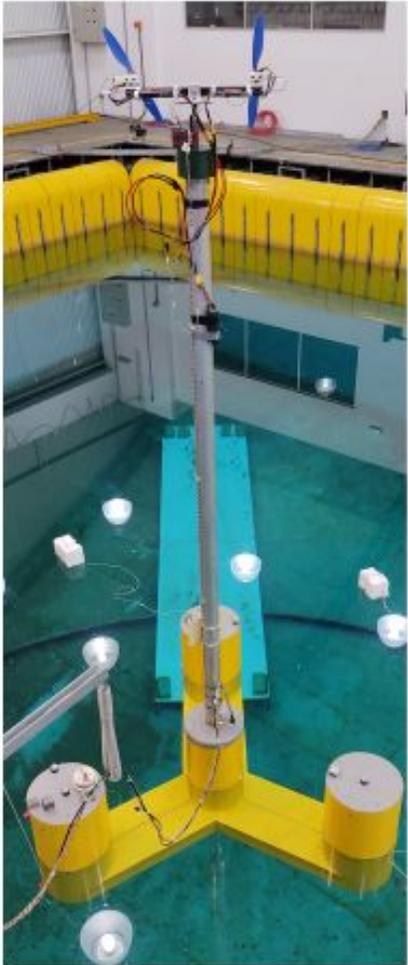
(a) Blade Pitch Schedule



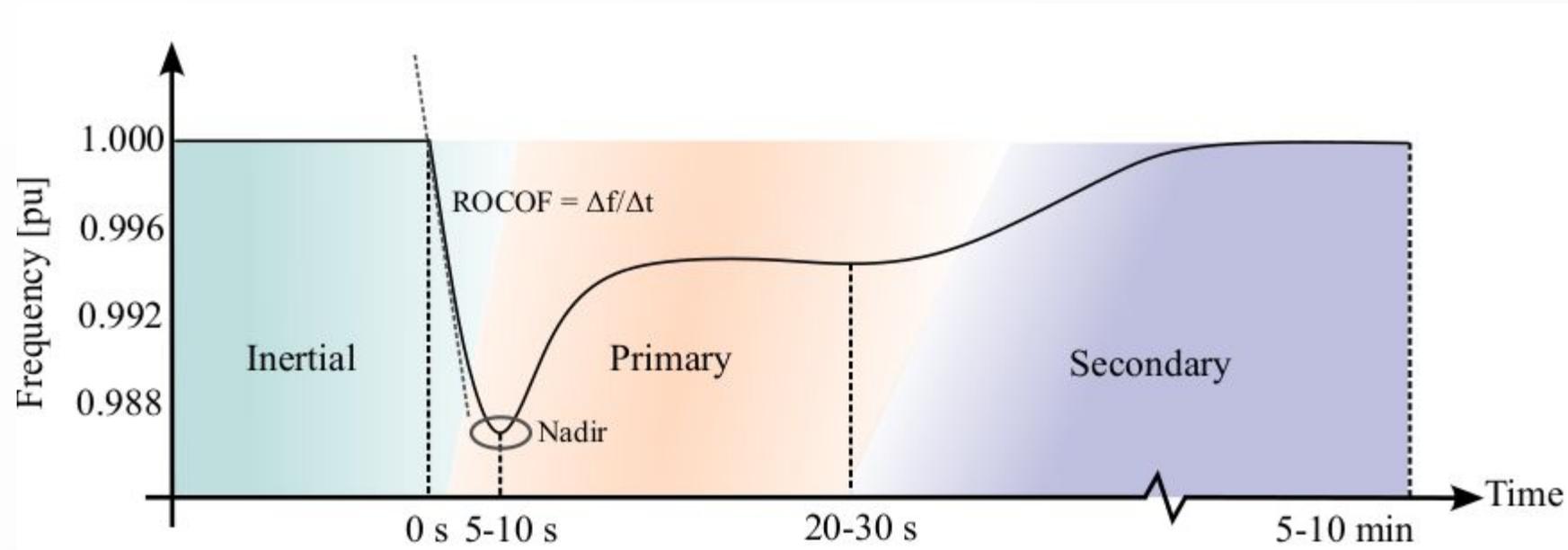
(b) Rotor Thrust



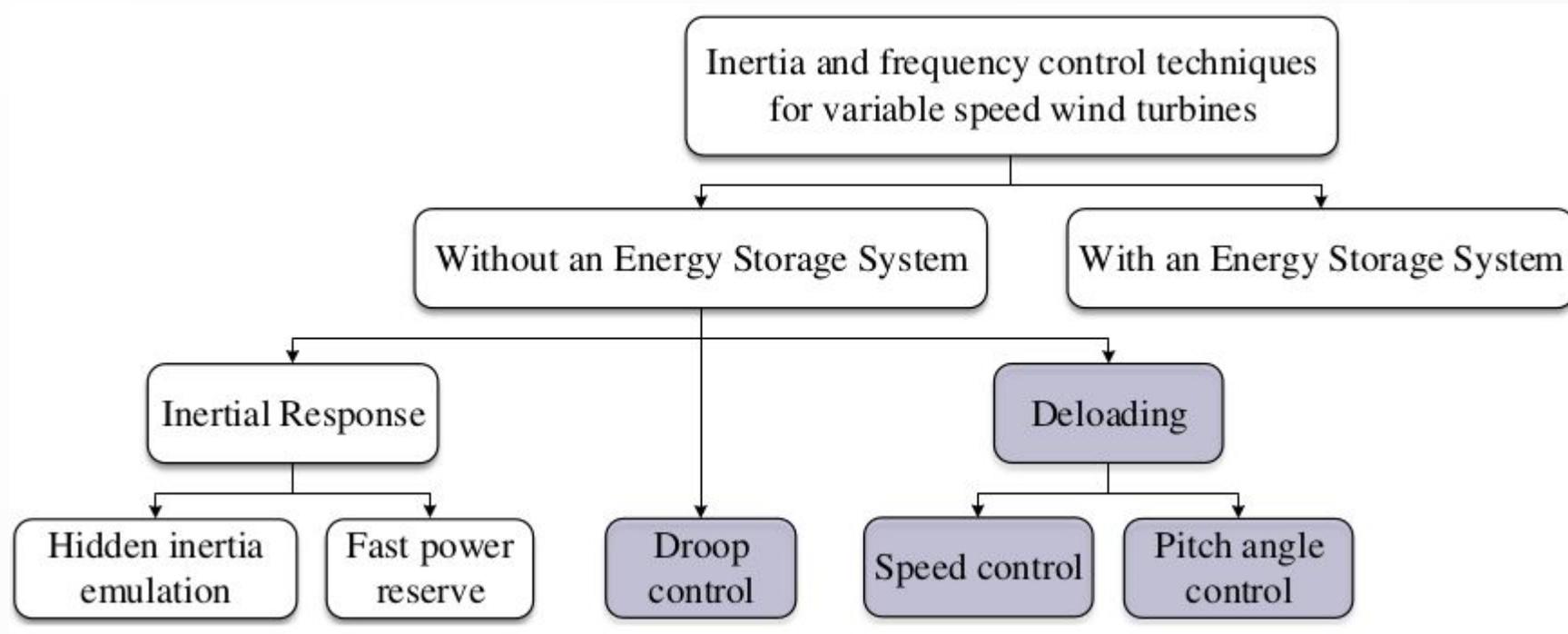
## Ensaio TPN IEA-15MW Flutuante para águas Profundas



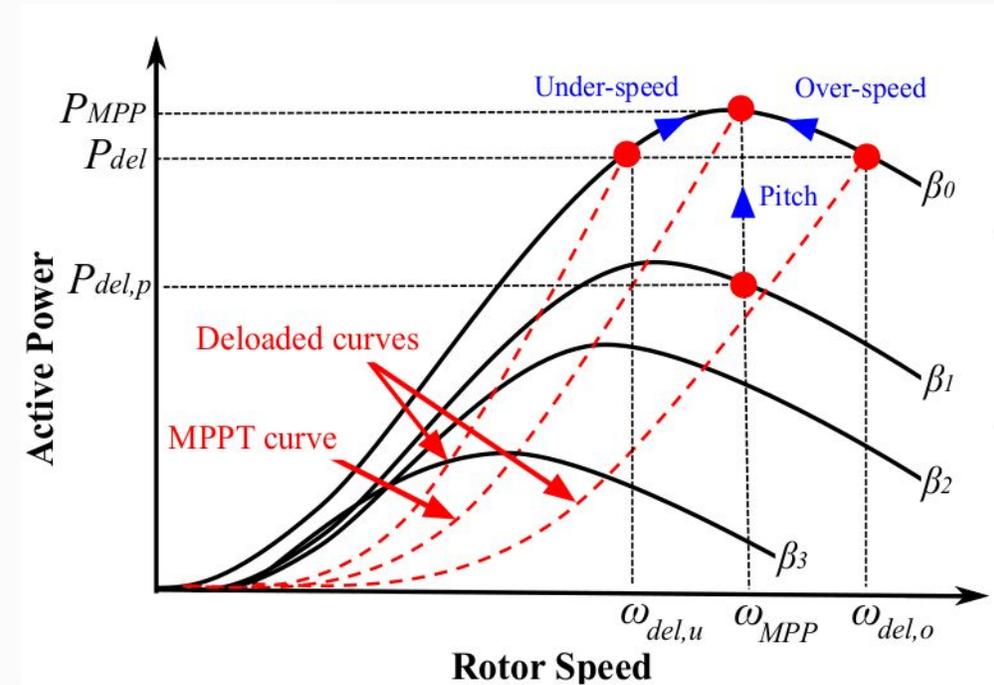
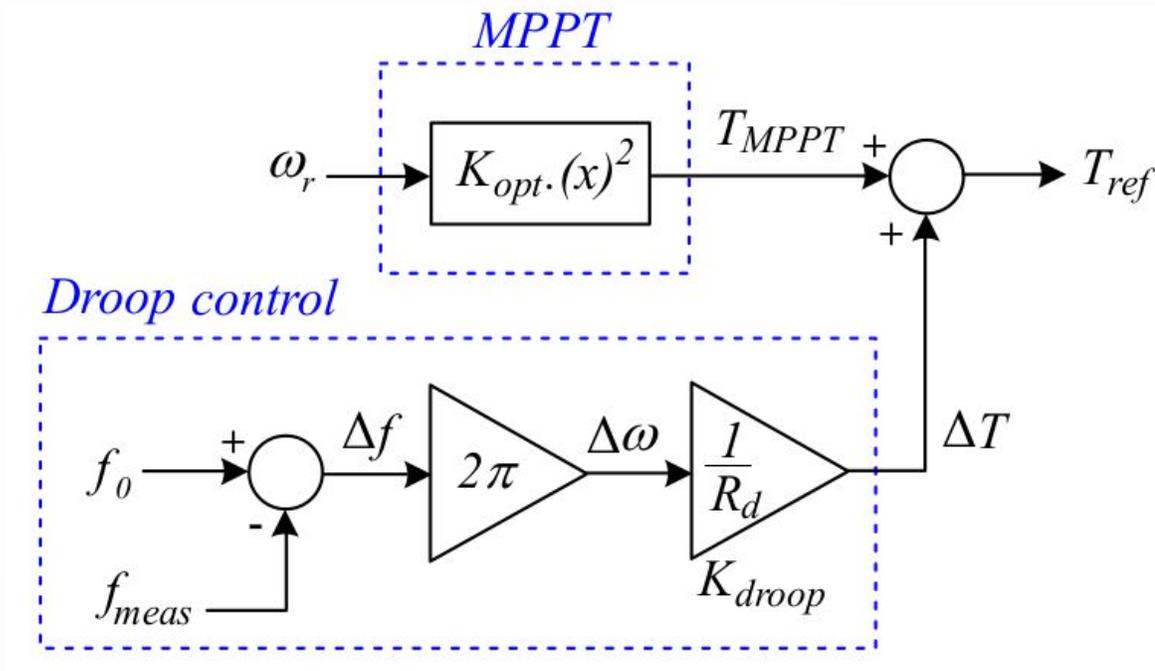
# Suporte de Frequência



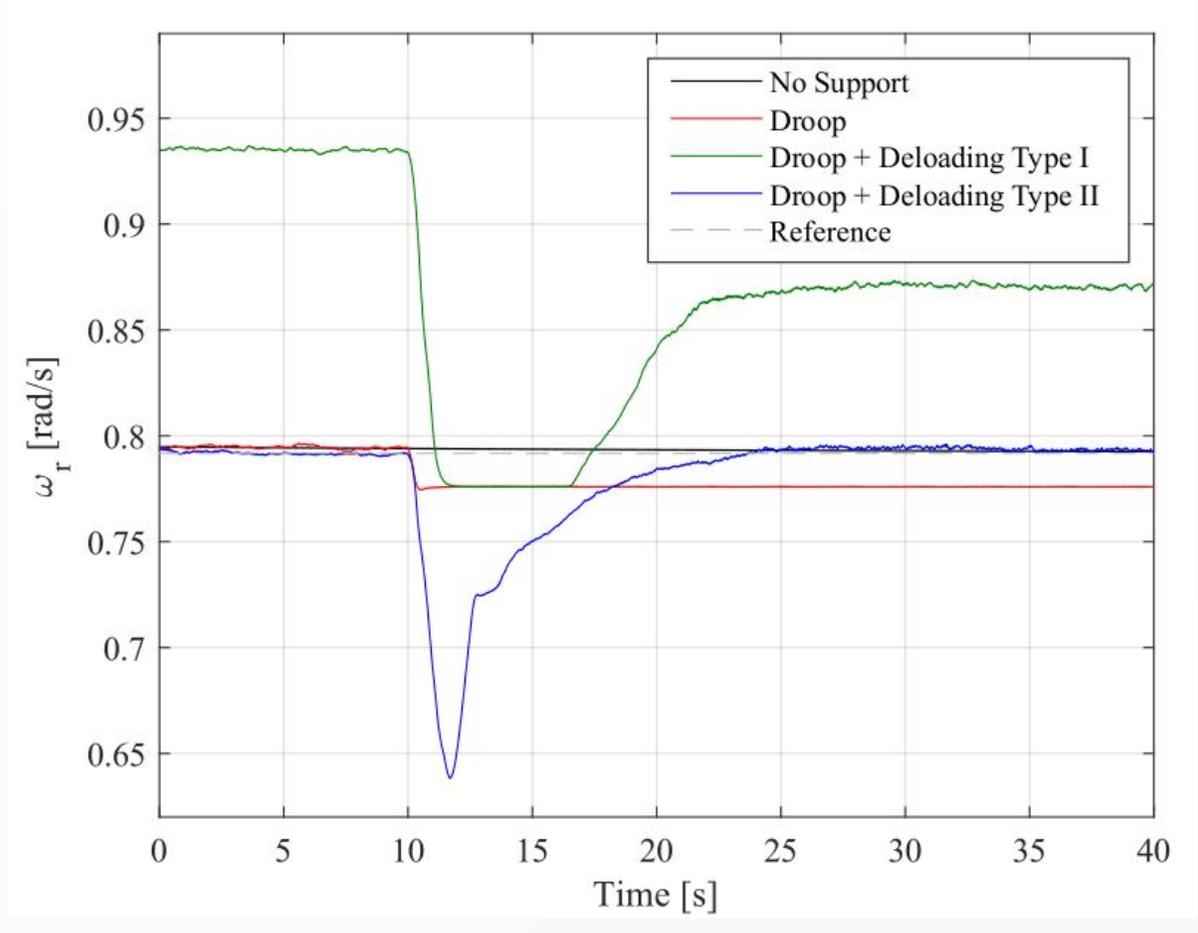
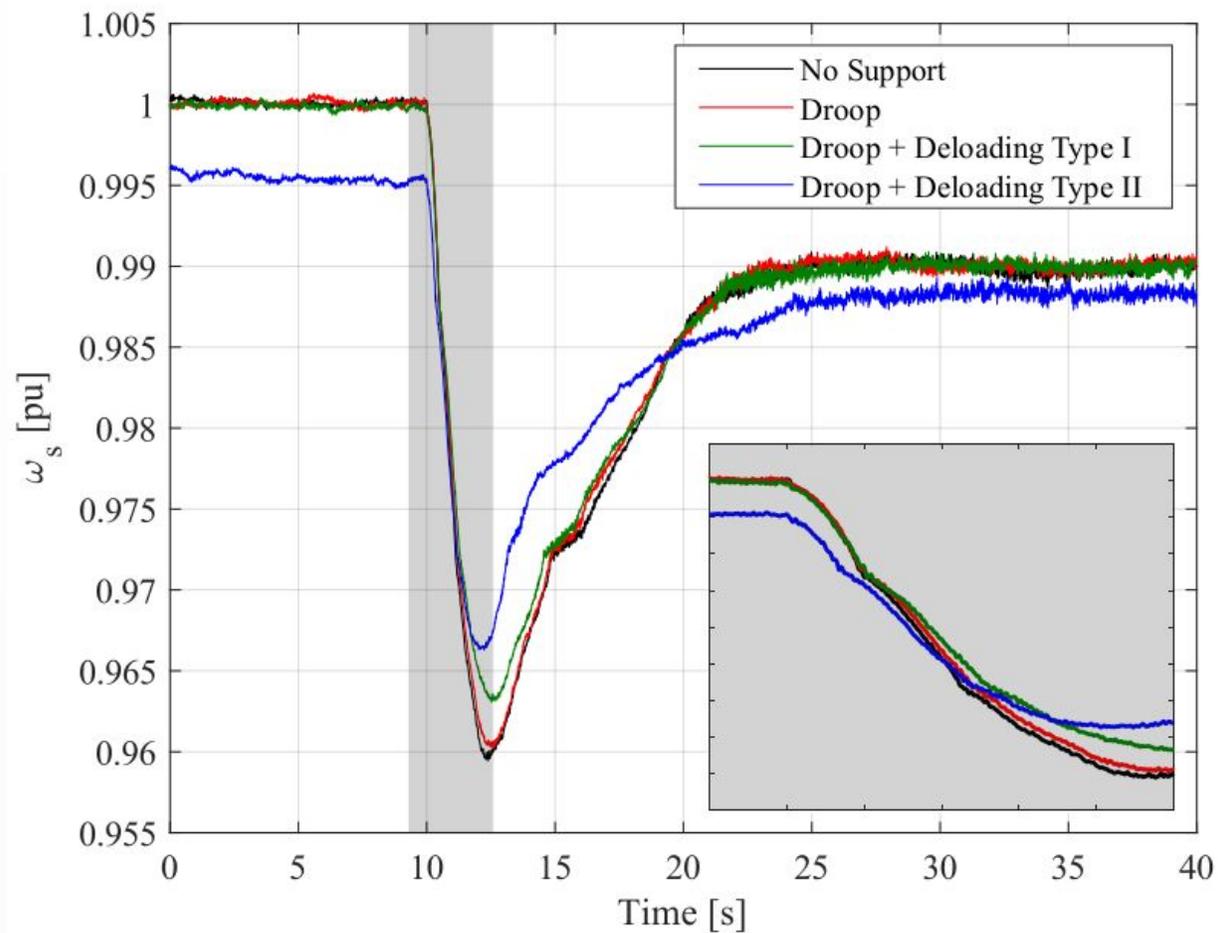
# Suporte de Frequência



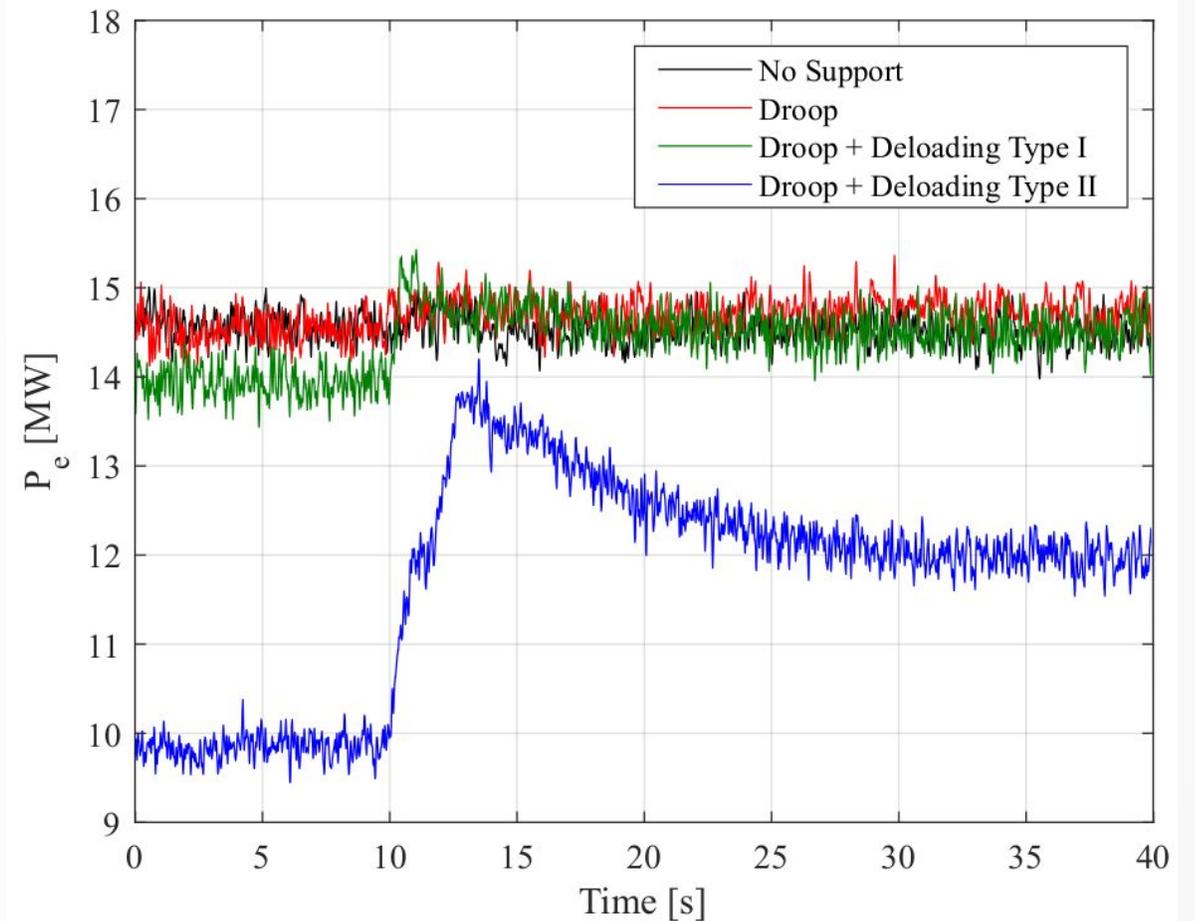
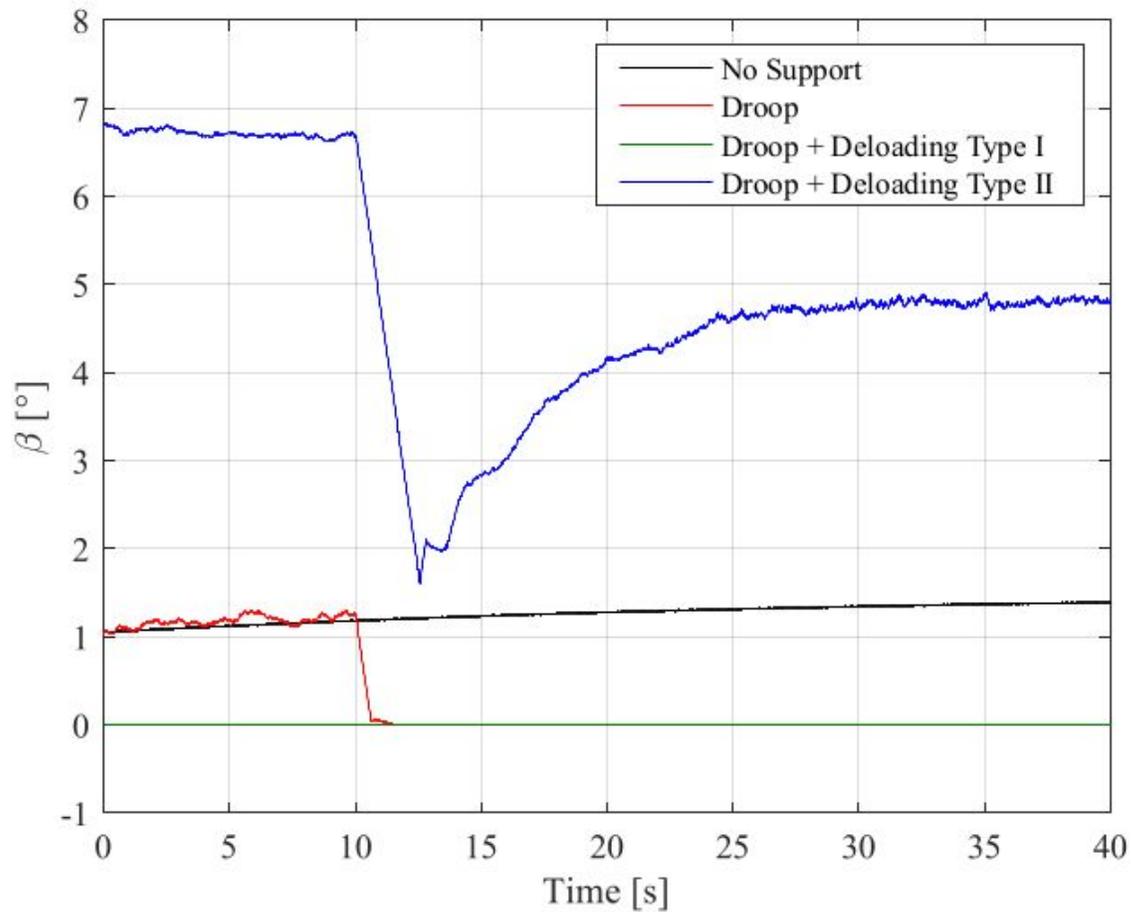
# Suporte de Frequência-Droop & Deloading



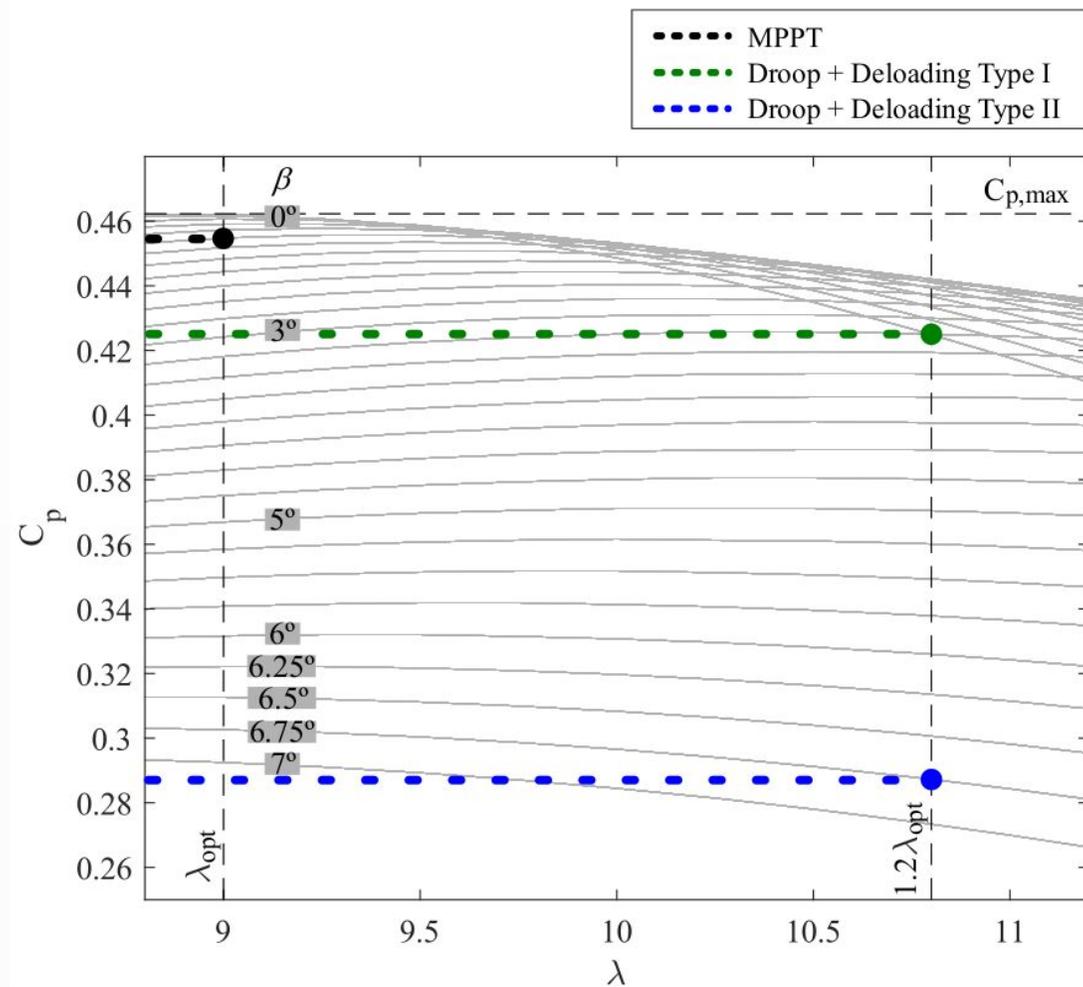
# Suporte de Frequência-Droop & Deloading



# Suporte de Frequência-Droop & Deloading



# Suporte de Frequência-Droop





Obrigado!

contato: monaro@usp.br



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