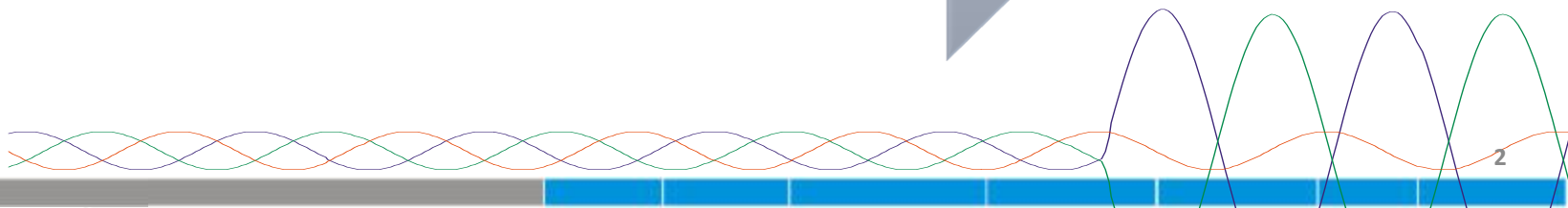
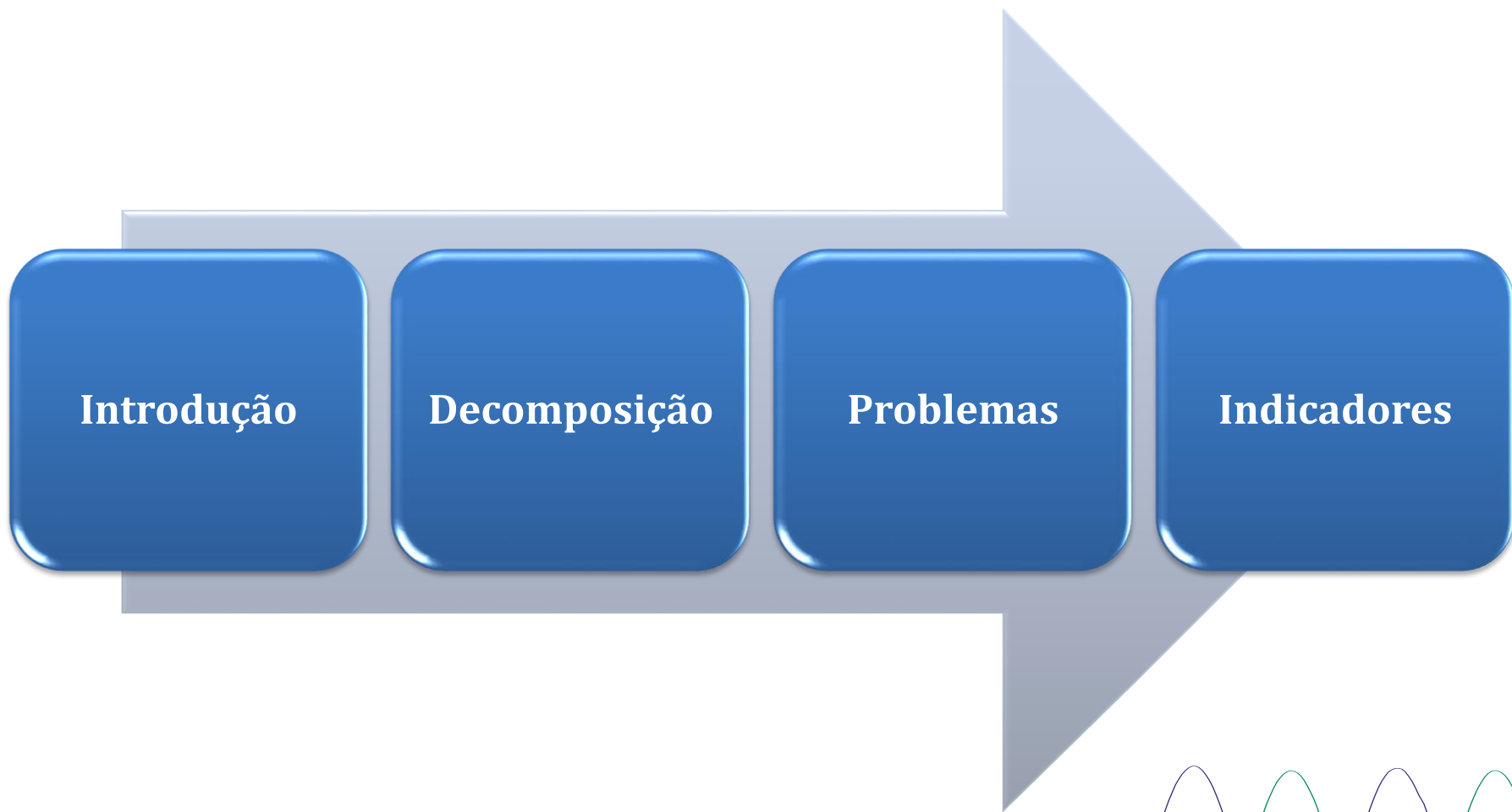


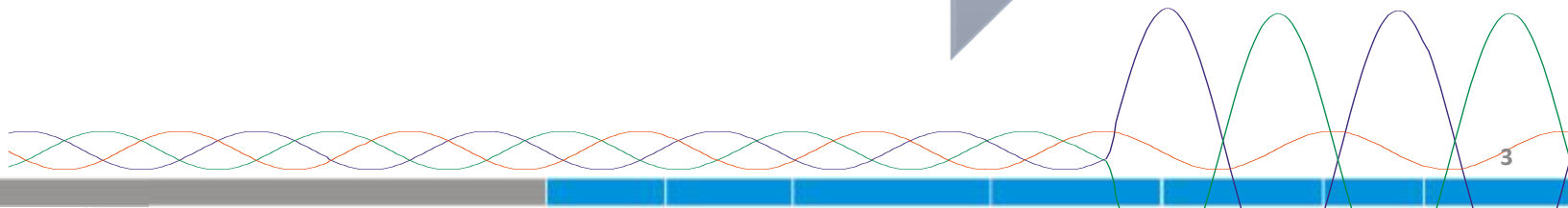
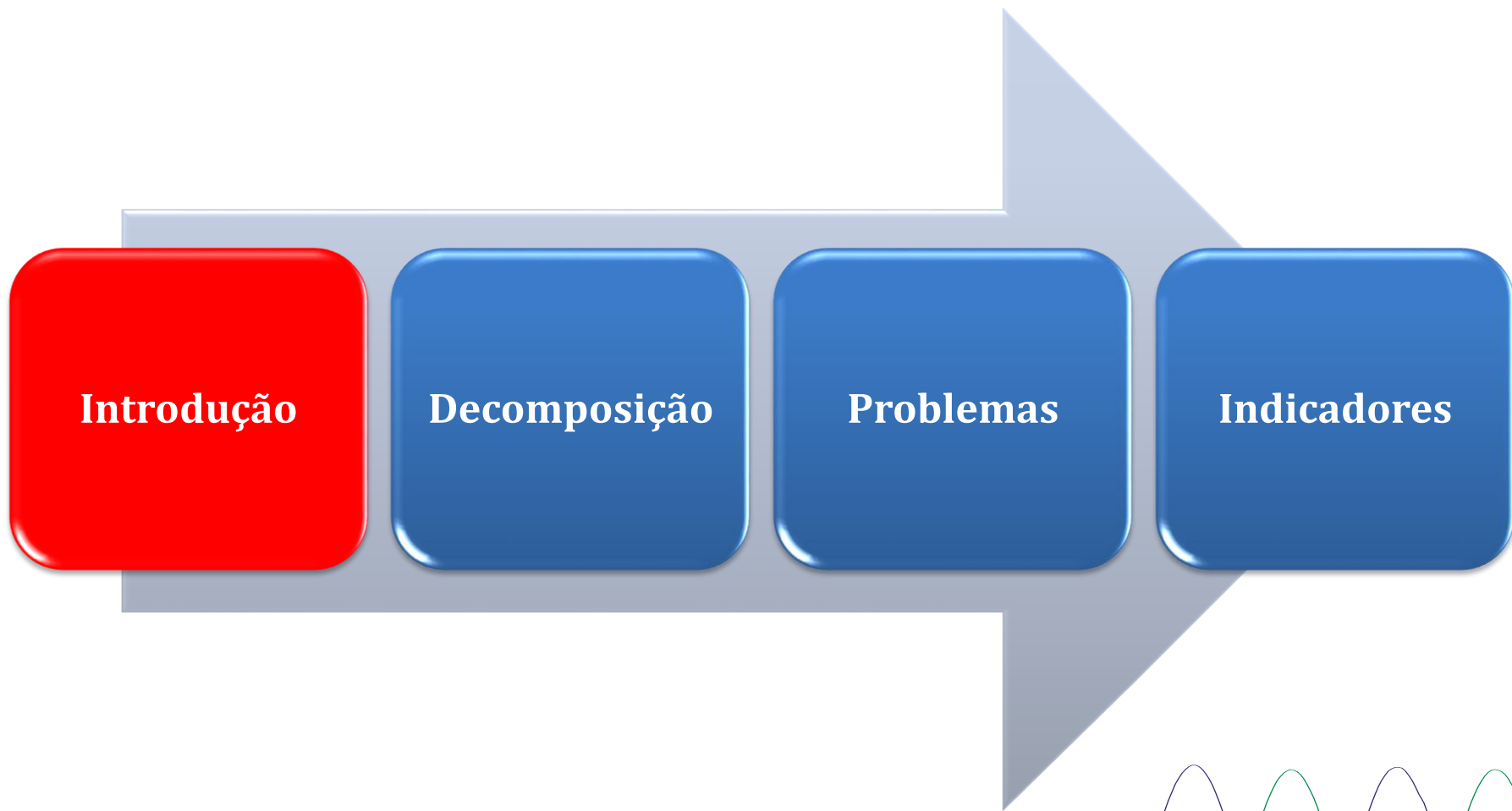
AULA LABORATORIAL EXPOSITIVA: DISTORÇÕES HARMÔNICAS – LAMQEE

CARLOS BEUTER, PROF. DR. MÁRIO OLESKOVICZ.
(cbeuter@usp.br)

Apresentação

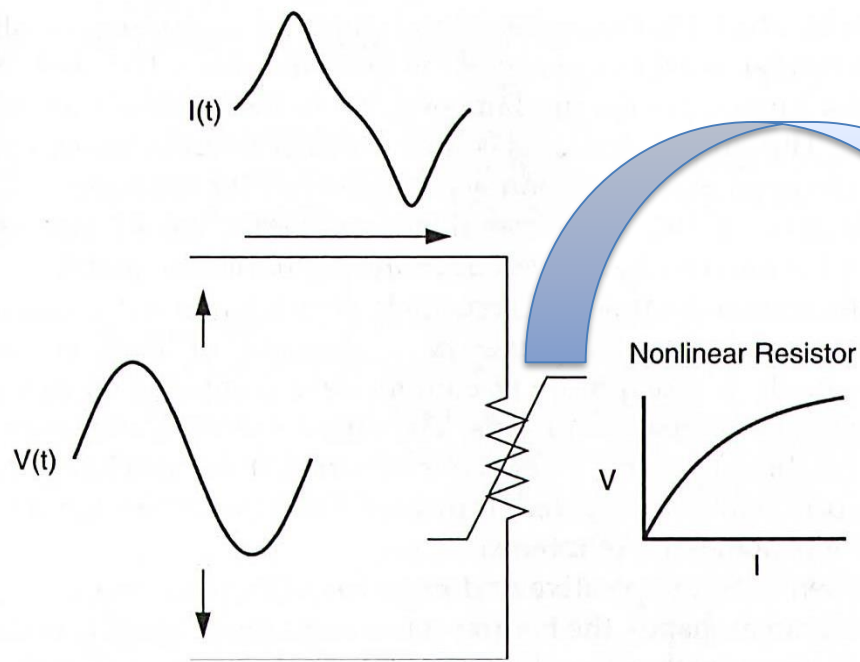


Apresentação



Introdução

- Distorção Harmônica
 - É causada por cargas não lineares no sistema;
 - A corrente não é linearmente proporcional à tensão aplicada



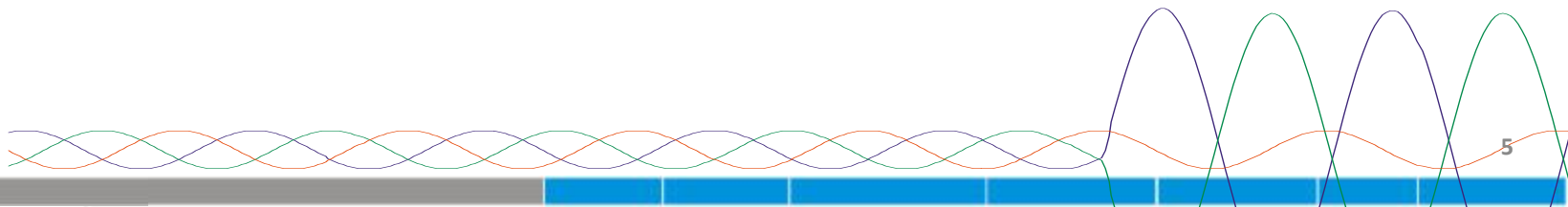
Fonte : Dugan et al, (2012)



Introdução

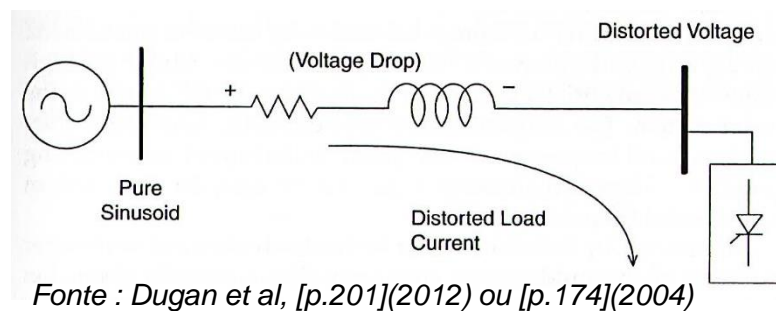
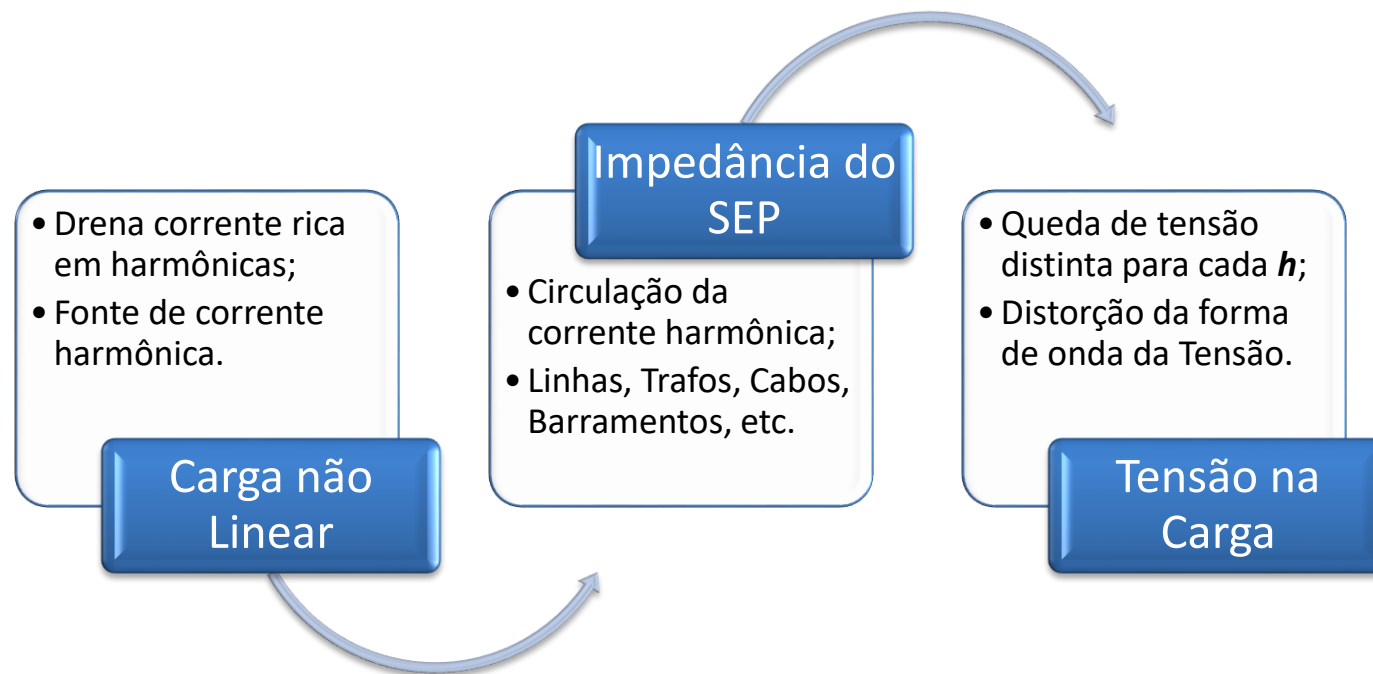
- Componentes Harmônicas
 - Sinal de Tensão ou Corrente;
 - Frequências múltiplas inteiras da componente fundamental do sistema (60Hz);

$$f_h = N \times f_0$$

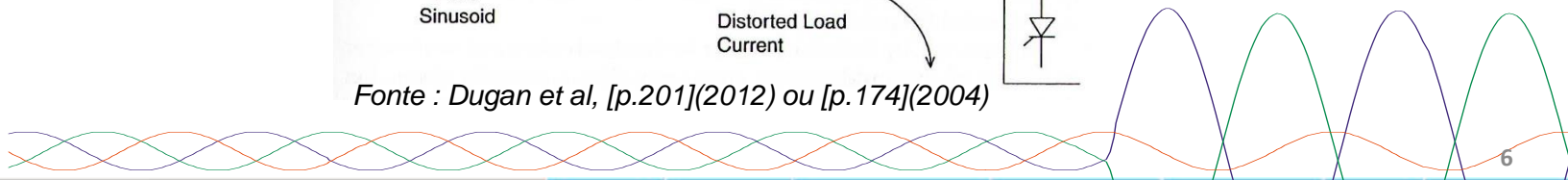


Introdução

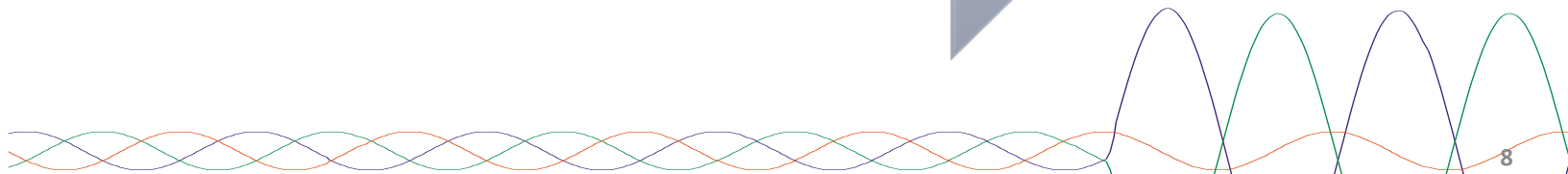
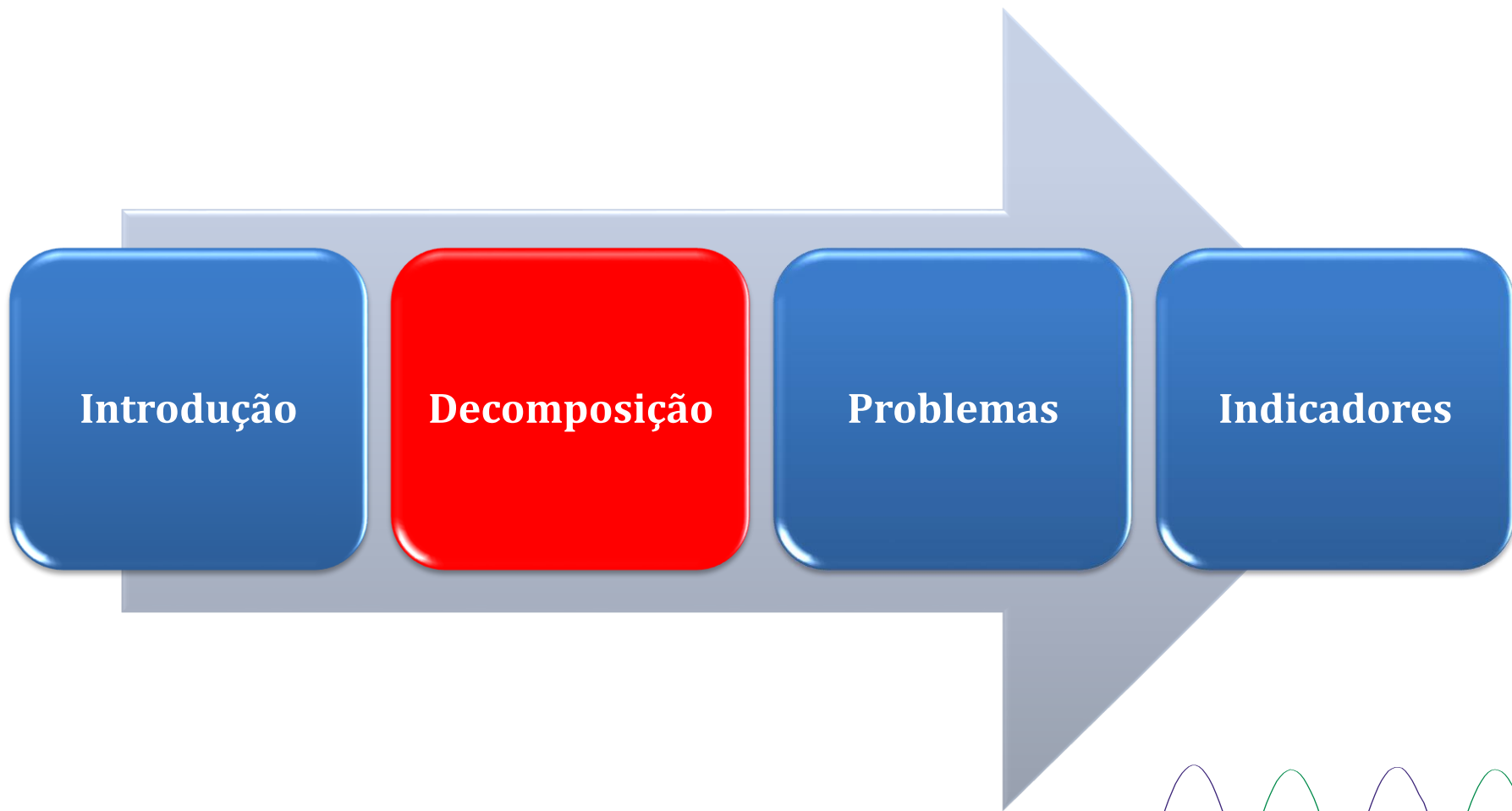
- Relação entre distorção harmônica de *Tensão e Corrente*



Fonte : Dugan et al, [p.201](2012) ou [p.174](2004)



Apresentação

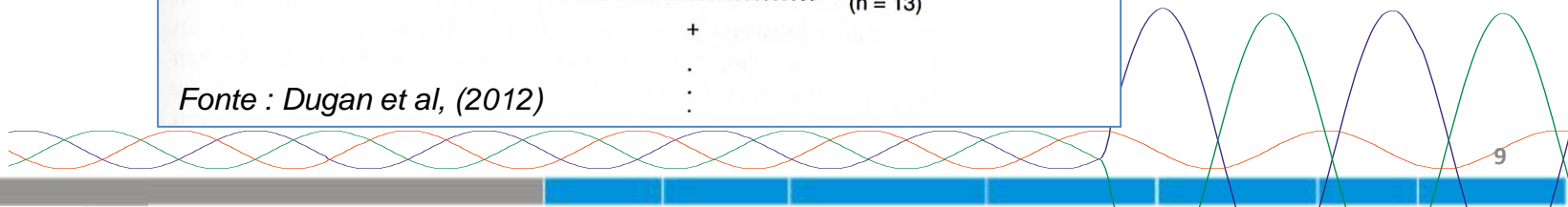
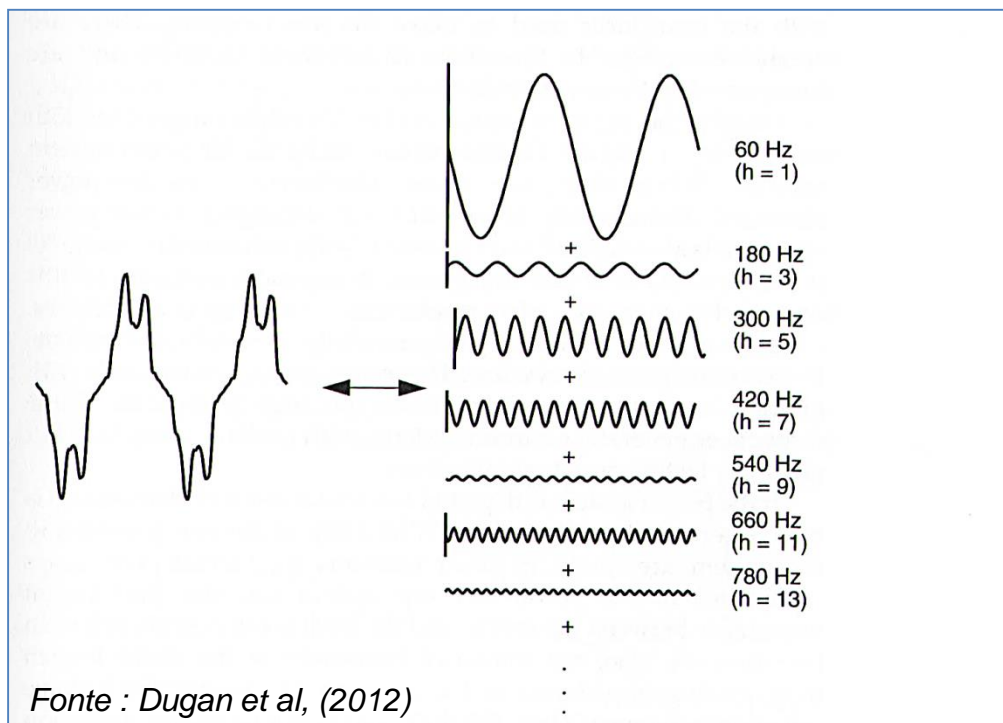


Decomposição em série de Fourier

- Ondas não senoidais \rightarrow série trigonométrica de Fourier

$$v(t) = V_0 + \sum_{k=1}^{\infty} (a_k \cos k\omega t + b_k \sin k\omega t)$$

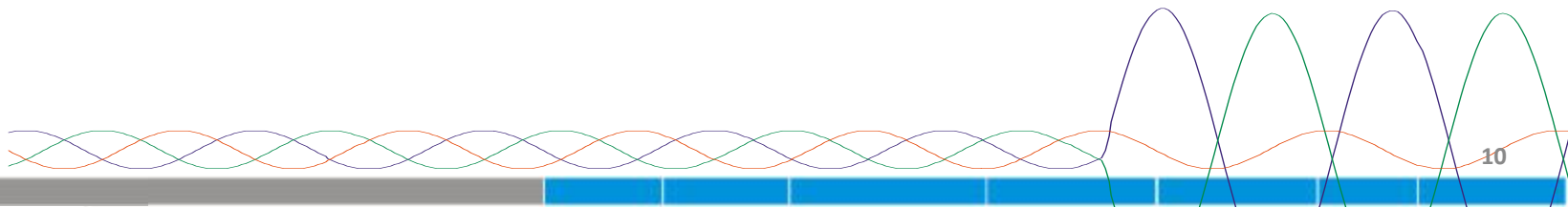
- Efeitos de V ou I não senoidais \rightarrow Estudar as harmônicas individualmente



Harmônicas Pares e Ímpares

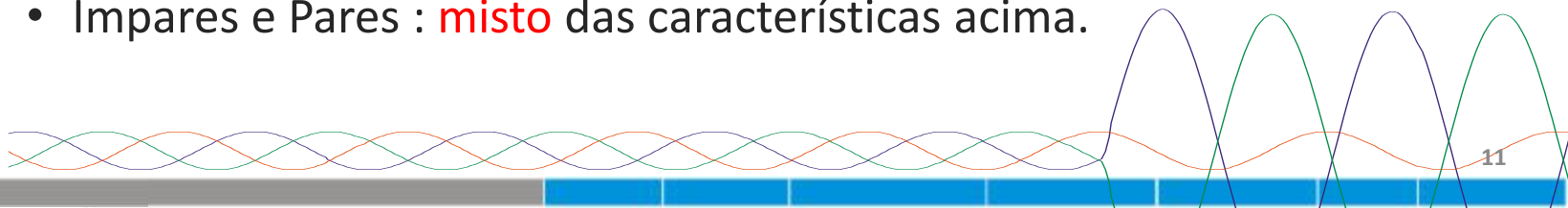
- *Ímpares*
 - Maioria das cargas não lineares.

- *Pares*
 - Menos frequente;
 - Correntes de magnetização de trafos, fornos a arco durante a inicialização.



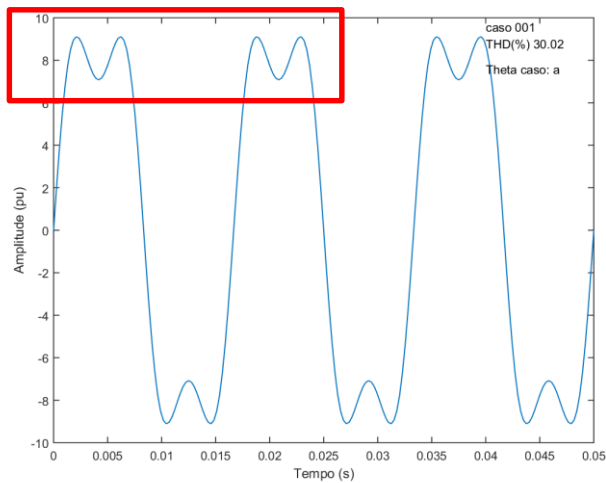
Harmônicas Pares e Ímpares

- Características visuais da forma de onda
 - Harmônicas ímpares;
 - Harmônicas Pares; e
 - Harmônicas Mistas (ímpares e pares).
- Como identificar?
 - Bastante caracterizadas pela deformação:
 - Ímpares: **apenas nas porções mais extremas** dos semi-ciclos positivo e negativo;
 - Pares: **nas regiões de transição** entre os semi-ciclos positivo e negativo; e
 - Ímpares e Pares : **misto** das características acima.

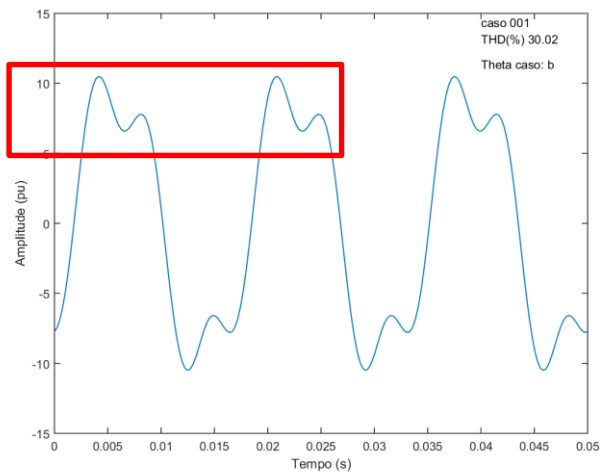


Harmônicas Ímpares

$$i = I_0 \text{sen}(\omega t + \phi)$$

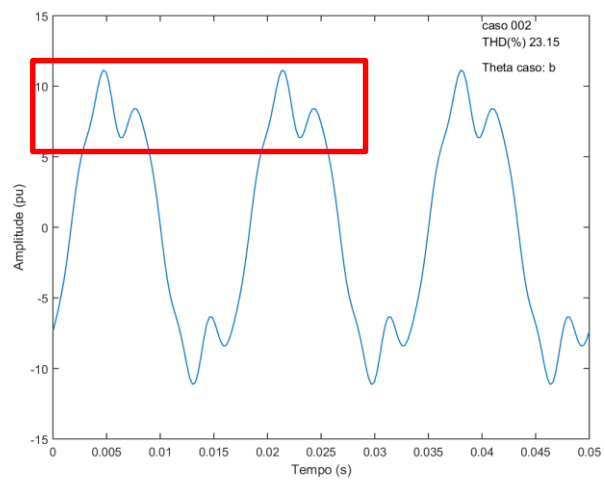
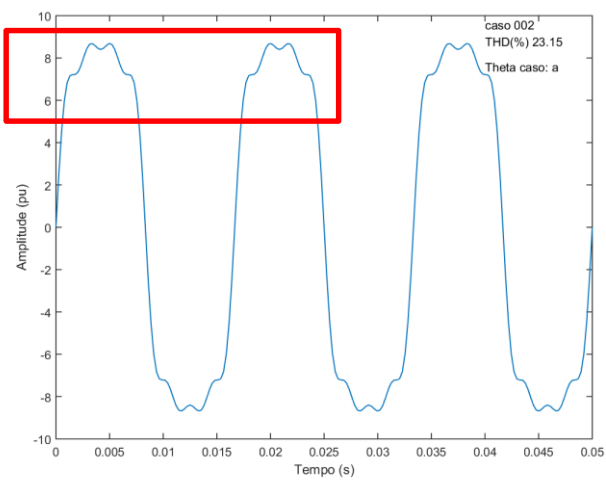


$\phi = 0^\circ$

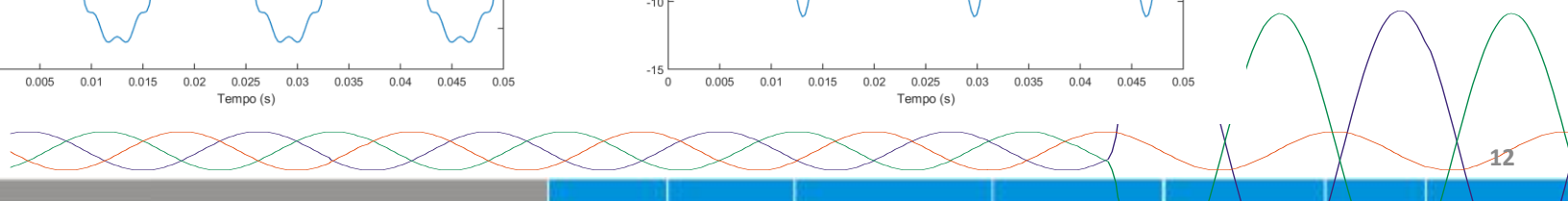


$\phi = \text{aleatório}$

- $h_1 = 10,0$
- $h_3 = 3,0$
- $h_5 = 0,1$
- $h_7 = 0,2$

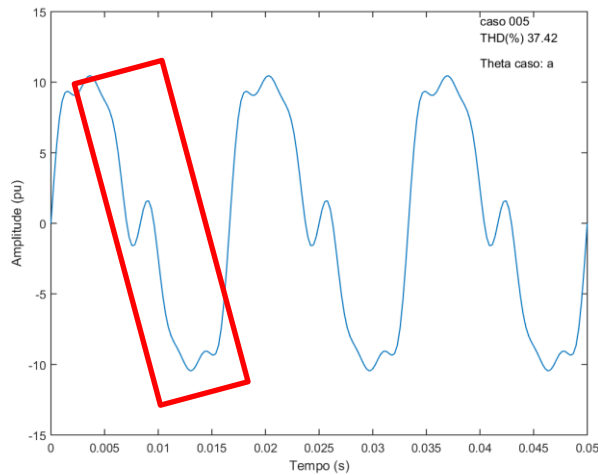


- $h_1 = 10,0$
- $h_3 = 2,0$
- $h_5 = 1,0$
- $h_7 = 0,6$

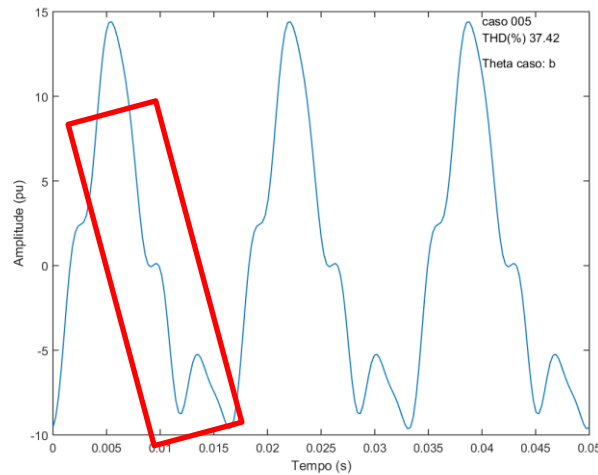


Harmônicas Pares

$$i = I_0 \text{sen}(\omega t + \phi)$$

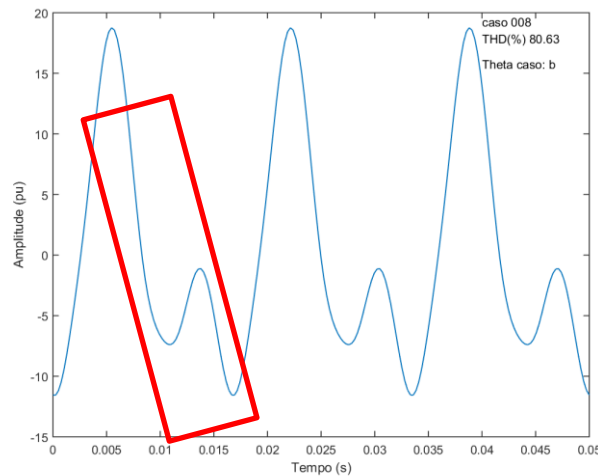
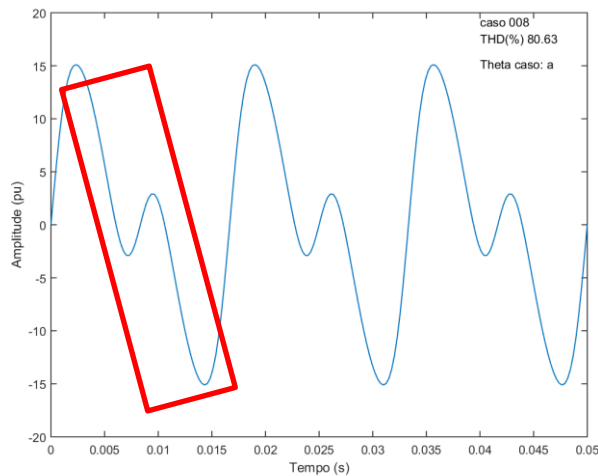


$\phi = 0^\circ$



$\phi = \text{aleatório}$

- $h_1 = 10,0$
- $h_2 = 3,0$
- $h_4 = 2,0$
- $h_6 = 1,0$

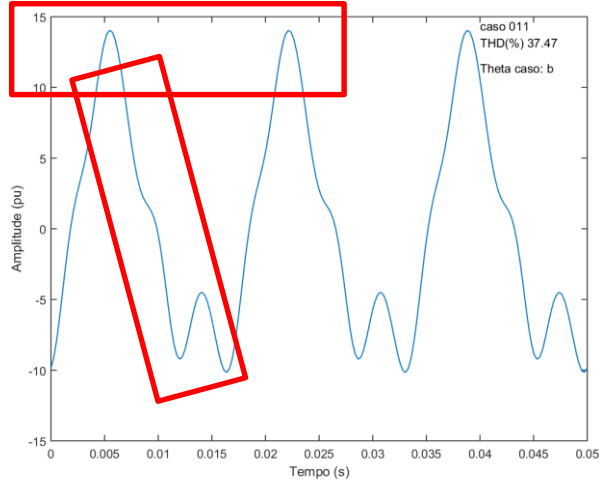
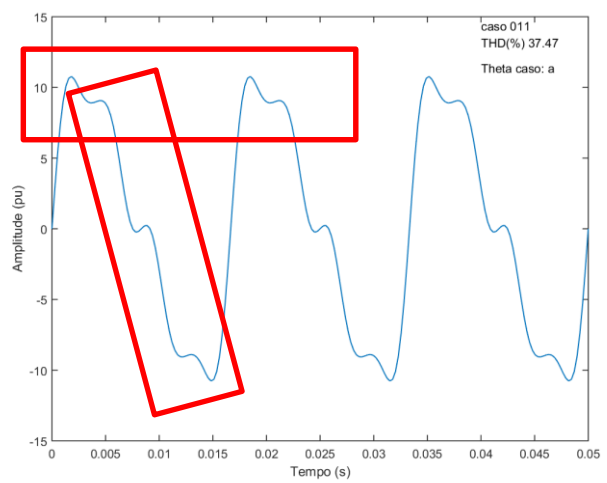


- $h_1 = 10,0$
- $h_2 = 8,0$
- $h_4 = 1,0$
- $h_6 = 0,1$



Harmônicas Mistas

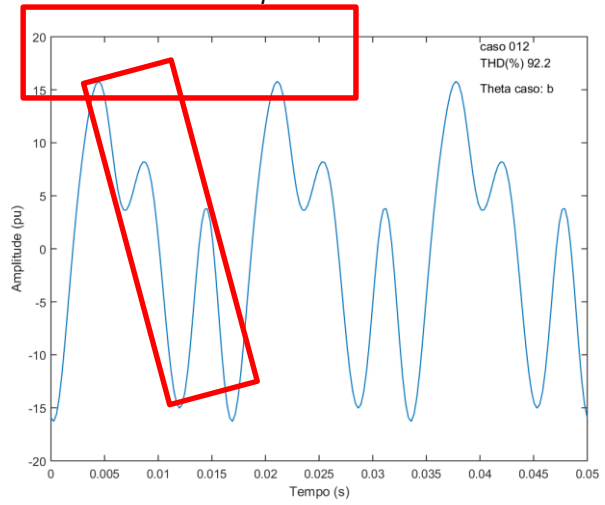
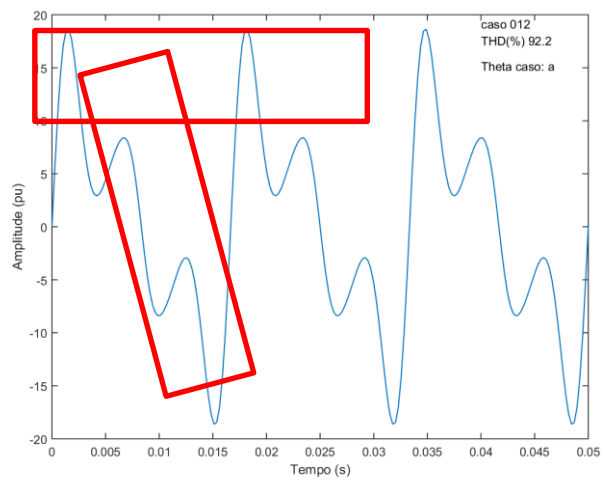
$$i = I_0 \text{sen}(\omega t + \phi)$$



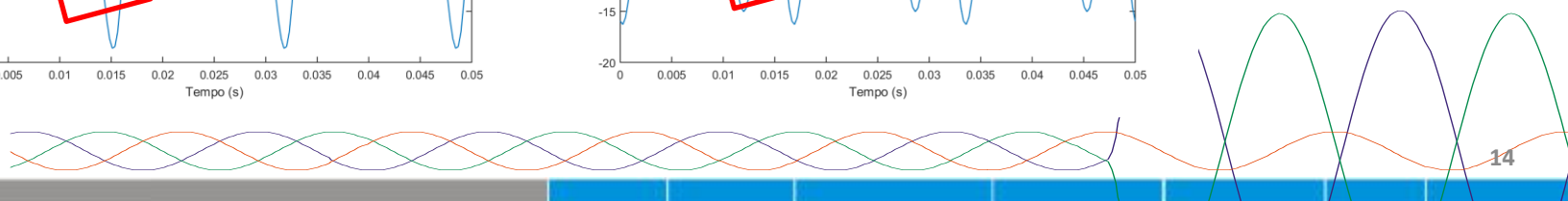
- $h_1 = 10,0$
- $h_2 = 3,0$
- $h_4 = 1,0$
- $h_4 = 2,0$
- $h_5 = 0,0$
- $h_6 = 0,2$
- $h_7 = 0,0$

$\phi = 0^\circ$

$\phi = \text{aleatório}$

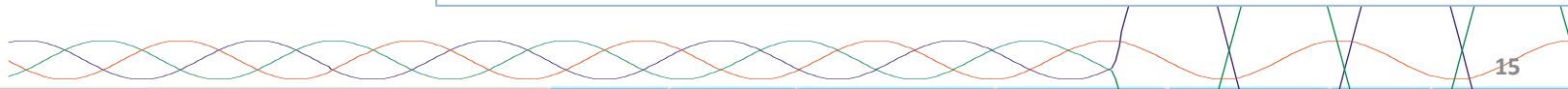
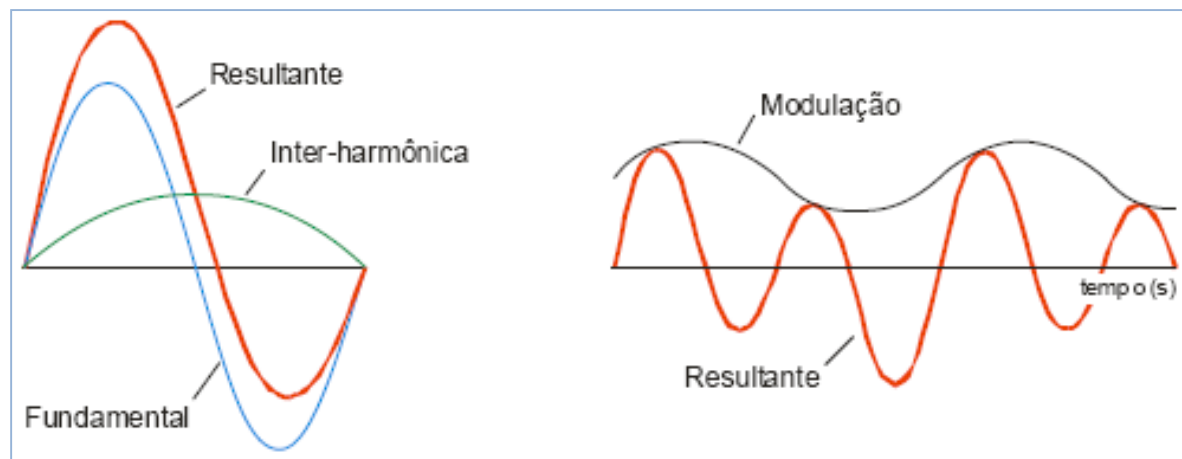
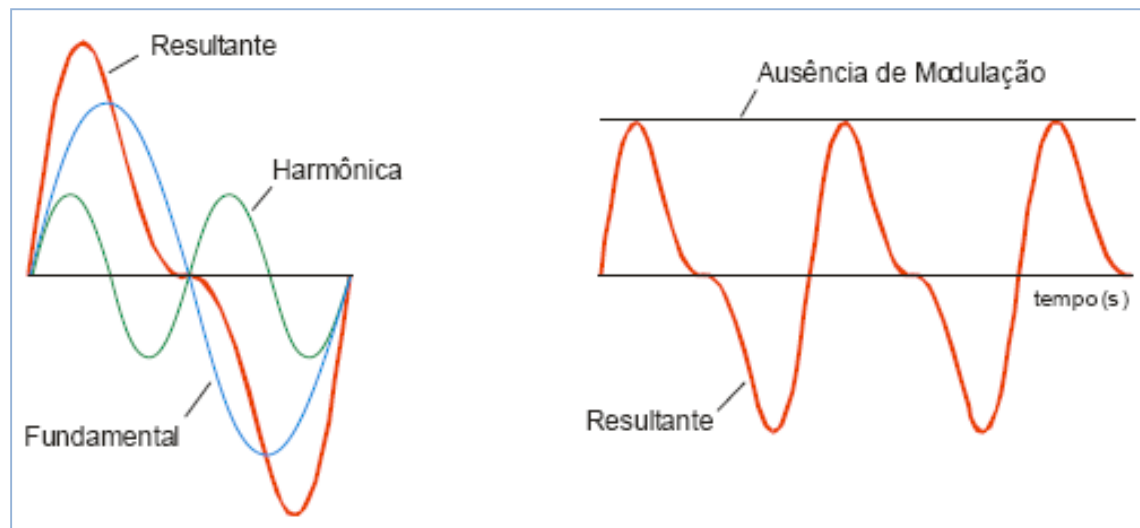


- $h_1 = 10,0$
- $h_2 = 4,0$
- $h_4 = 8,0$
- $h_4 = 2,0$
- $h_5 = 1,0$
- $h_6 = 0,0$
- $h_7 = 0,1$



Sub-harmônicas

- Frequências abaixo da fundamental;
- Ressonância entre V e I harmônicas e as capacitâncias e indutâncias do SEP;
- Forno a arco: $\uparrow L$
- Banco Capac.: $\uparrow C$



Sequências

- Todas as harmônicas possuem a frequência fundamental como referência.

$$i_{a1} = I_{a1} \text{ sen}(\omega t)$$

$h=1$

$$i_{b1} = I_{b1} \text{ sen}(\omega t - 120^\circ)$$

$$i_{c1} = I_{c1} \text{ sen}(\omega t - 240^\circ)$$

$$i_{a2} = I_{a2} \text{ sen}(2\omega t)$$

$h=2$

$$i_{b2} = I_{b2} \text{ sen}(2\omega t - 240^\circ)$$

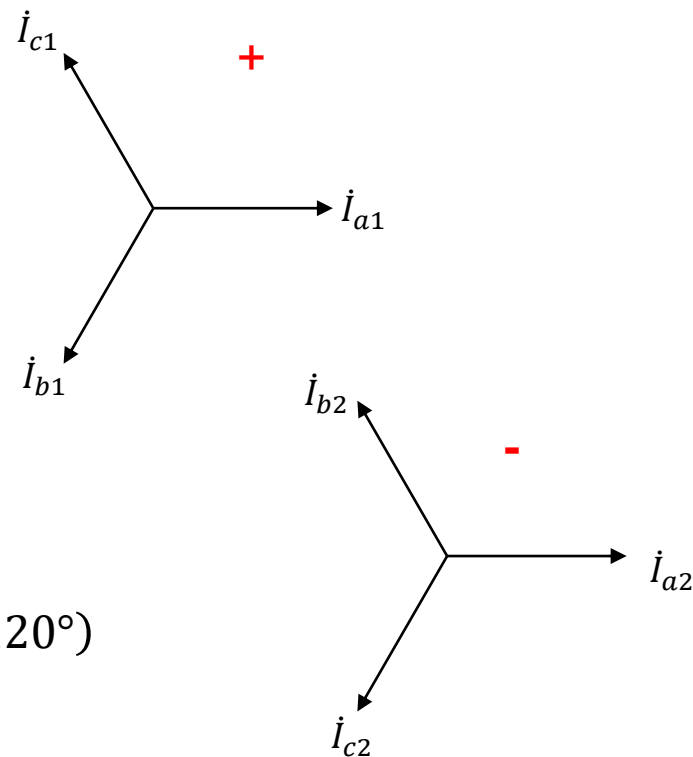
$$i_{c2} = I_{c2} \text{ sen}(2\omega t - 480^\circ) = I_{c2} \text{ sen}(2\omega t - 120^\circ)$$

$$i_{a3} = I_{a3} \text{ sen}(3\omega t)$$

$h=3$

$$i_{b3} = I_{b3} \text{ sen}(3\omega t - 360^\circ) = I_{b3} \text{ sen}(3\omega t)$$

$$i_{c3} = I_{c3} \text{ sen}(3\omega t - 720^\circ) = I_{c3} \text{ sen}(3\omega t)$$



Sequências

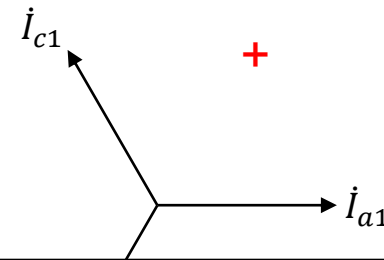
- Todas as harmônicas possuem a frequência fundamental como referência.

$$i_{a1} = I_{a1} \text{sen}(\omega t)$$

$h=1$

$$i_{b1} = I_{b1} \text{sen}(\omega t - 120^\circ)$$

$$i_{c1} = I_{c1} \text{sen}(\omega t - 240^\circ)$$



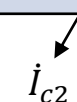
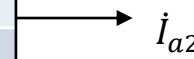
$h=2$

$$i_{a2} =$$

$$i_{b2} =$$

$$i_{c2} =$$

Ordem Harmônica (h)	Sequência
1, 4, 7, 10, 13, 16, 19	Positiva
2, 5, 8, 11, 14, 17, 20	Negativa
3, 6, 9, 12, 15, 18, 21	Zero



$h=3$

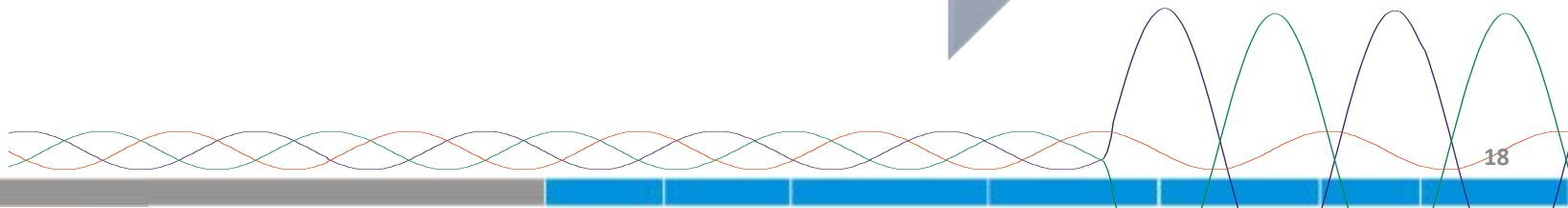
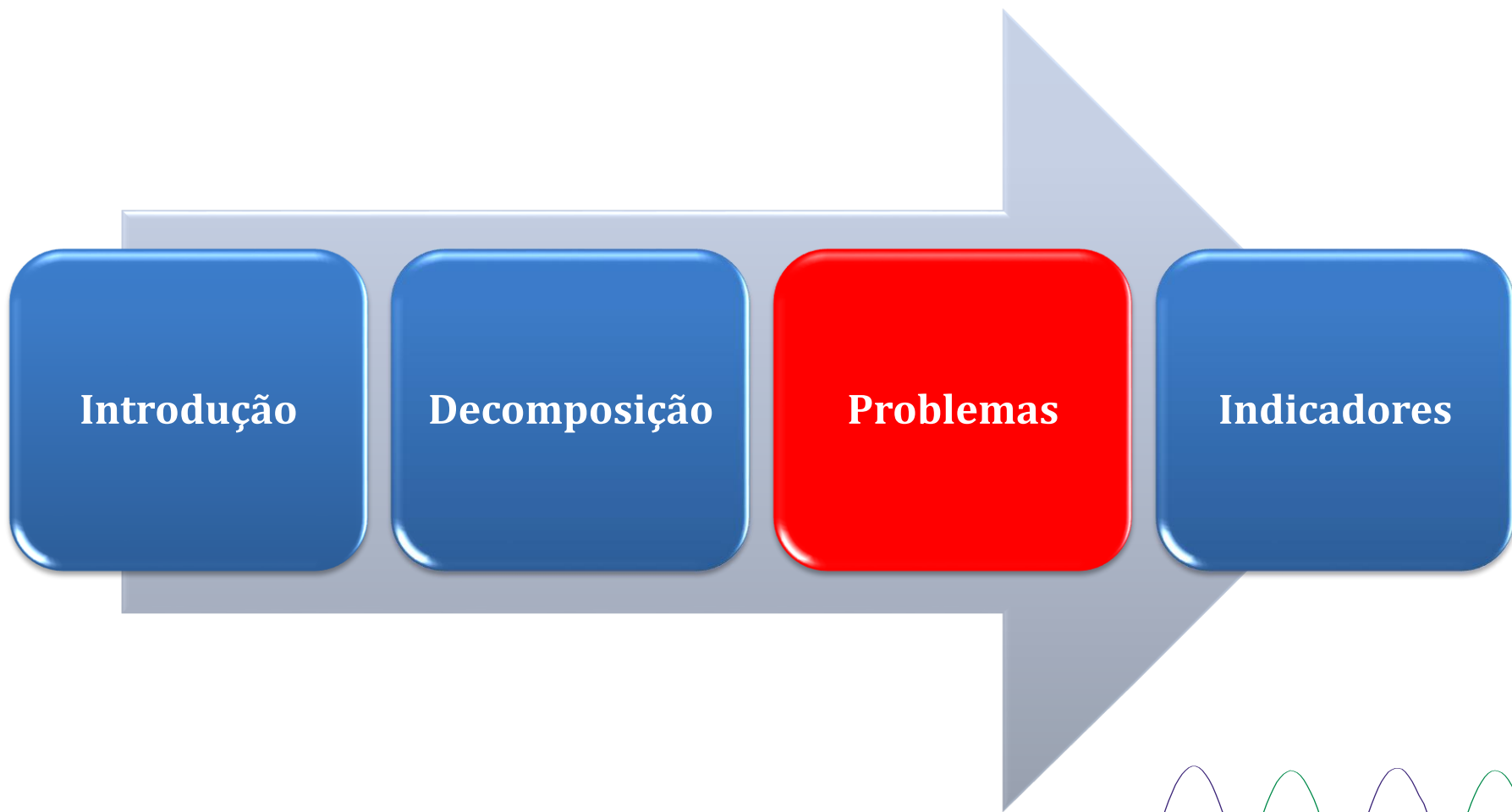
$$i_{a3} = I_{a3} \text{sen}(3\omega t)$$

$$i_{b3} = I_{b3} \text{sen}(3\omega t - 360^\circ) = I_{b3} \text{sen}(3\omega t)$$

$$i_{c3} = I_{c3} \text{sen}(3\omega t - 720^\circ) = I_{c3} \text{sen}(3\omega t)$$



Apresentação

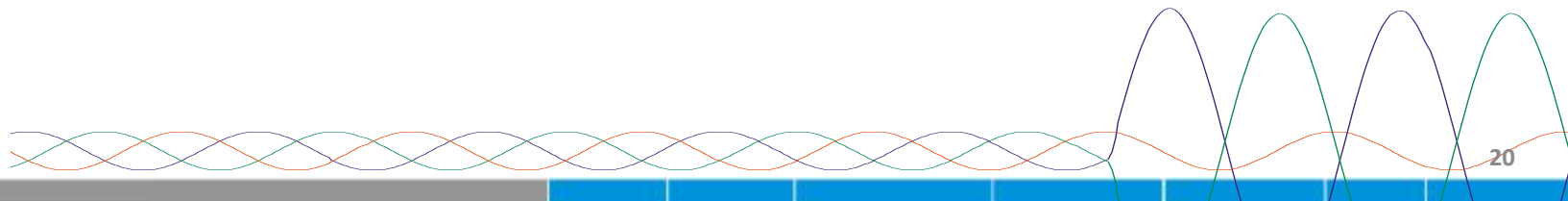
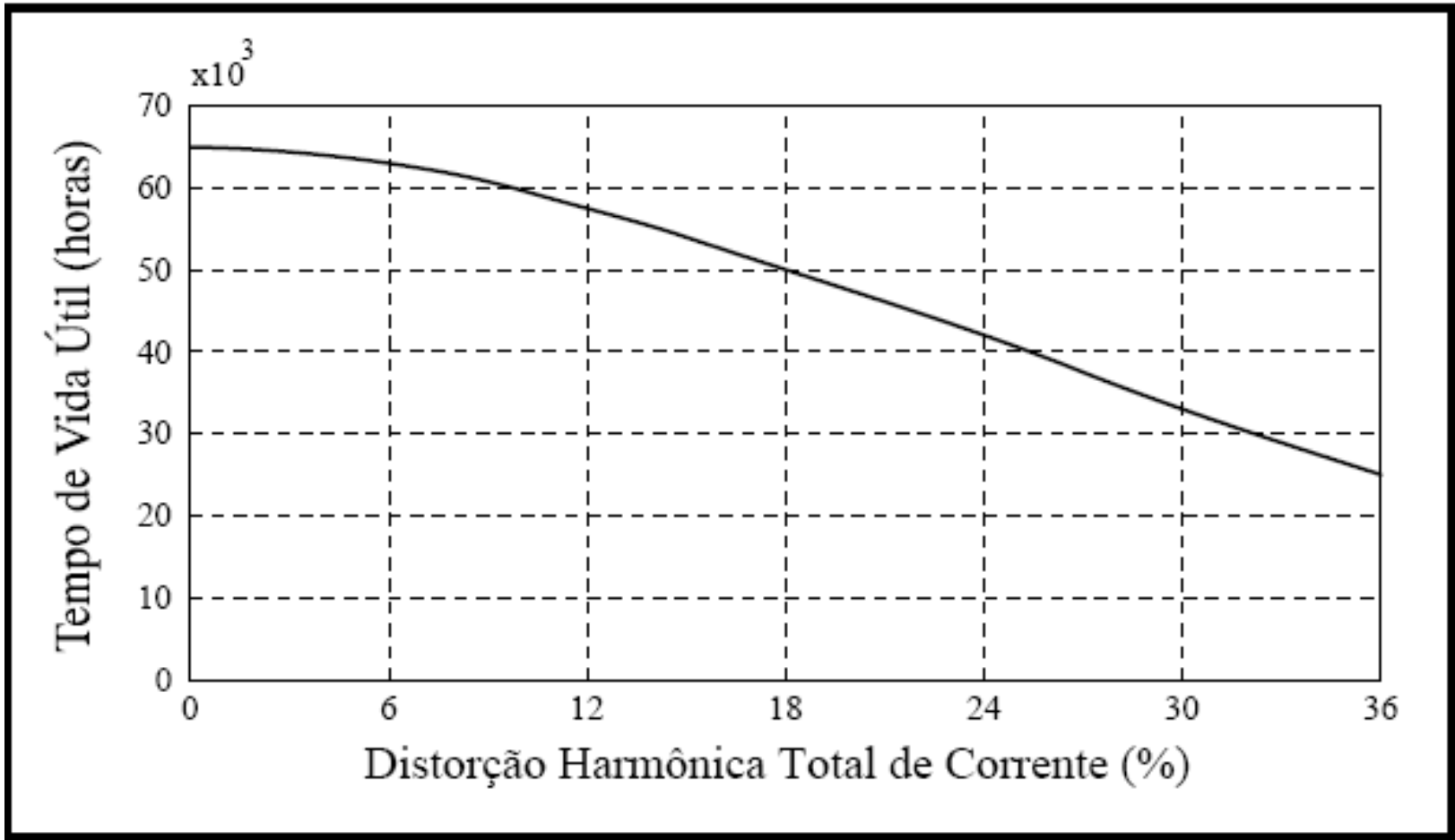


Problemas

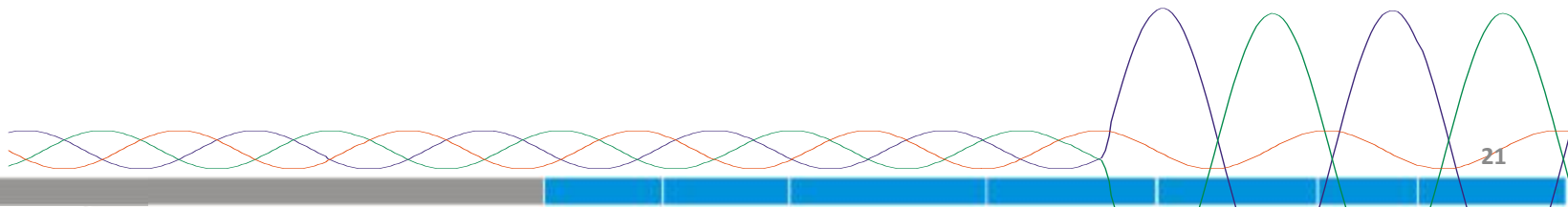
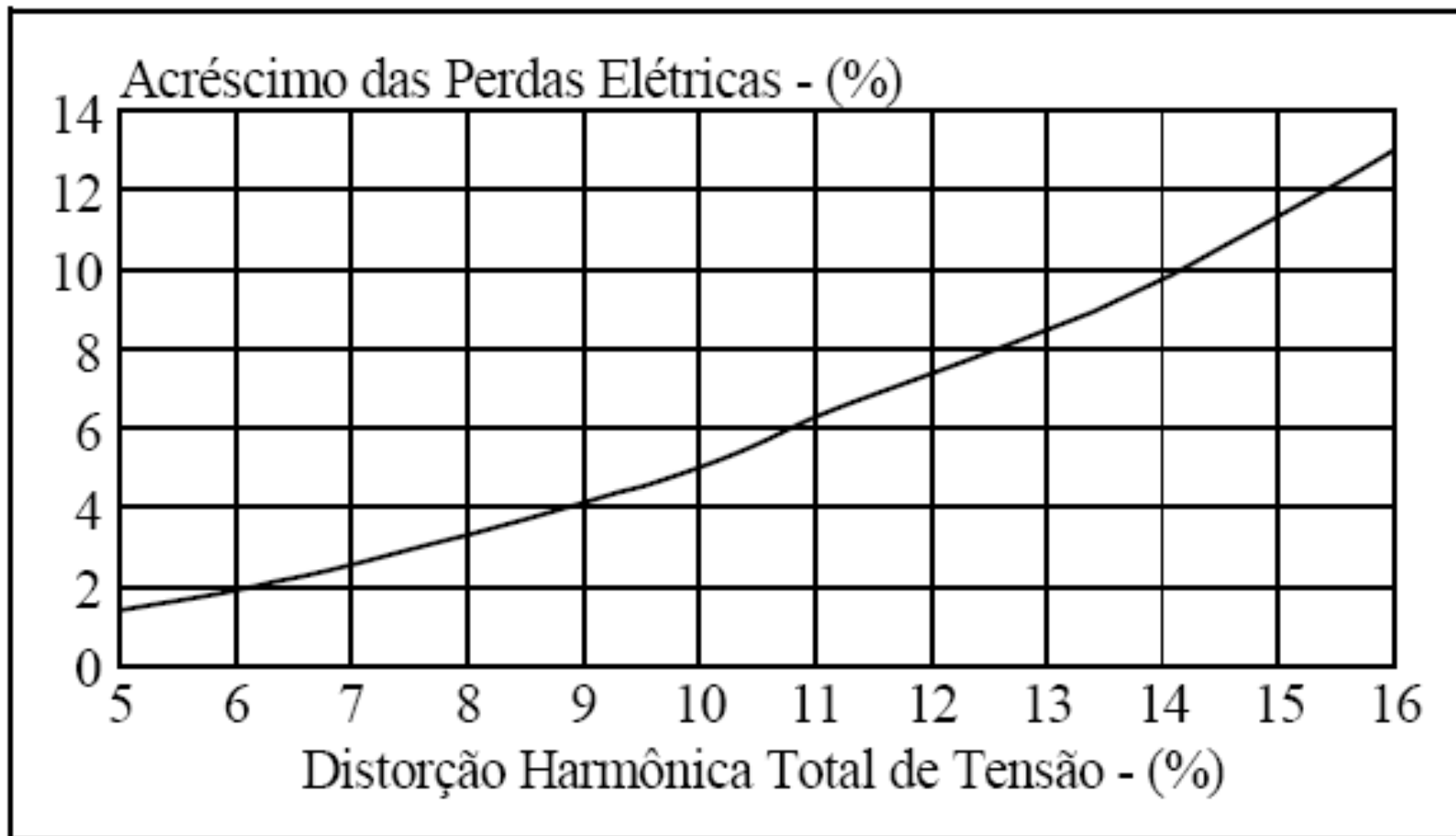
- Transformadores
 - Perdas Joule nos enrolamentos;
- Motores AC
 - Perdas Joule nos enrolamentos;
 - Oscilações torcionais (torque oscilante);
 - H. seq. (-) : campo girante oposto e mais rápido ($h=5$)
 - H. seq (+): campo girante mesmo sentido e mais rápido ($h=7$);



Transformador



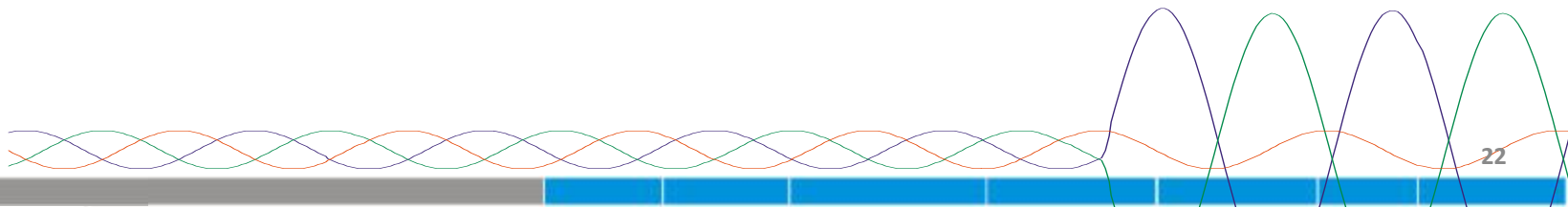
Motor de Indução



Problemas

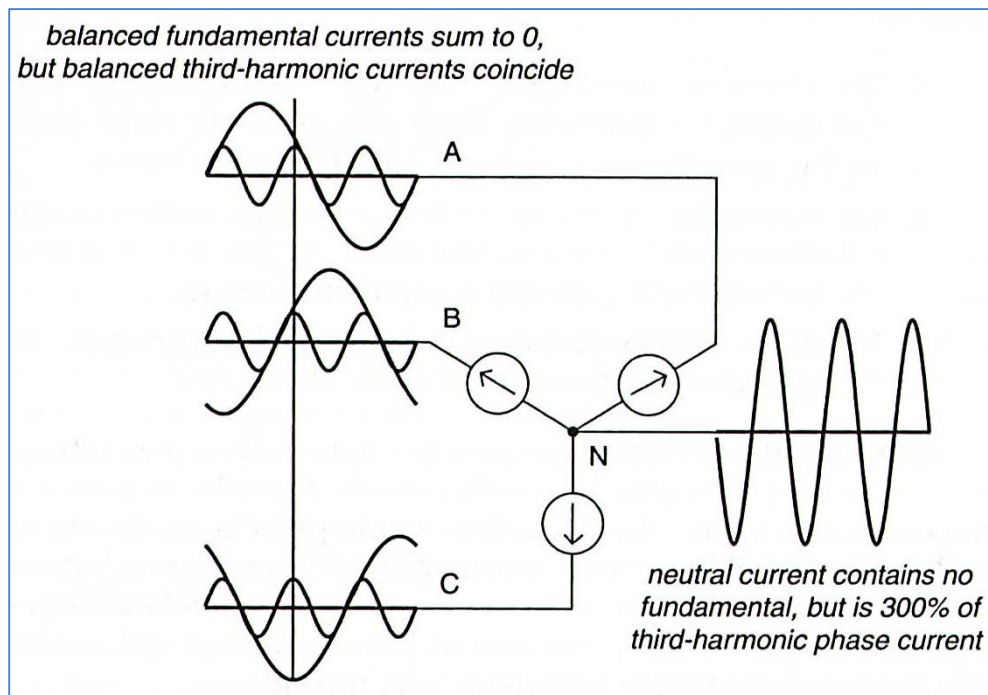
- Banco de Capacitores
 - Ressonância harmônica;
 - X_c e X_L se igualam na frequência harmônica;
 - Elevação substancial das V ou I ;

- Cabos
 - Perdas Joule adicionais;
 - Resistência do cabo aumenta com a ordem harmônica devido ao efeito pelicular;

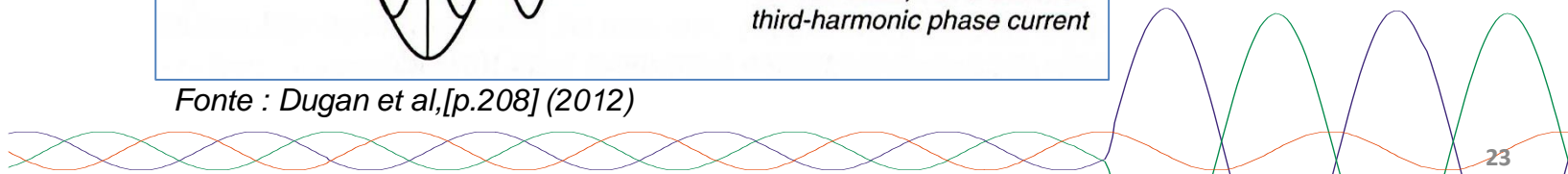


Harmônicos Múltiplos de 3ª ordem

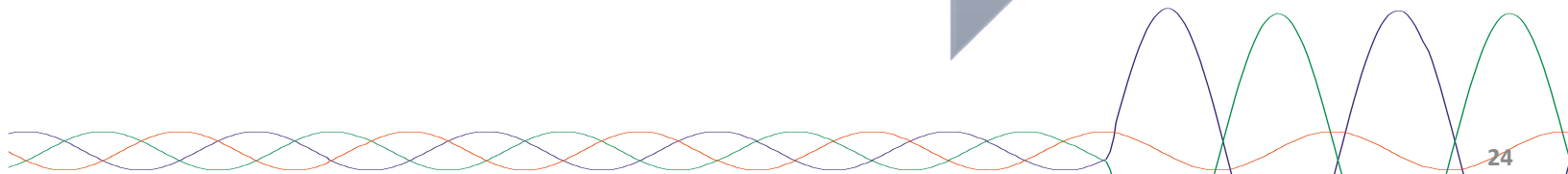
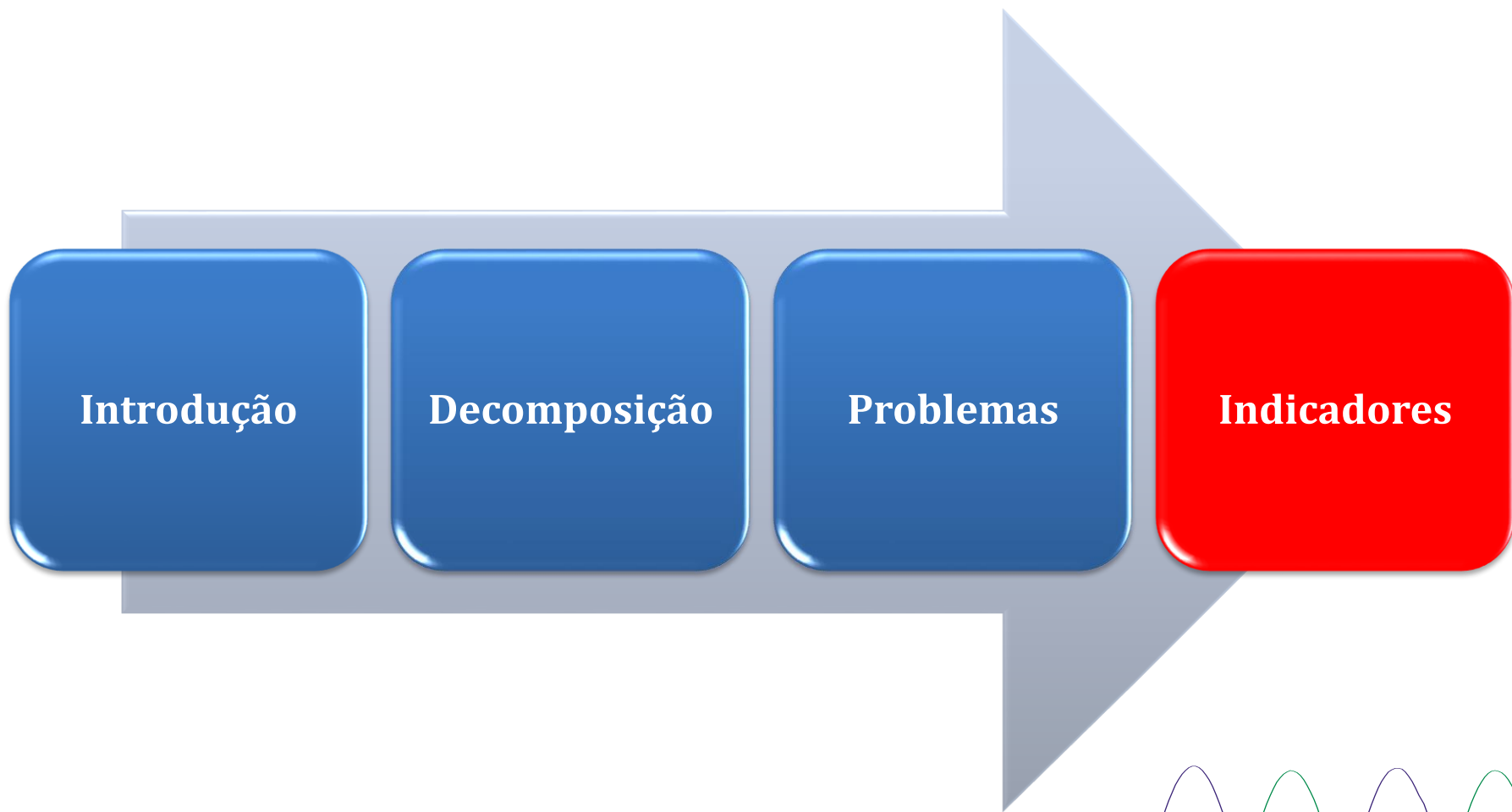
- $h = 3, 9, 15, 21, \dots$
 - Resposta do sistema consideravelmente distinta;
 - Importante em sistemas aterrados em Y com corrente fluindo pelo neutro;
 - Sobrecarga na corrente do neutro;



Fonte : Dugan et al,[p.208] (2012)



Apresentação



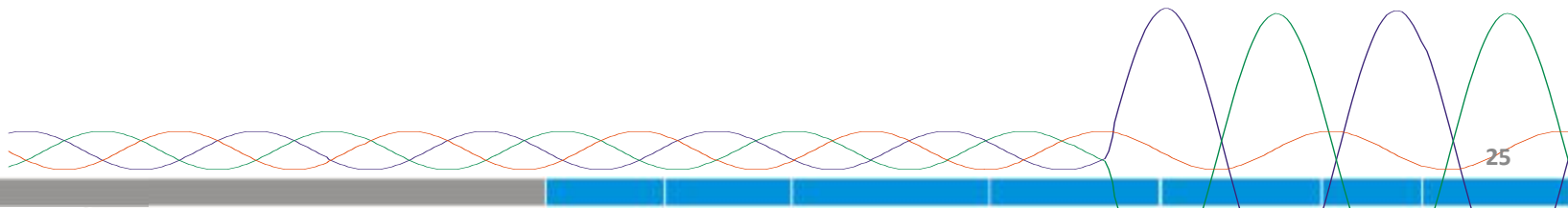
Indicador de Distorção Harmônica

- A ANEEL determina cálculos de índices de distorção harmônica da tensão até $h=25$.

$$DIT_h = \frac{V_h}{V_1} \times 100\%$$

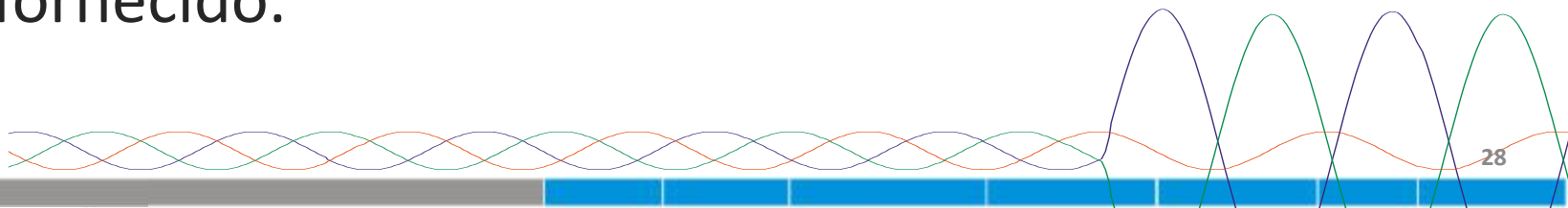
$$DTT = \sqrt{\frac{\sum_{h>1}^{h_{\text{máx}}} V_h^2}{V_1^2}} \times 100\%$$

Tensão Nominal	DTT (%)
< 1kV	10
de 1kV até 13,8kV	8
de 13,8kV até 69kV	6
de 69kV até 230kV	3



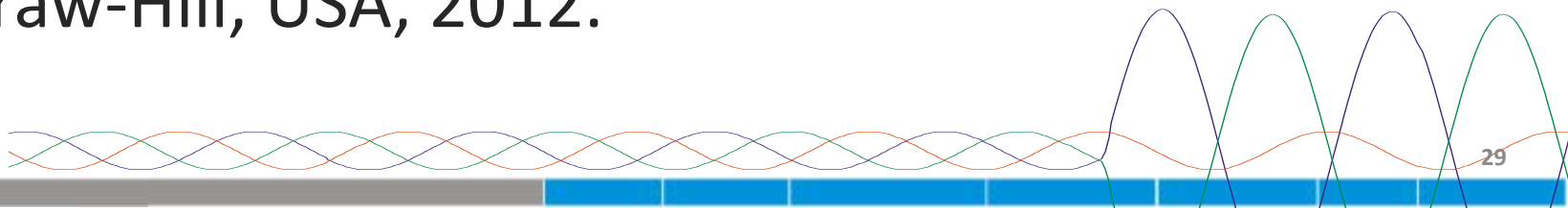
Exercícios Propostos

1. Cálculo dos Índices de Qualidade
 - DHT, DHI, RMS e FC a partir dos harmônicos de uma sinal; e
2. Cálculo dos fasores a partir das amostras do sinal.
 - Amplitudes de cada harmônico e sua respectiva fase;
 - Recalcular todos os índices anteriores para o sinal fornecido.



Referências Bibliográficas

- [1] N. Kagan, E. J. Robba e H. P. Schmidt, Estimação de Indicadores de Qualidade da Energia Elétrica, São Paulo: Blucher, 2009.
- [2] M. H. J. Bollen, Understanding Power Quality Problems, IEEE Press, 2000.
- [3] IEEE, Std 446-1995, IEEE, 1995.
- [4] ANEEL, PRODIST modulo 8, ver 8, 2016.
- [5] DUGAN, R. C., Electrical Power Systems Quality, McGraw-Hill, USA, 2012.



AULA LABORATORIAL EXPOSITIVA: DISTORÇÕES HARMÔNICAS – LAMQEE

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