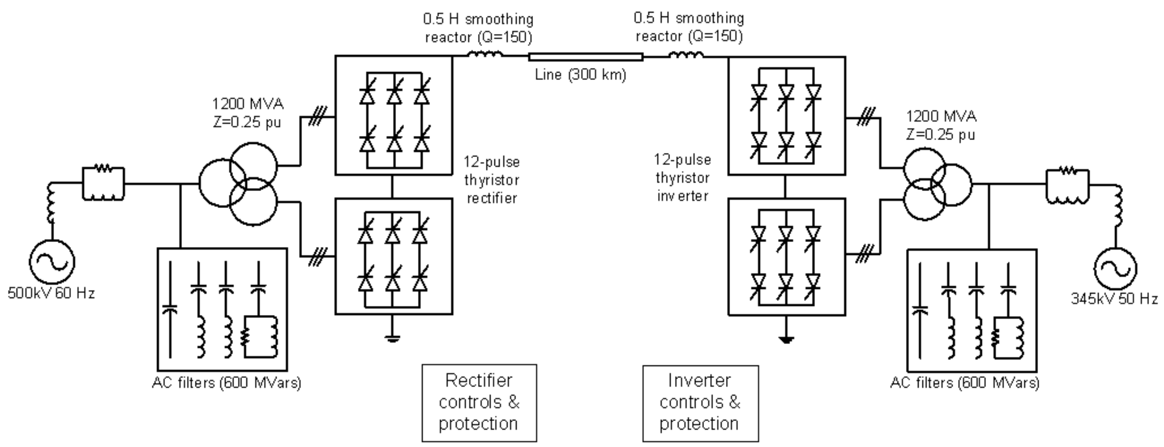


Retificadores Controlados

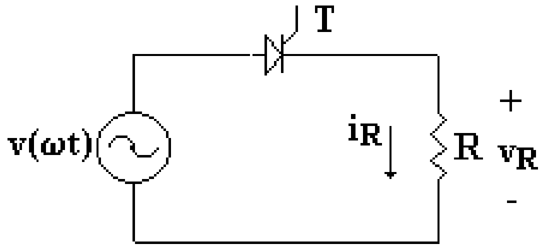
Material Formatado por Anderson Soares

Fonte: "Eletrônica de Potência"

Prof. Dr. Ing Ivo Barbi

Prof. Dr. Leandro Michels

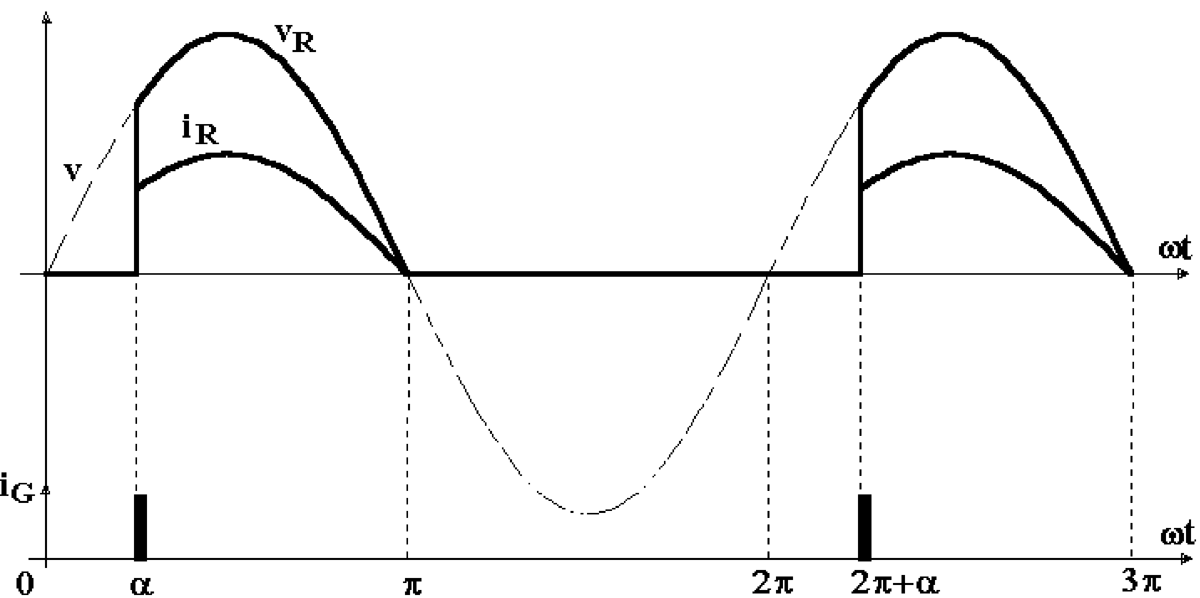
Retificador Monofásico de Meia Onda a Tiristor
Carga Resistiva

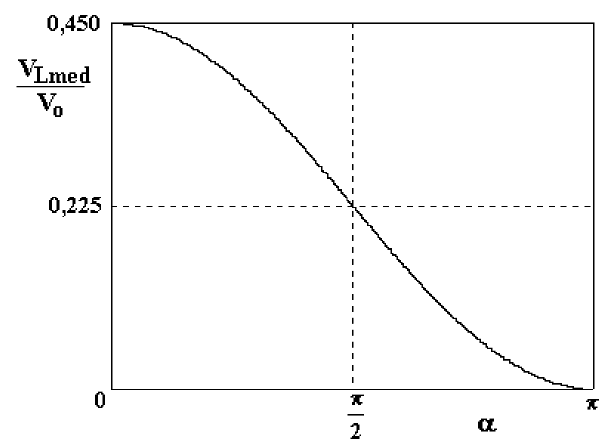


$$v(\omega t) = \sqrt{2}\, V_o \operatorname{sen}(\omega t)$$

A tensão média na carga

$$V_{Lmed} = \frac{1}{2\pi}\int_{\alpha}^{\pi} \sqrt{2}\, V_o \operatorname{sen}(\omega t)\, d(\omega t) \cong 0{,}225\, V_o (1+\cos\alpha)$$

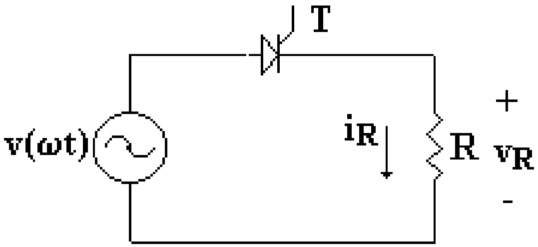




A corrente média na carga

$$I_{Lmed} = \frac{V_{Lmed}}{R} \cong \frac{0{,}225\, V_o}{R}(1+\cos\alpha)$$

Retificador Monofásico de Meia Onda a Tiristor
Carga Resistiva



$$v(\omega t) = \sqrt{2}\, V_o \,\text{sen}\,(\omega t)$$

Corrente eficaz na Carga

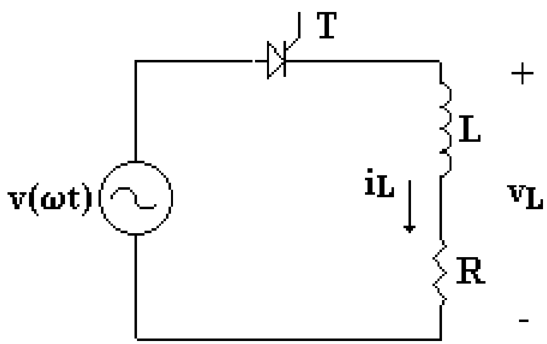
$$I_{Lef} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\pi}\left(\frac{\sqrt{2}\,V_o}{R}\right)^2 \text{sen}^2(\omega t)\, d(\omega t)} = \frac{V_o}{R}\sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi}\text{sen}^2(\omega t) d(\omega t)}$$

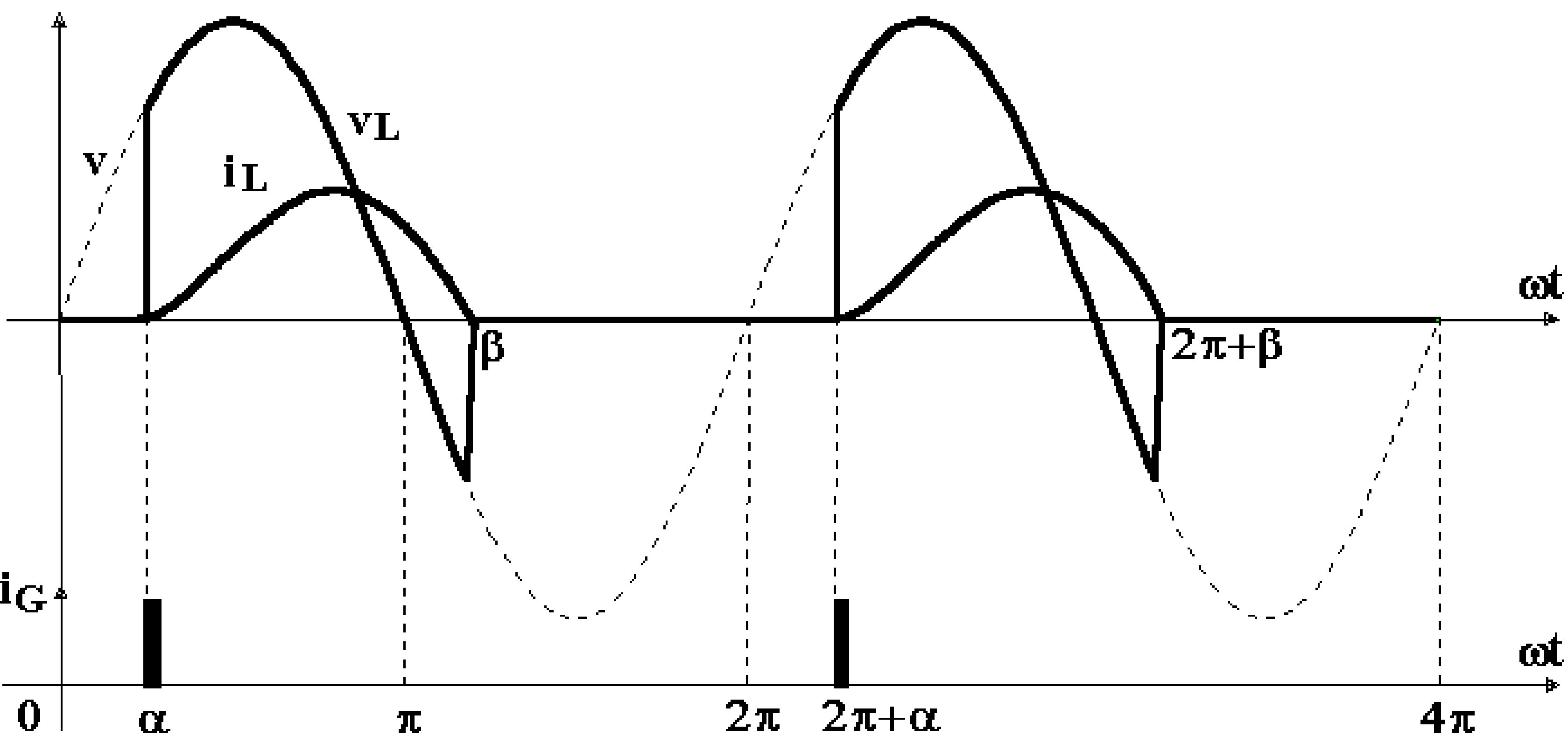
$$I_{Lef} = \frac{V_o}{R}\sqrt{\frac{1}{2} - \frac{\alpha}{2\pi} + \frac{\text{sen}\,2\alpha}{4\pi}}$$

Potência Média na Carga

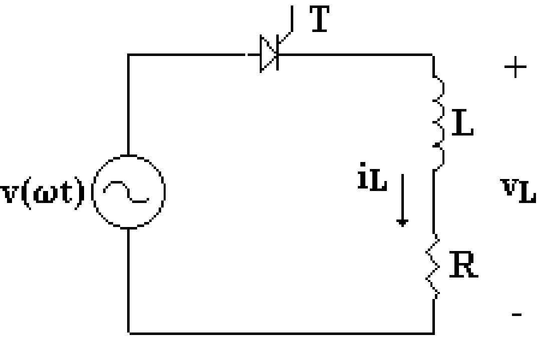
$$P_R = R I_{Lef}^{\;2} = \frac{V_0^{\;2}}{R}\left(\frac{1}{2} - \frac{\alpha}{2\pi} + \frac{\text{sen}(2\alpha)}{4\pi}\right)$$

Retificador Monofásico de Meia Onda a Tiristor
Carga RL





Retificador Monofásico de Meia Onda a Tiristor Carga RL



Corrente de Carga

$$v(\omega t) = R\,i(\omega t) + L\frac{di(\omega t)}{dt} = \sqrt{2}V_o\,\mathrm{sen}(\omega t)$$

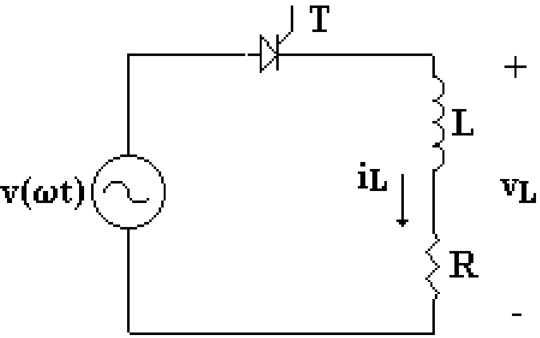
$$i(\omega t) = \frac{\sqrt{2}\,V_o}{\sqrt{R^2+X^2}}\left[\mathrm{sen}(\omega t - \phi) - \mathrm{sen}(\alpha - \phi)\cdot e^{-t'/\zeta}\right]$$

$$X = \omega L \qquad \phi = \arctan\frac{X}{R} \qquad \zeta = \frac{L}{R} \qquad t' = t - \frac{\alpha}{\omega}$$

$$i_1(\omega t) = \frac{\sqrt{2}\,V_o}{\sqrt{R^2+X^2}}\,\mathrm{sen}(\omega t - \phi)$$

$$i_2(\omega t) = \frac{-\sqrt{2}\,V_o}{\sqrt{R^2+X^2}}\,\mathrm{sen}(\alpha - \phi)\cdot e^{-t'/\zeta}$$

Retificador Monofásico de Meia Onda a Tiristor Carga RL



Tensão Média na Carga (V_{Lmed})

$$V_{Lmed} = \frac{1}{2\pi}\int_{\alpha}^{\beta} \sqrt{2}\, V_o \,\mathrm{sen}(\omega t)\, d(\omega t) \cong 0{,}225 V_o \left(\cos\alpha - \cos\beta\right)$$

Corrente Média na Carga (I_{Lmed})

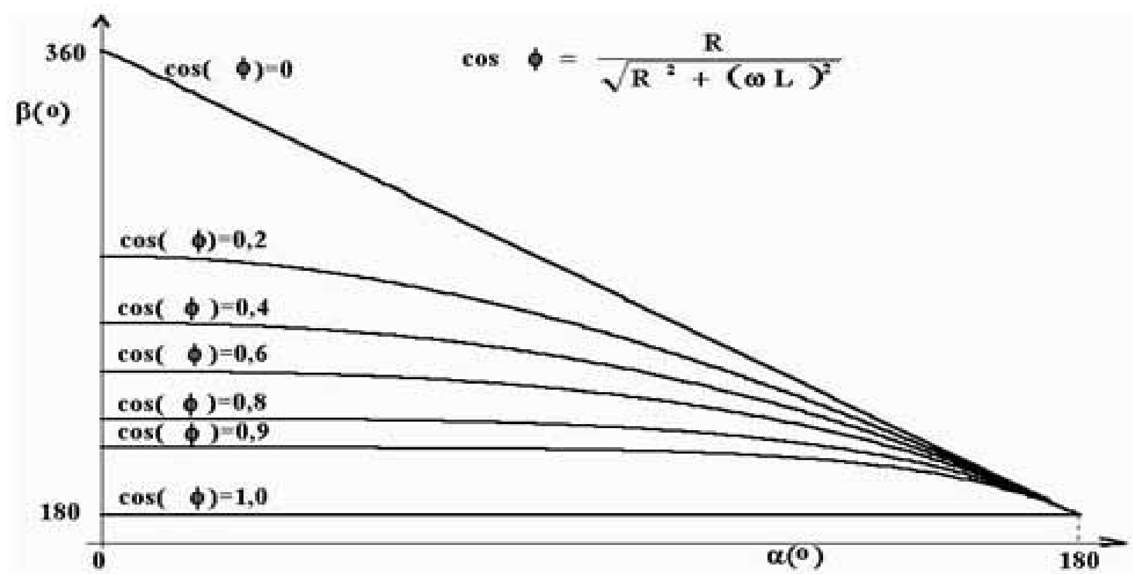
$$I_{Lmed} = \frac{V_{Lmed}}{R} \cong \frac{0{,}225 V_o}{R}(\cos\alpha - \cos\beta)$$

Ângulo de Extinção (β)

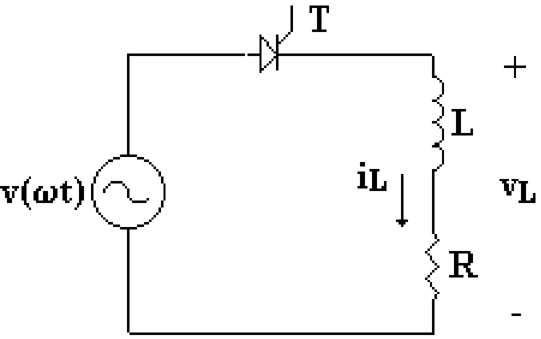
$$0 = \mathrm{sen}(\beta - \phi) - \mathrm{sen}(\alpha - \phi)\cdot e^{-\frac{R}{\omega L}(\beta - \alpha)}$$

Ângulo de Condução (γ)

$$\gamma = \beta - \alpha$$

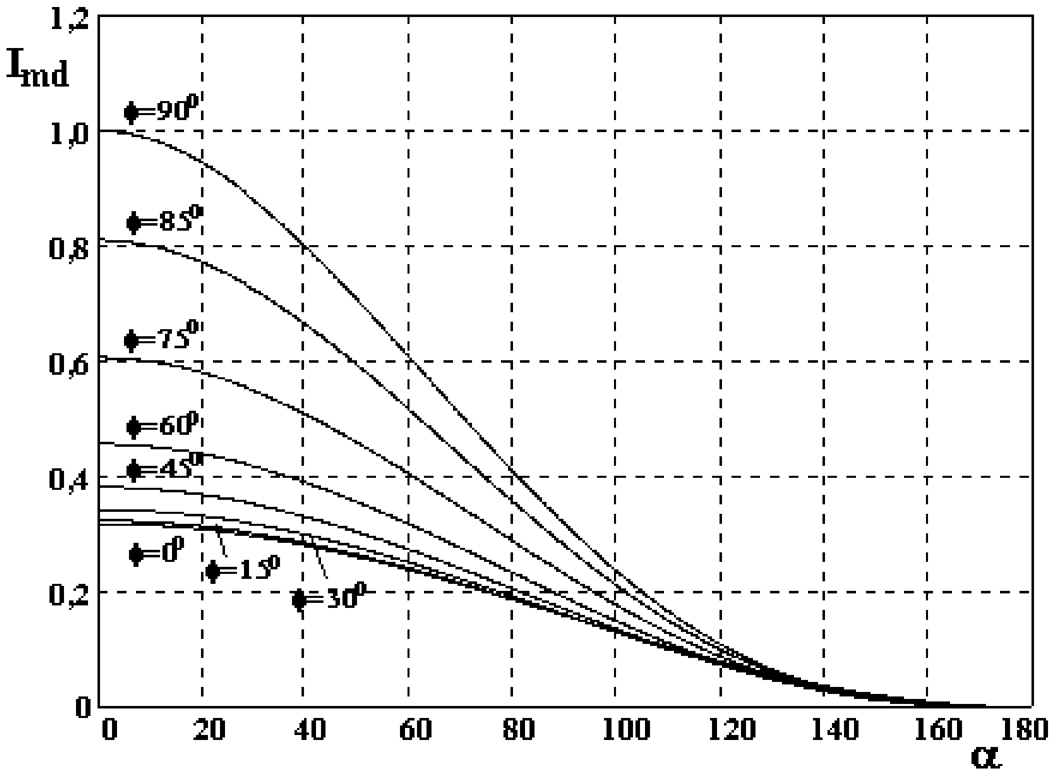


Retificador Monofásico de Meia Onda a Tiristor Carga RL

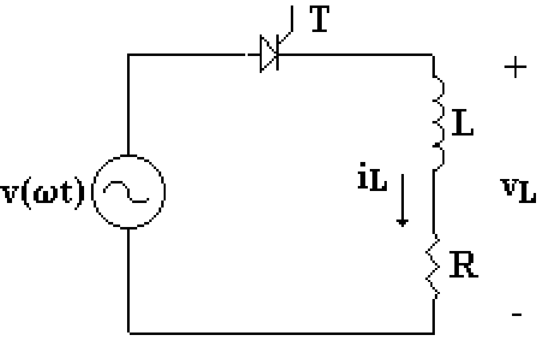


Corrente Média Normalizada (I_{md})

$$I_{md} = \frac{R\, I_{Lmed}}{0{,}225\, V_o} = (\cos\alpha - \cos\beta)$$



Retificador Monofásico de Meia Onda a Tiristor Carga RL



Corrente Eficaz na carga (I_{Lef})

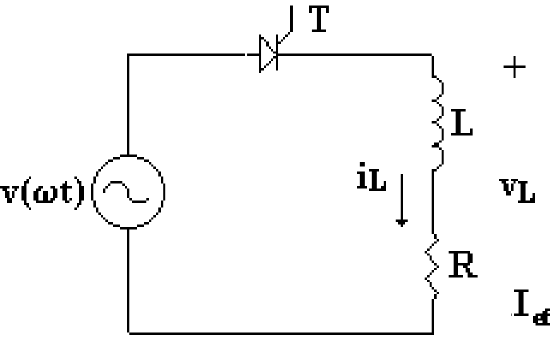
$$I_{Lef} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\beta} i(\omega t)^2 \, d(\omega t)}$$

$$I_{Lef} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\beta}\left\{\frac{\sqrt{2}\,V_o}{\sqrt{R^2+X^2}}\left[\operatorname{sen}(\omega t-\phi)-\operatorname{sen}(\alpha-\phi)\cdot e^{-\frac{R}{\omega L}(\omega t-\alpha)}\right]\right\}^2 d(\omega t)}$$

Corrente Eficaz Normalizada na carga (I_{ef})

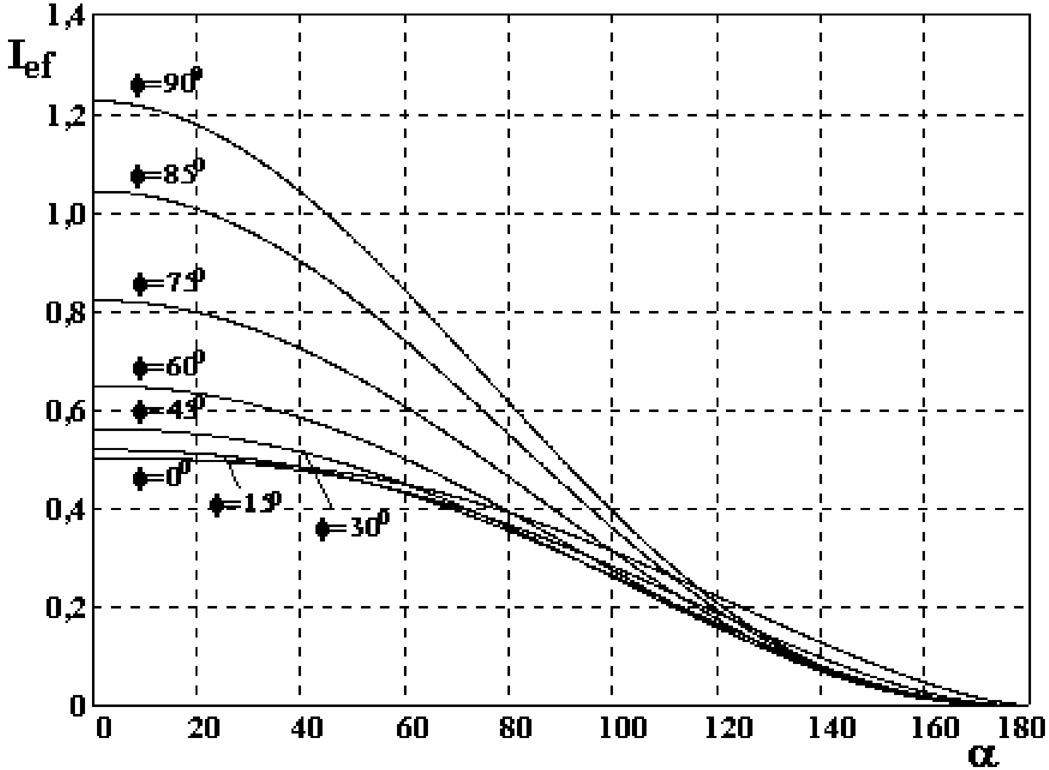
$$I_{ef} = \frac{\sqrt{R^2+X^2}\,I_{Lef}}{\sqrt{2}V_o} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\beta}\left[\operatorname{sen}(\omega t-\phi)-\operatorname{sen}(\alpha-\phi)\cdot e^{-\frac{R}{\omega L}(\omega t-\alpha)}\right]^2 d(\omega t)}$$

Retificador Monofásico de Meia Onda a Tiristor Carga RL



Corrente Eficaz Normalizada na carga (I_{ef})

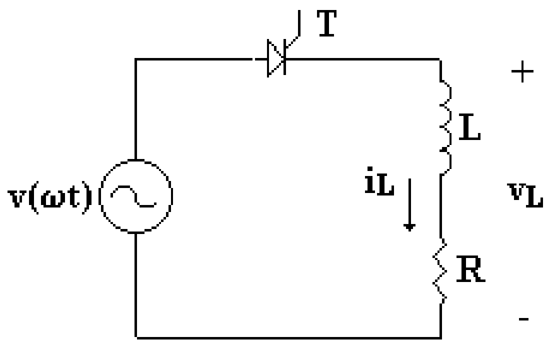
$$I_{ef} = \frac{\sqrt{R^2 + X^2}\, I_{Lef}}{\sqrt{2}V_o} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\beta}\left[\operatorname{sen}(\omega t - \phi) - \operatorname{sen}(\alpha - \phi)\cdot e^{-\frac{R}{\omega L}(\omega t - \alpha)}\right]^2 d(\omega t)}$$



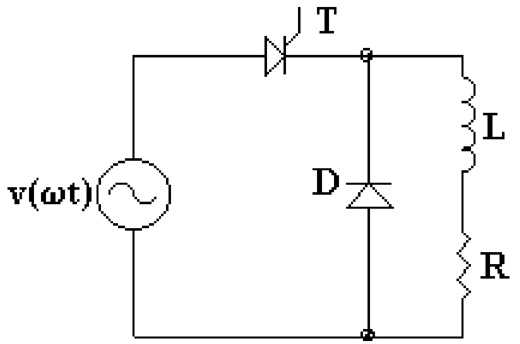
Exemplo 01

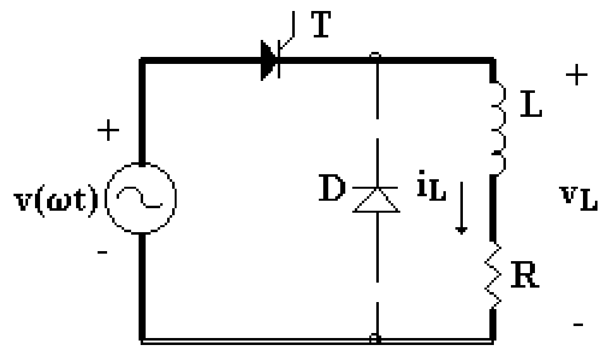
Seja o retificador monofásico controlado de meia-onda carga RL, conforme mostra o circuito abaixo. Onde: $L= 100mH$, $R=100\Omega$, $v(wt)= 311sen(wt)$ e $\alpha= 40°$. Determine:

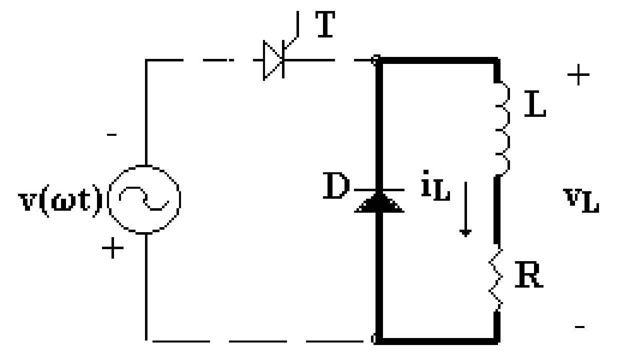
a) Tensão média na carga
b) Corrente média na carga
c) Ângulo de extinção (β)
d) Corrente eficaz na carga
e) Represente graficamente a tensão e corrente aplicada a carga. Dê ênfase ao ângulo de extinção β.

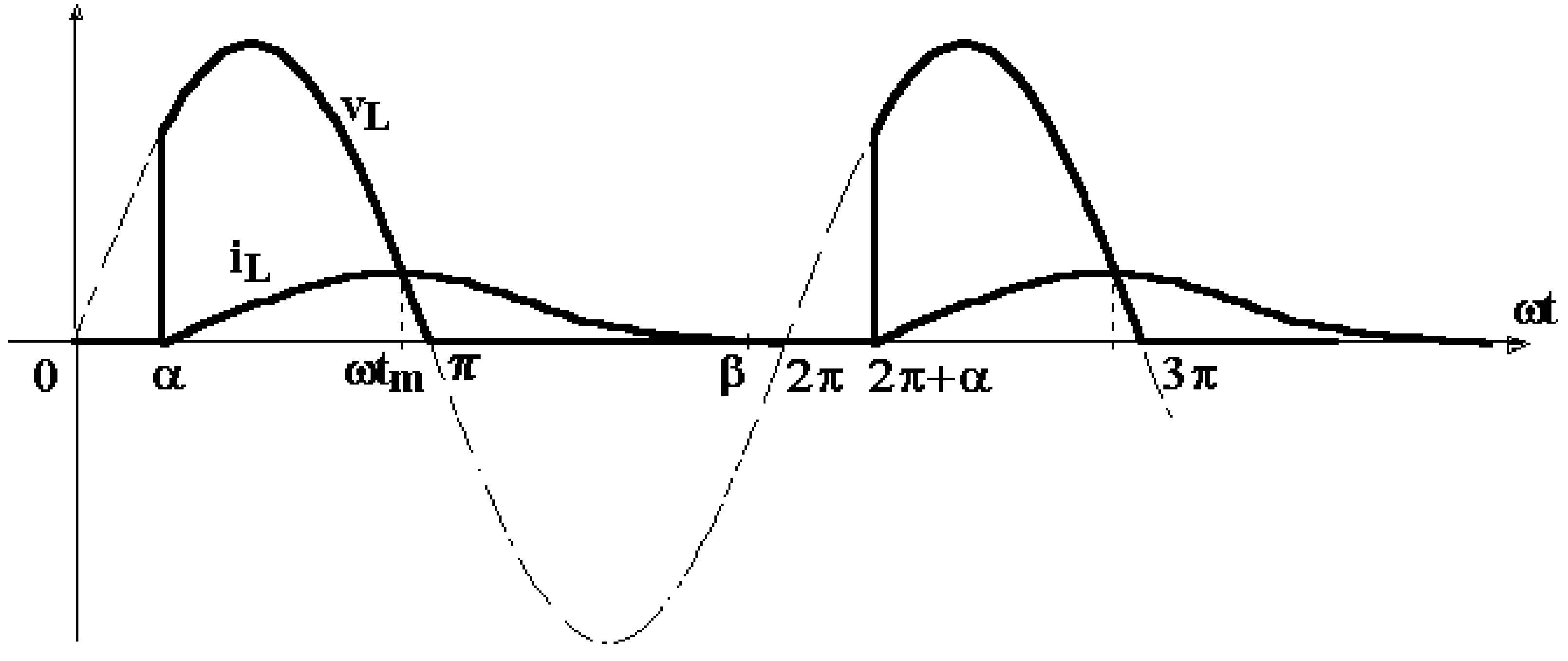


Retificador Monofásico de Meia Onda a Tiristor
Carga com Diodo de Roda Livre

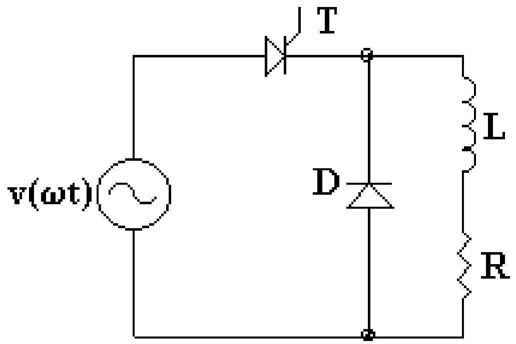








Retificador Monofásico de Meia Onda a Tiristor
Carga com Diodo de Roda Livre



$di(wt)/d(\omega t) = 0$ **$v_l(\omega t)=0$**

$v(\omega t)=v_R(\omega t)+v_l(\omega t)= R.i(\omega t)+ L.di(\omega t)/d(\omega t)$

$v(\omega t_m)=v_R(\omega t_m)$

Tensão média na carga

$$V_{Lmed} = \frac{1}{2\pi}\int_{\alpha}^{\pi} \sqrt{2}\,V_o \,\mathrm{sen}\,(\omega t)\, d(\omega t) = 0{,}225 V_o(1+\cos\alpha)$$

Corrente média na carga

$$i_1(\omega t) = \frac{\sqrt{2}\,V_o}{\sqrt{R^2+X^2}}\left[\mathrm{sen}(\omega t-\phi) - \mathrm{sen}(\alpha-\phi)\cdot e^{-t'/\zeta}\right]$$ Intervalo (α à π)

$$t' = t - \frac{\alpha}{\omega} \qquad \zeta = \frac{L}{R}$$

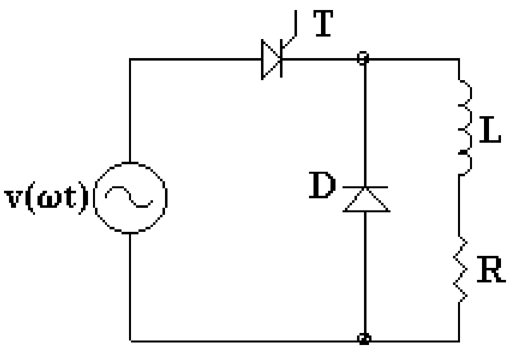
$$i_2(\omega t) = I_1 \cdot e^{-t''/\zeta} \qquad t'' = t - \frac{\pi}{\omega}$$ Intervalo (π à β ($\pi+5\sigma$))

$$i_2(\omega t) = \frac{\sqrt{2}\,V_o}{\sqrt{R^2+X^2}}\left[\mathrm{sen}\,(\pi-\phi) - \mathrm{sen}\,(\alpha-\phi)\cdot e^{-\frac{(\pi-\alpha)}{\omega\zeta}}\right]\cdot e^{-\frac{(t-\pi/\omega)}{\zeta}}$$

Exemplo 02

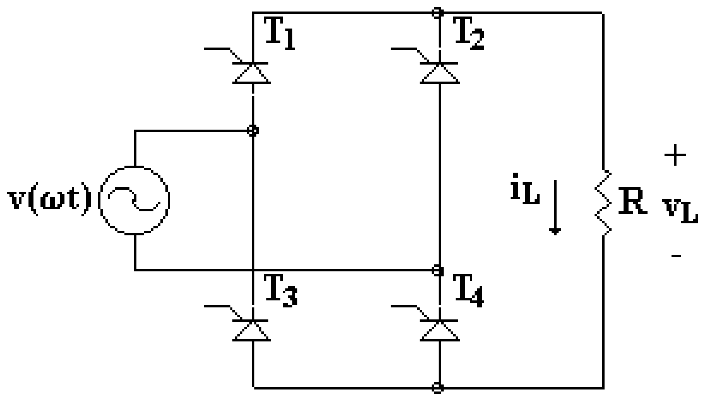
Seja o retificador monofásico controlado de meia-onda carga RL, conforme mostra o circuito abaixo. Onde: L= 100mH, R=100Ω, v(wt)= 311sen(wt) e α= 40°. Determine:

a) Tensão média na carga
b) Corrente média na carga
c) Ângulo de extinção (β)
d) Represente graficamente a tensão e corrente aplicada a carga. Dê ênfase ao ângulo de extinção β.

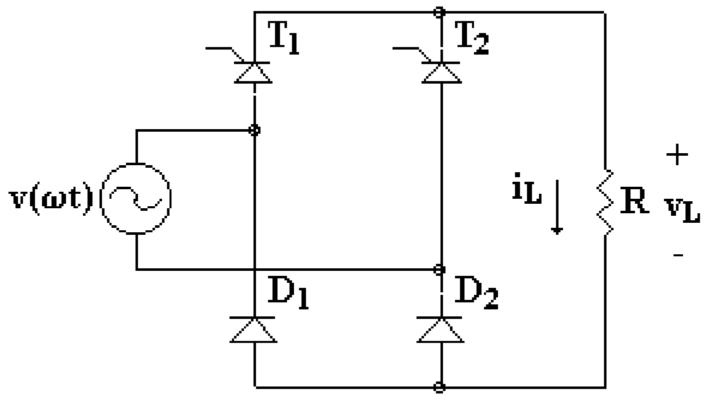


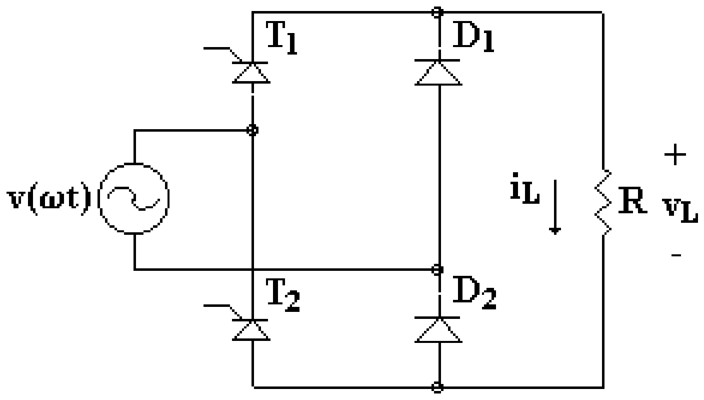
Retificador Monofásico de Onda Completa a Tiristor

A) Ponte Completa



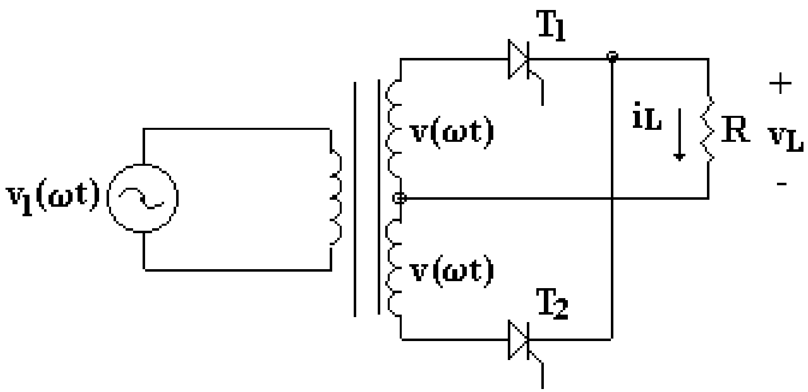
B) Ponte Mista





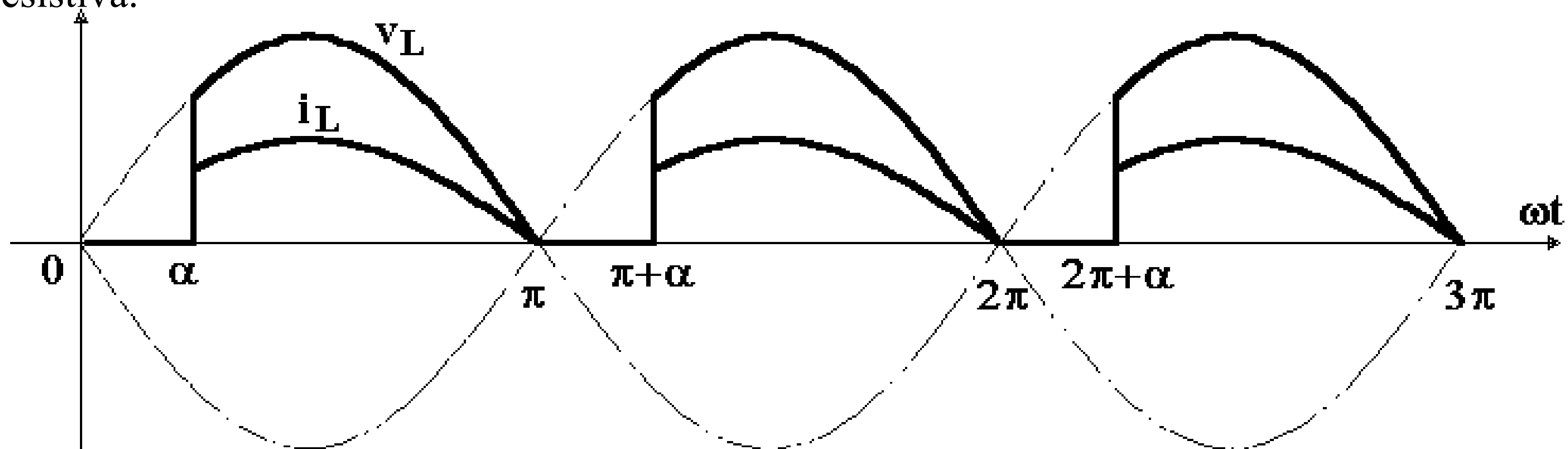
Retificador Monofásico de Onda Completa a Tiristor

C) Retificador Com Ponto Médio

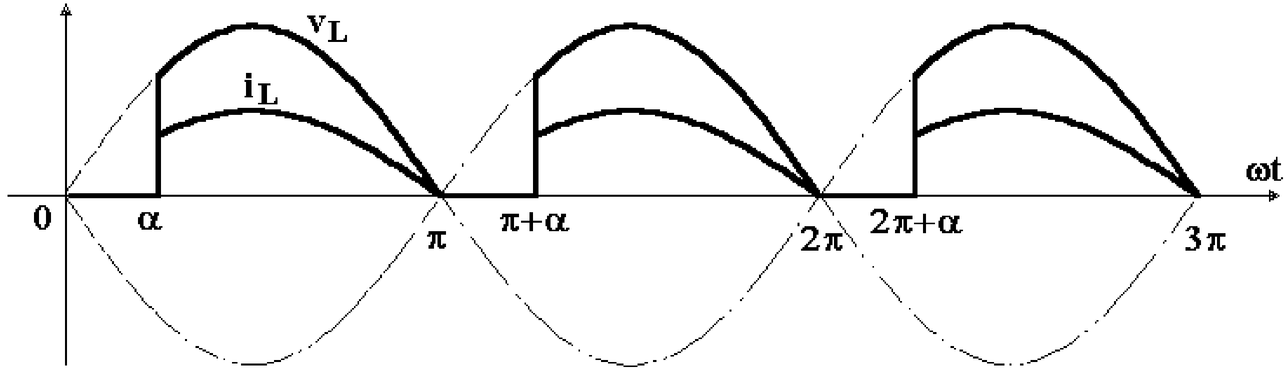


Comportamento para Cargas Resistivas

Todas as estruturas apresentam o mesmo comportamento quando alimentam carga resistiva.



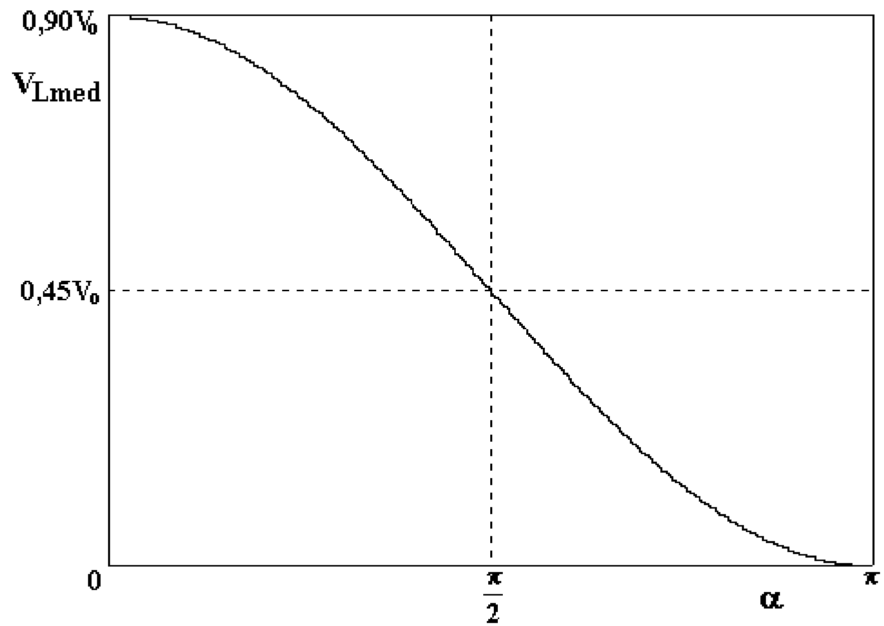
Retificador Monofásico de Onda Completa a Tiristor



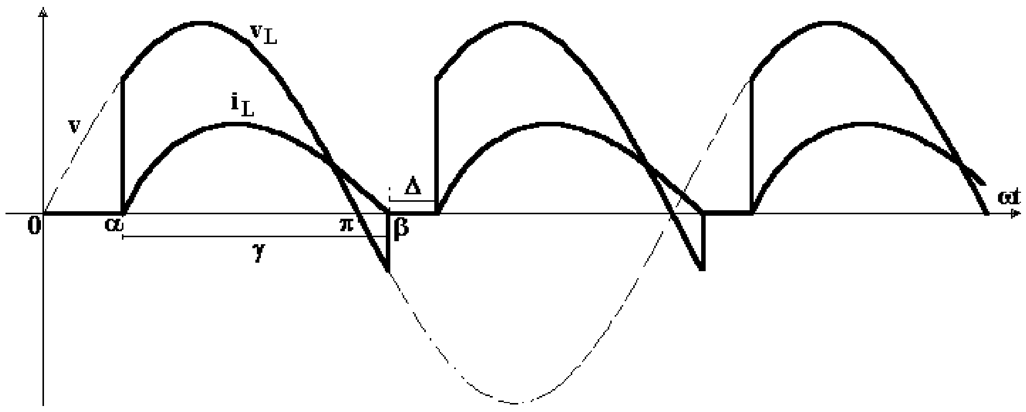
Tensão Média na Carga

$$V_{Lmed} = \frac{1}{\pi}\int_{\alpha}^{\pi} \sqrt{2}\, V_o \operatorname{sen}(\omega t)\, d(\omega t)$$

$$V_{Lmed} = \frac{\sqrt{2}\, V_o}{\pi}(1+\cos\alpha) \cong 0{,}45 V_o (1+\cos\alpha)$$



Retificador Monofásico de Ponte Completa a Tiristor com Carga RL



Tensão Média na Carga

$$V_{Lmed} = \frac{1}{\pi}\int_{\alpha}^{\beta} \sqrt{2}\, V_o \,\mathrm{sen}\,(\omega t)\, d(\omega t)$$

$$V_{Lmed} = 0{,}45\, V_o\, (\cos\alpha - \cos\beta)$$

Corrente da Carga

$$i(\omega t) = \frac{\sqrt{2}\, V_o}{\sqrt{R^2 + X^2}}\left[\mathrm{sen}\,(\omega t - \phi) - \mathrm{sen}\,(\alpha - \phi)\cdot e^{-t'/\zeta}\right]$$

$$\phi = \arctan\frac{X}{R} \qquad \zeta = \frac{L}{R} \qquad t' = t - \frac{\alpha}{\omega}$$

Retificador Monofásico de Ponte Completa a Tiristor, carga RL, como Inversor

$$V_{Lmed} = 0.45V_o\,(\cos\alpha - \cos\beta)$$

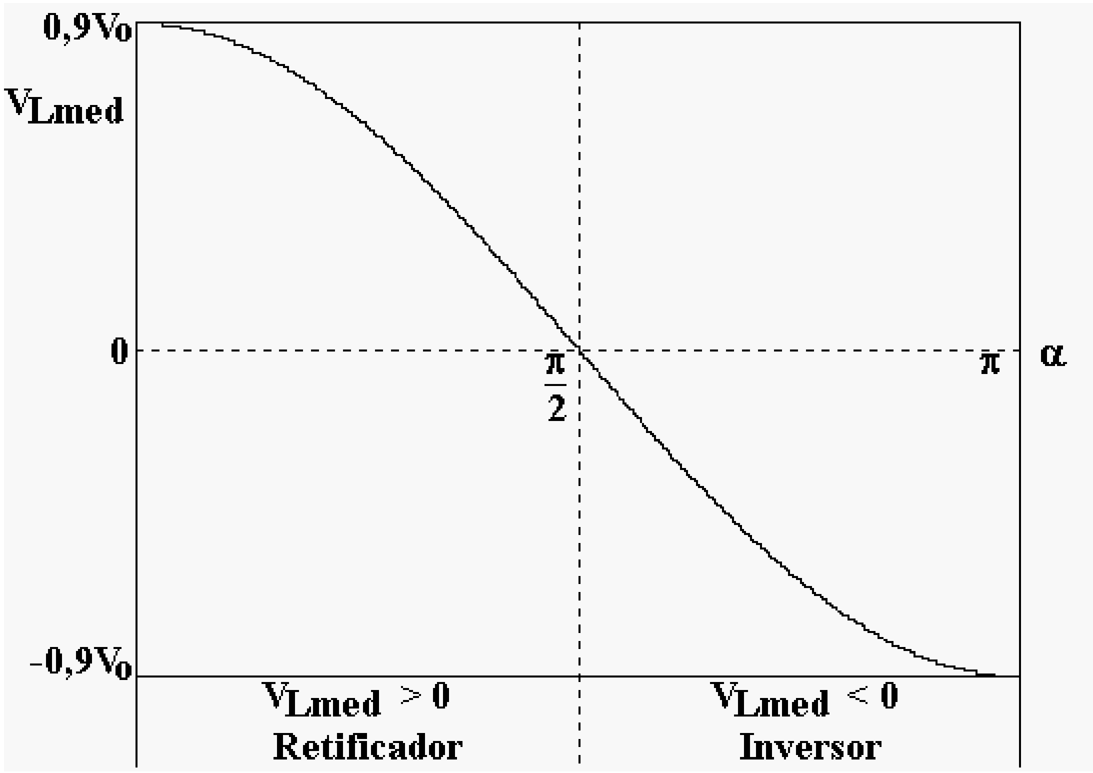
$\beta = \pi + \alpha$ Operação contínua

$$V_{Lmed} = 0.9\,V_o \cos\alpha$$

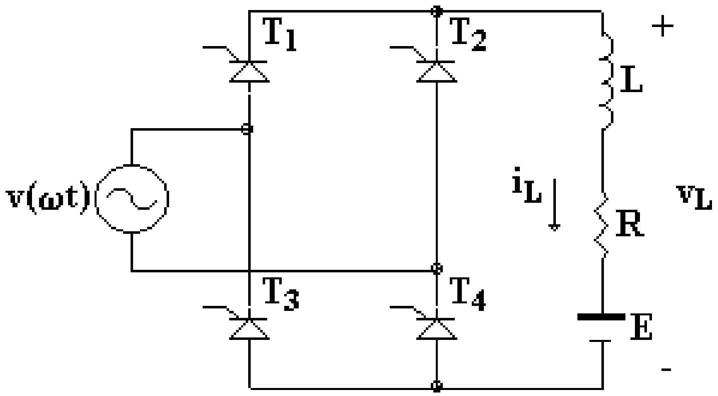
Como a corrente na carga é sempre positivo, o sentido do fluxo da potência da fonte para a carga é dada pelo valor da tensão média.

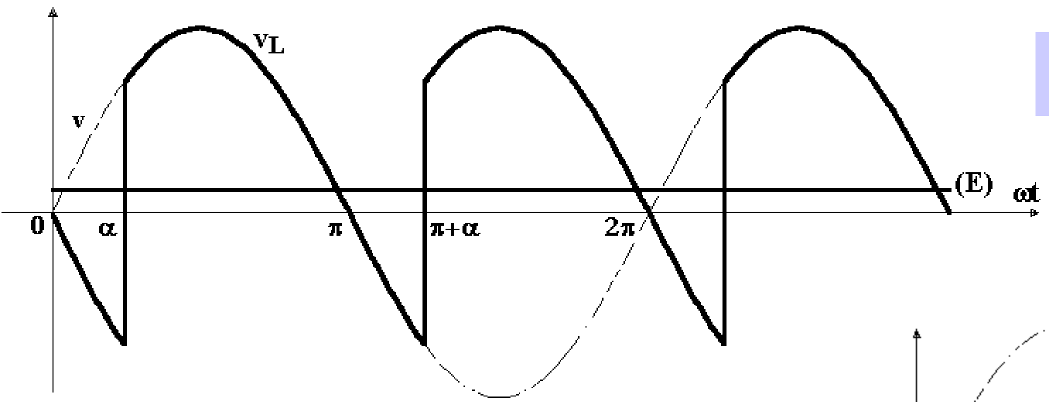
VLmed > 0 Retificador

VLmed < 0 Inversor

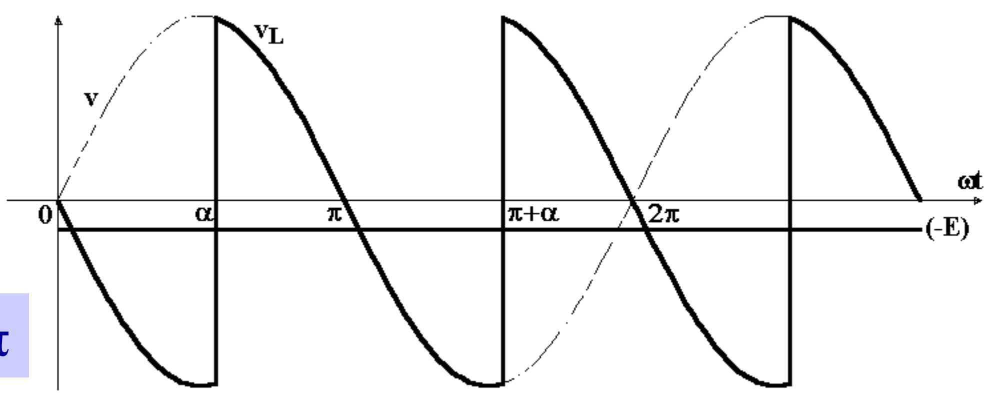


Retificador Monofásico de Ponte Completa a Tiristor como Inversor com Carga RLE



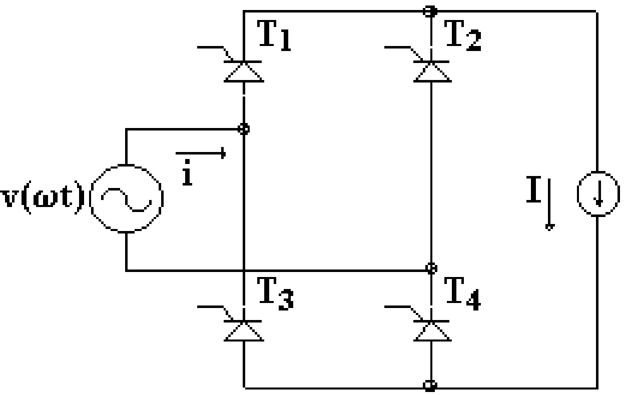


Retificador $0 < \alpha < \pi/2$



Inversor $\pi/2 < \alpha < \pi$

Retificador Monofásico de Ponte Completa a Tiristor Fator de Potência



$$\cos\phi = \cos\alpha$$

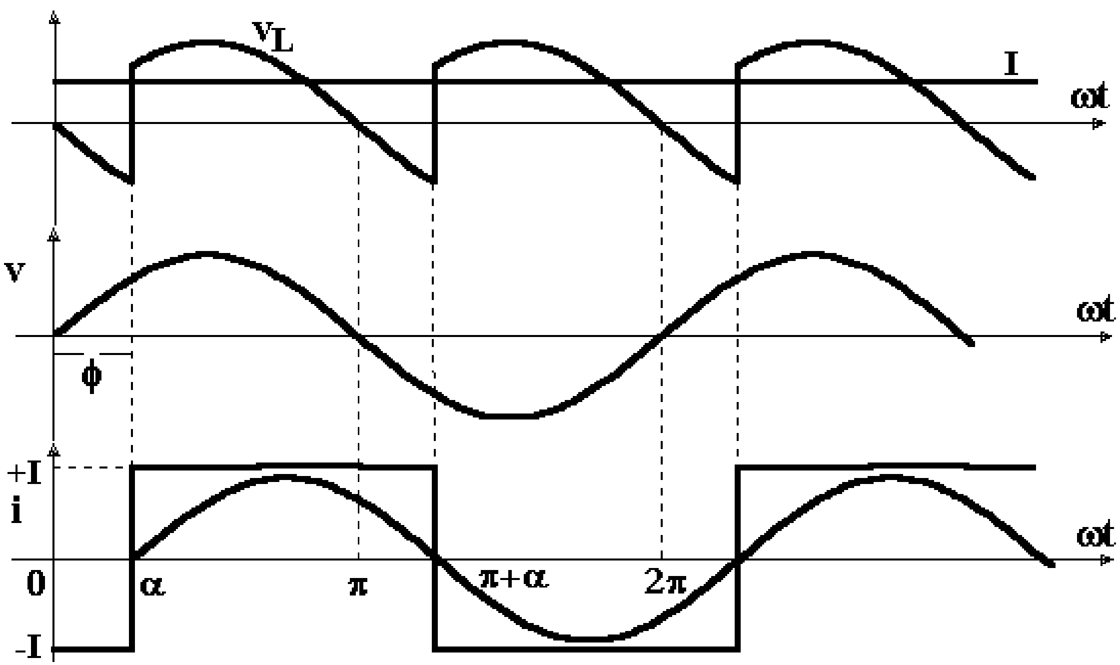
$$P = 0{,}9\, V_o\, I \cos\alpha$$

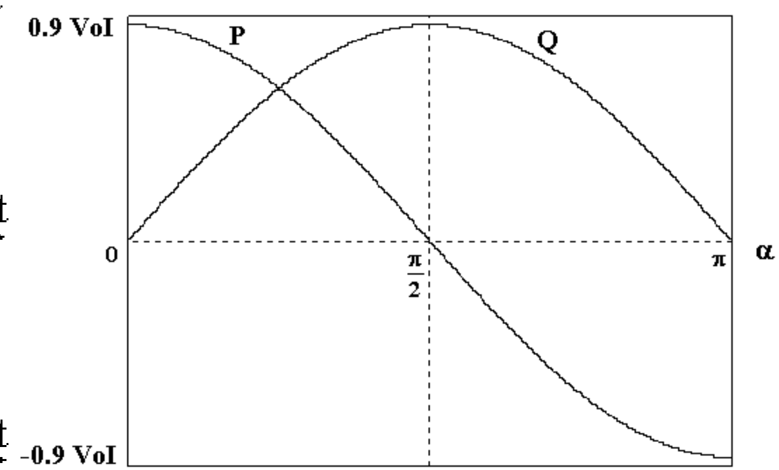
$$Q = 0{,}9\, V_o\, I \,\mathrm{sen}\, \alpha$$

$$S_T = V_o\, I$$

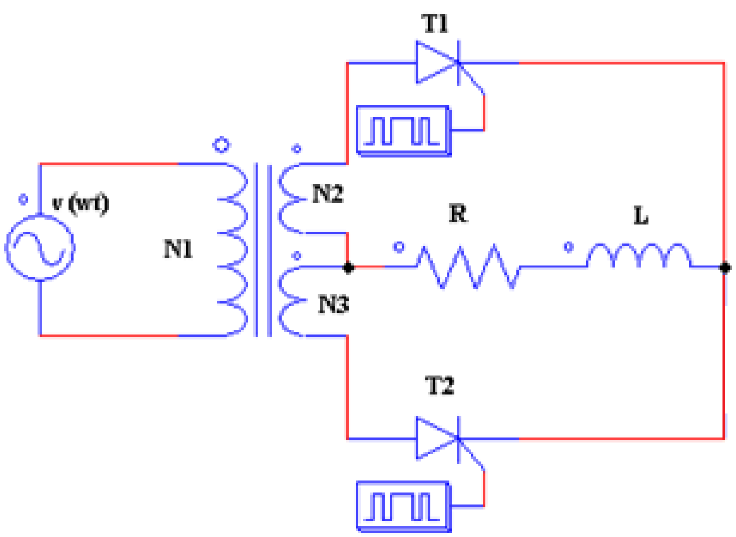
$$FP = \frac{P}{S_T}$$

$$FP = 0{,}9 \cos\alpha$$





Ex. 01) O circuito é alimentado por uma fonte senoidal de 60Hz e tensão eficaz de 220V. O transformador possui em seu enrolamento primário N1=100 espiras, enquanto que em N2= N3= 50 espiras. Todo o circuito alimenta uma carga do tipo RL, que possui R= 100Ω e L= 600mH. Desta forma, determine:

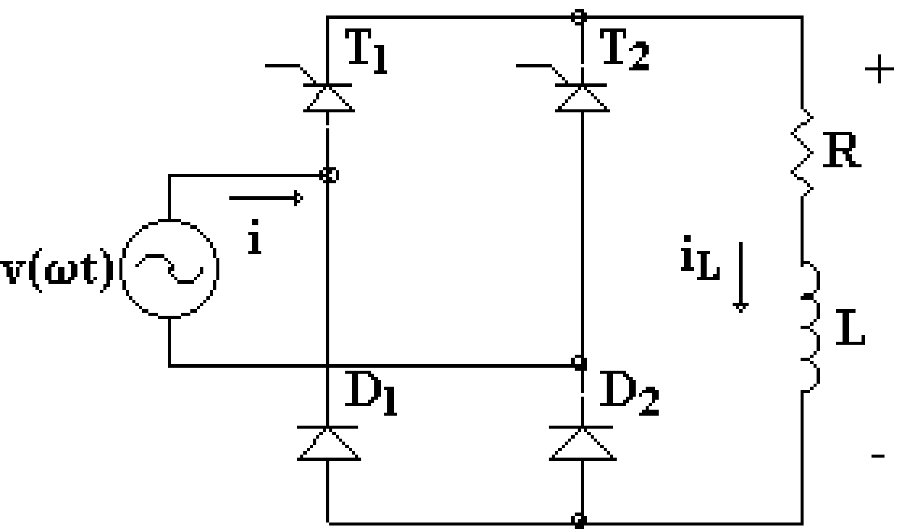


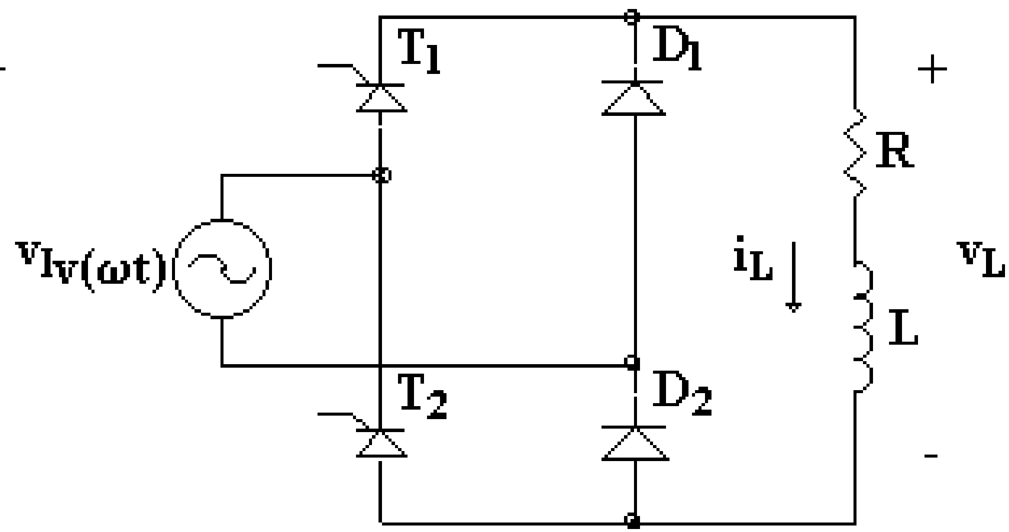
a) Ângulo de extinção da corrente α= 90°, informe o modo de condução;

b) Tensão e corrente media aplicada à carga, α= 90°;

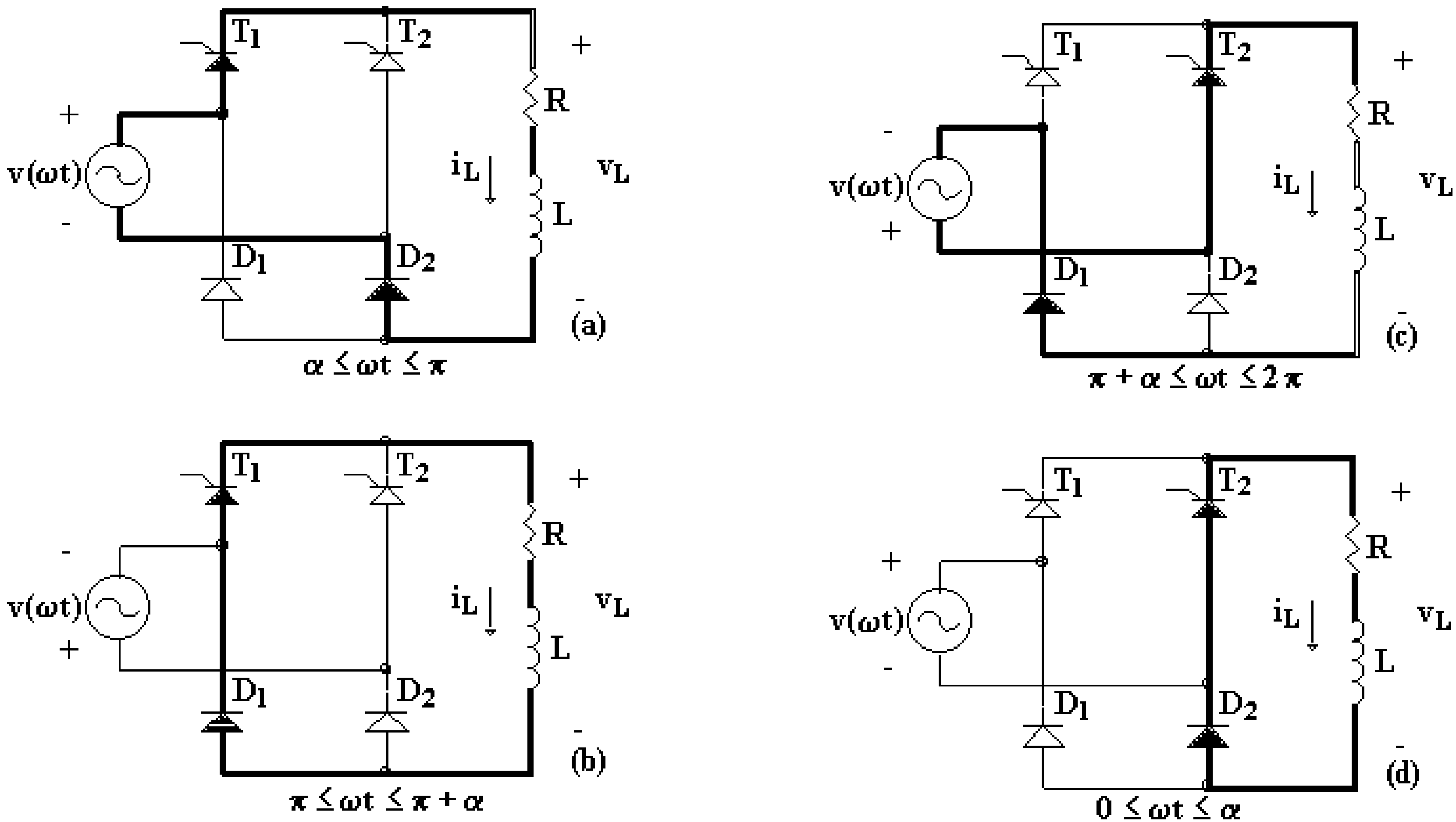
c) Representação da tensão e corrente aplicada à carga, α= 90°;

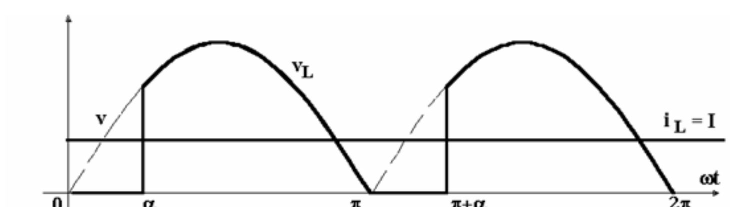
Retificador Monofásico de Ponte Mista Carga RL





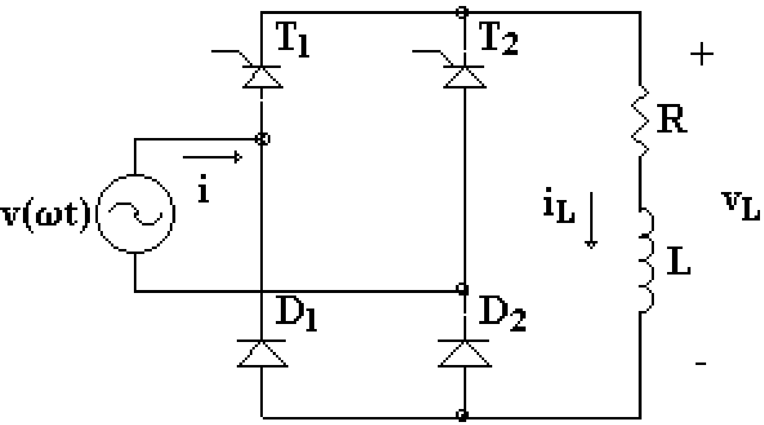
Retificador Monofásico de Ponte Mista Carga RL

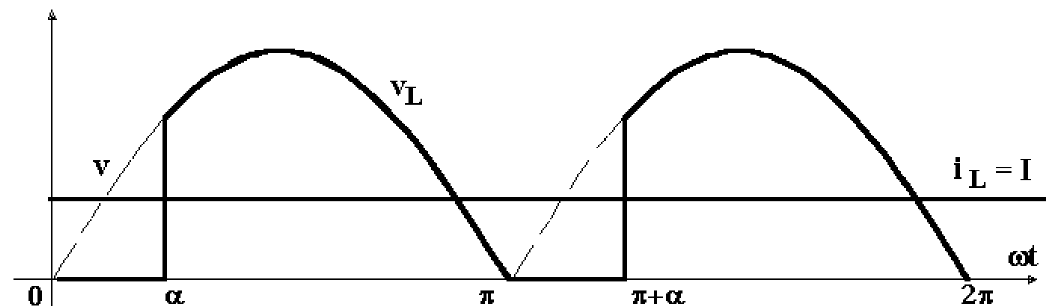




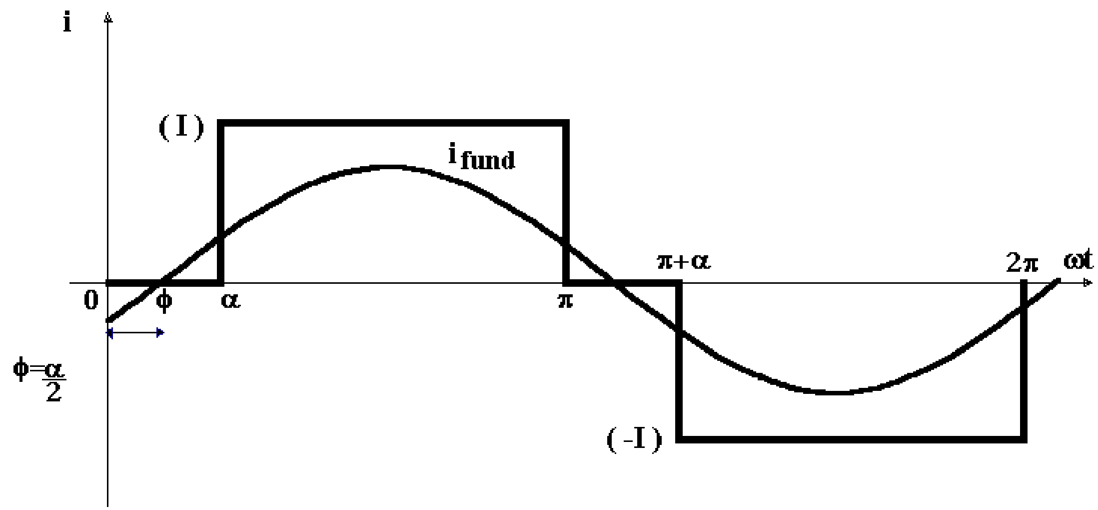
(d)	(a)	(b)	(c)
T_2, D_2	T_1, D_2	T_1, D_1	T_2, D_1

Retificador Monofásico de Ponte Mista Carga RL





(d)	(a)	(b)	(c)
T_2,D_2	T_1,D_2	T_1,D_1	T_2,D_1

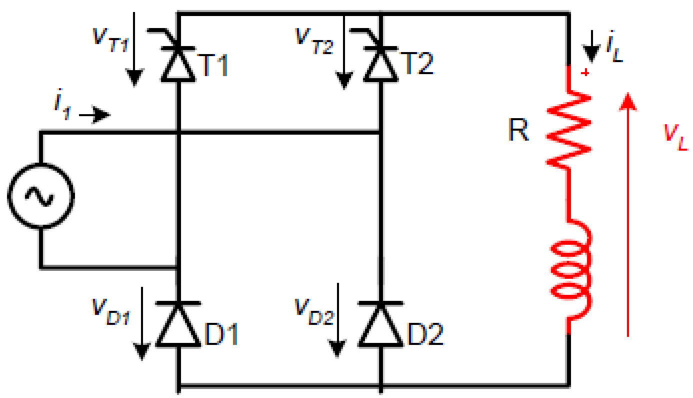


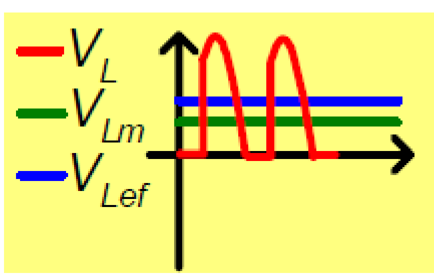
Fator de Deslocamento

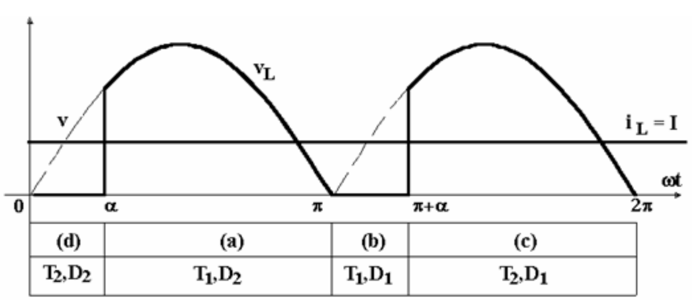
$$\cos(\phi)=\cos\left(\frac{\alpha}{2}\right)$$

Retificador Monofásico de Ponte Mista Carga RL

Tensão na carga







Médio

$$V_{Lmed} = \frac{1}{\pi}\int_{\alpha}^{\pi} \sqrt{2}V_o \,\mathrm{sen}(\omega t)\, d(\omega t)$$

$$\boxed{V_{Lmed} \cong 0.45 V_o \left(1+\cos(\alpha)\right)}$$

Eficaz

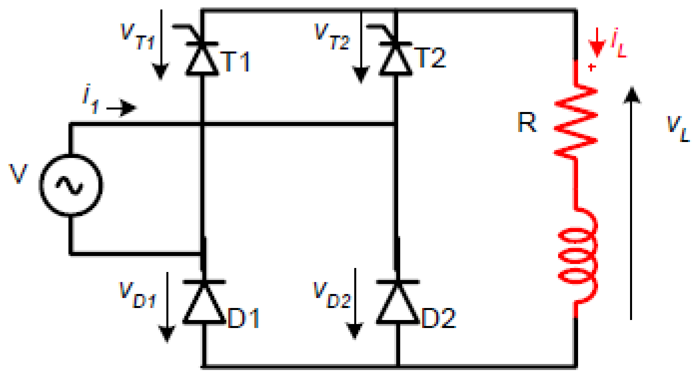
$$V_{Lef} = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi} \left[\sqrt{2}V_o \,\mathrm{sen}(\omega t)\right]^2 d(\omega t)}$$

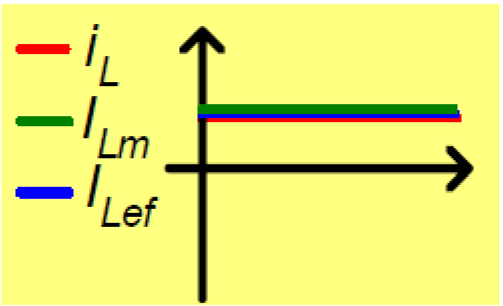
$$\boxed{V_{Lef} \cong V_o \sqrt{1-\frac{\alpha}{\pi}+\frac{\mathrm{sen}(2\alpha)}{2\pi}}}$$

A ponte mista não funciona como inversor. A tensão média é sempre positiva.

Retificador Monofásico de Ponte Mista Carga RL

Corrente na carga





Médio

$$I_{Lmed} = \frac{1}{2\pi}\int_{\alpha}^{\pi} \sqrt{2}\frac{V_o}{R}\operatorname{sen}(\omega t)\, d(\omega t)$$

$$\boxed{I_{Lmed} \cong 0.45\frac{V_o}{R}\left(1+\cos(\alpha)\right)}$$

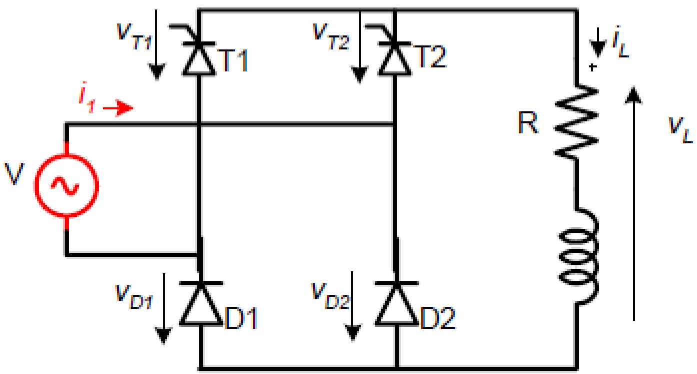
Eficaz **CARGA R**

$$I_{Lef} = \sqrt{\frac{1}{2\pi}\int_{\alpha}^{\pi}\left[\sqrt{2}\frac{V_o}{R}\operatorname{sen}(\omega t)\right]^2 d(\omega t)}$$

$$\boxed{I_{Lef} \cong \frac{V_o}{R}\sqrt{1-\frac{\alpha}{\pi}+\frac{\operatorname{sen}(2\alpha)}{\pi}}}$$

Retificador Monofásico de Ponte Mista Carga RL

Corrente na entrada

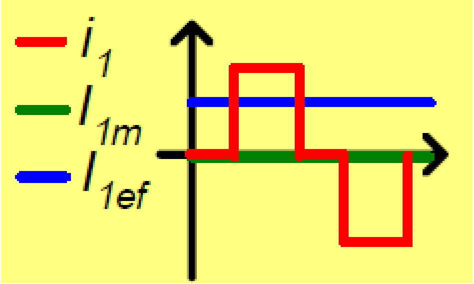


Médio

$$\boxed{I_{1med} = 0}$$

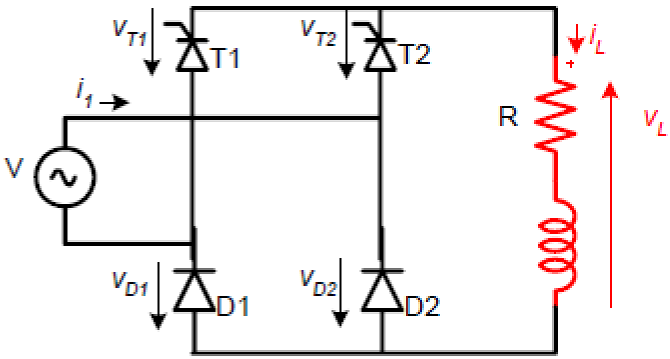
Eficaz

$$I_{1ef} = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi} {I_{Lmed}}^{2} d(\omega t)}$$



$$\boxed{I_{1ef} \cong 0.45\frac{V_o}{R}\left(1+\cos(\alpha)\right)\sqrt{1-\frac{\alpha}{\pi}}}$$

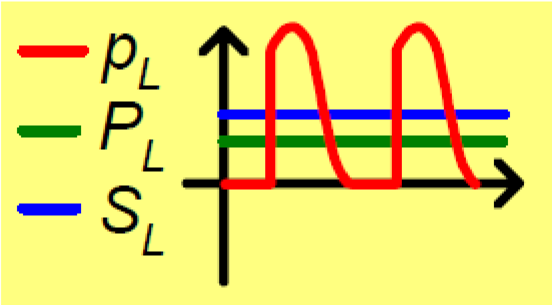
Potência na carga



Ativa

$$P_L = \int v_L(\omega t)\, i_L(\omega t)\, d\omega t$$

$$\boxed{P_L \cong \frac{\sqrt{2}}{\pi} V_o I_{Lmed}\left(1+\cos(\alpha)\right)}$$



Aparente

$$S_L = V_{Lef} I_{Lef}$$

$$\boxed{S_L \cong \frac{V_o^2}{R}\sqrt{1-\frac{\alpha}{\pi}+\frac{\operatorname{sen}(2\alpha)}{2\pi}}}$$

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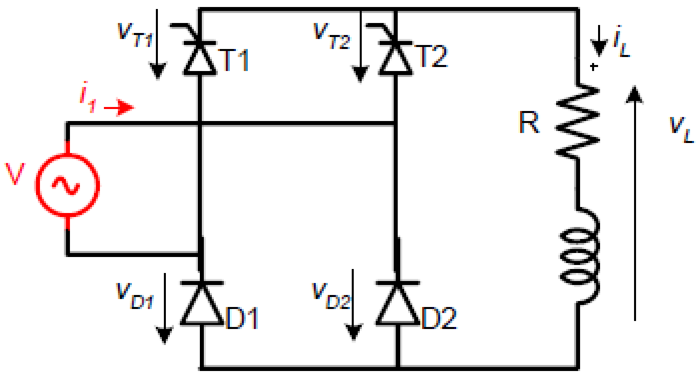
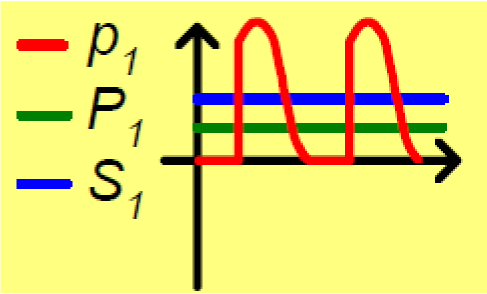
Retificador Monofásico de Ponte Mista Carga RL

Potência na entrada





Ativa

$$P_1 = \int v_1(\omega t) i_1(\omega t) d\omega t$$

$$\boxed{P_1 \cong \frac{\sqrt{2}}{\pi} V_o I_{Lmed} \left(1 + \cos(\alpha)\right)}$$

Aparente

$$S_1 = V_{1ef} I_{1ef}$$

$$\boxed{S_1 \cong V_o I_{Lmed} \sqrt{1 - \frac{\alpha}{\pi}}}$$

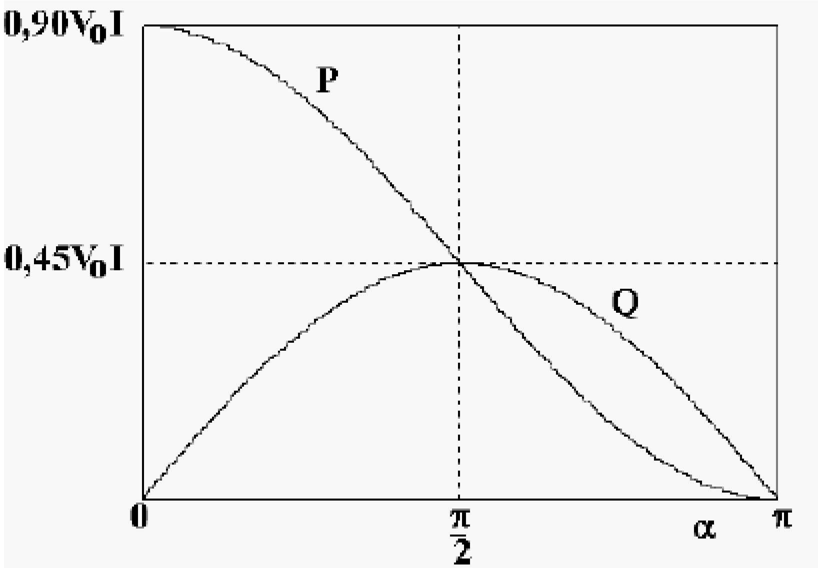
Retificador Monofásico de Ponte Mista Carga RL

Fator de potência

$$PF = \frac{P}{S} \qquad PF = \frac{\frac{\sqrt{2}}{\pi} V_o I_{Lmed} \left(1 + \cos(\alpha)\right)}{V_o I_{Lmed} \sqrt{1 - \frac{\alpha}{\pi}}}$$

$$\boxed{PF = \frac{\sqrt{2}\left(1 + \cos(\alpha)\right)}{\sqrt{\pi(\pi - \alpha)}}}$$

Potência ativa (P) e reativa (Q) em função de α

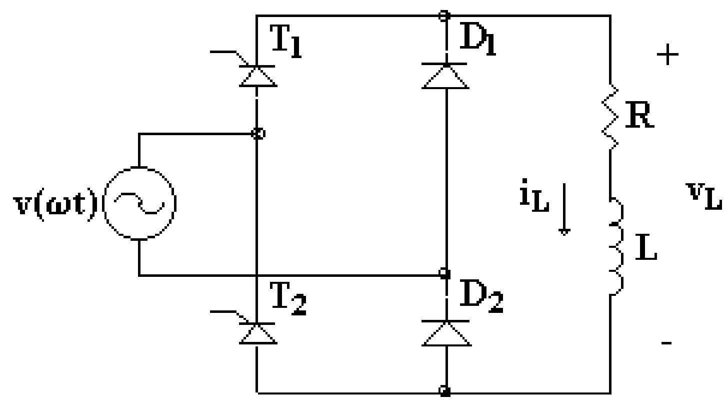


Retificador Monofásico de Ponte Mista Carga RL

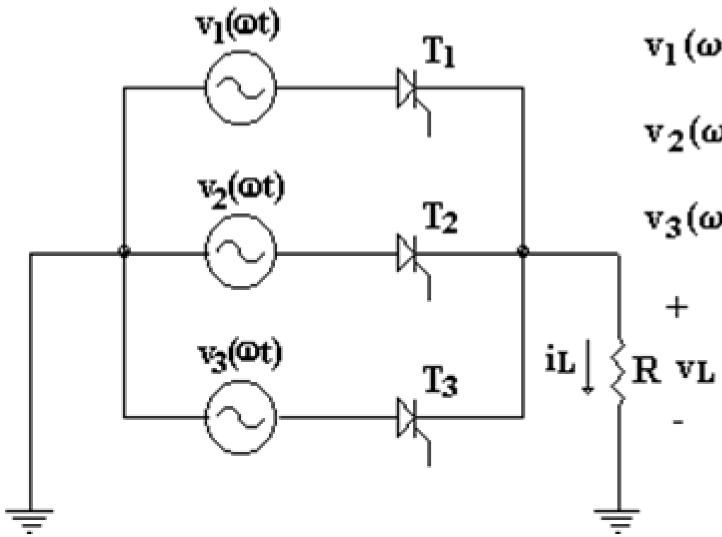
Um retificador monofásico em ponte mista, como mostra abaixo e f=60Hz, Vo=220V, I_{LMED}= 10A e α= 40°.

Determine:

a) Tensão média na carga;
b) Potência média transferida na carga;
c) Fator de deslocamento;
d) Corrente eficaz total de entrada;
e) Fator de potência da corrente de entrada.
f) Análise qualitativa
g) Formas de ondas da tensão e corrente na carga, corrente na entrada



Retificador Trifásico a Ponto Médio com Tiristor



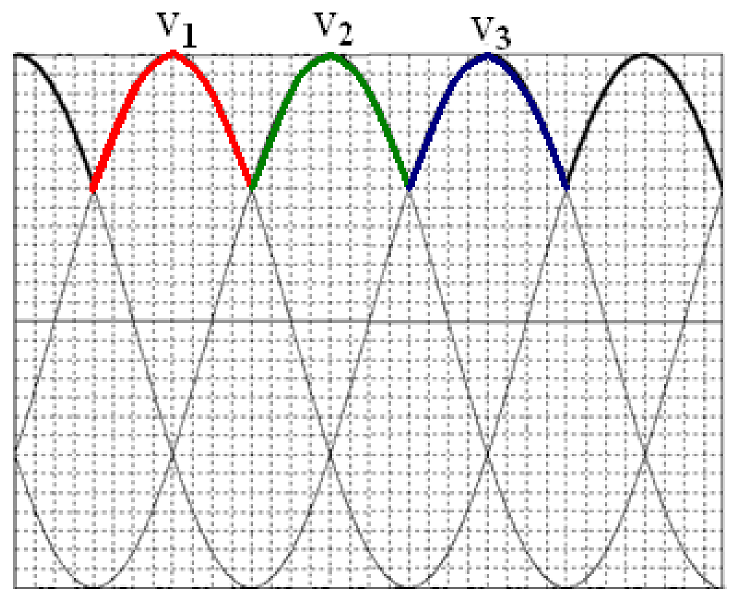
$$v_1(\omega t) = \sqrt{2}\,V_o\,\mathrm{sen}(\omega t)$$

$$v_2(\omega t) = \sqrt{2}\,V_o\,\mathrm{sen}(\omega t - 120^o)$$

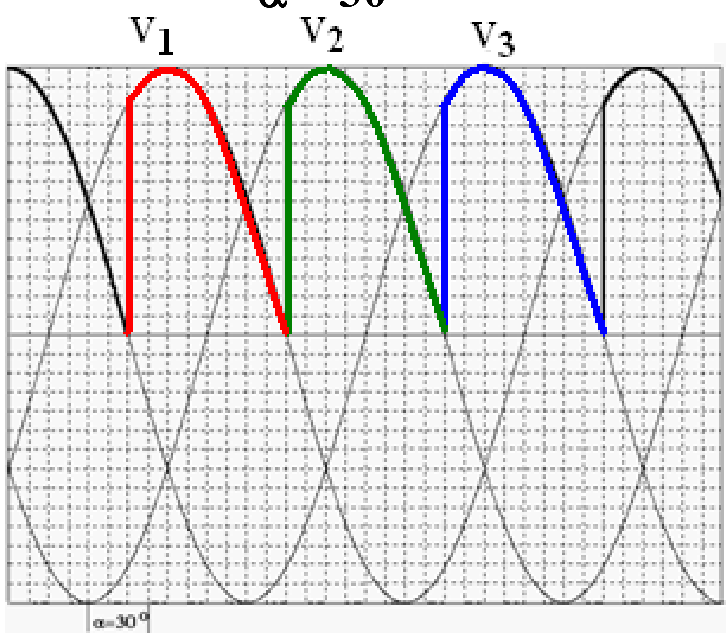
$$v_3(\omega t) = \sqrt{2}\,V_o\,\mathrm{sen}(\omega t + 120^o)$$

Condução Contínua $0 < \alpha < \pi/6$

$\alpha = 0^o$



$\alpha = 30^o$



$$V_{Lmed} = \frac{3}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\frac{5\pi}{6}+\alpha} \sqrt{2}\,V_o\,\mathrm{sen}(\omega t)\,d(\omega t)$$

$$V_{Lmed} = 1{,}17\,V_o\cos\alpha$$

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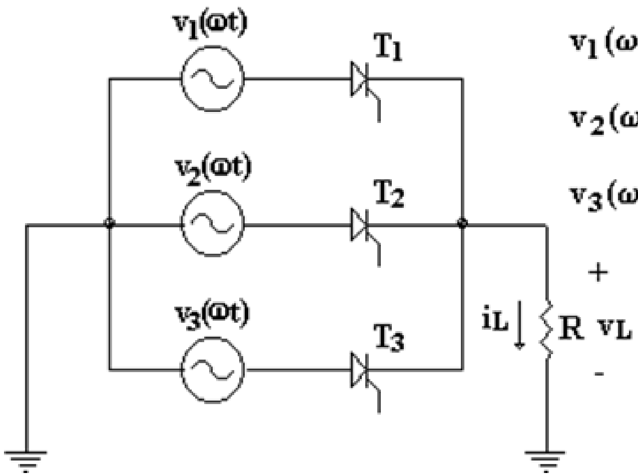
Retificador Trifásico a Ponto Médio com Tiristor

Condução Descontínua $\pi/6 < \alpha < 5\pi/6$

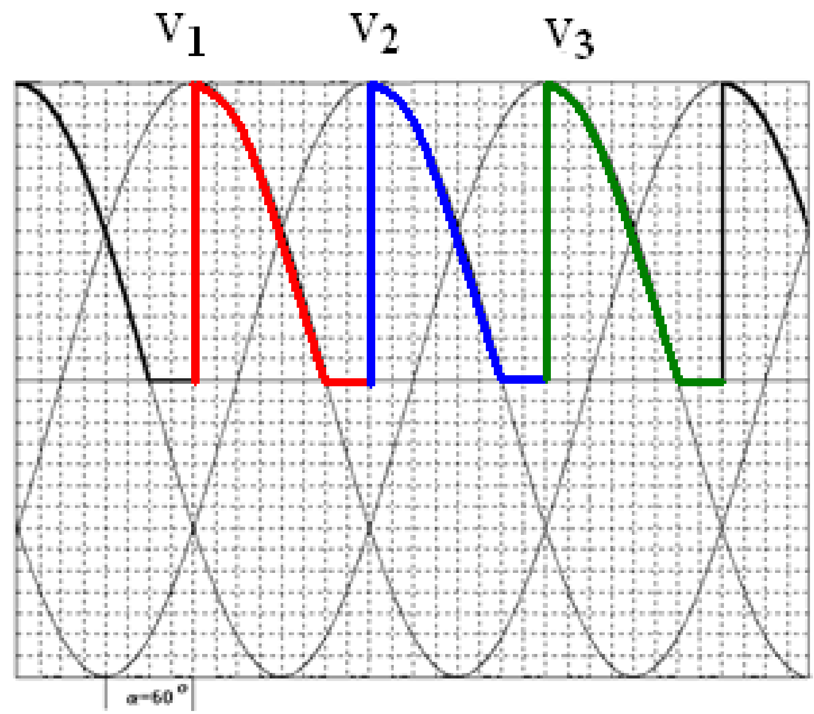


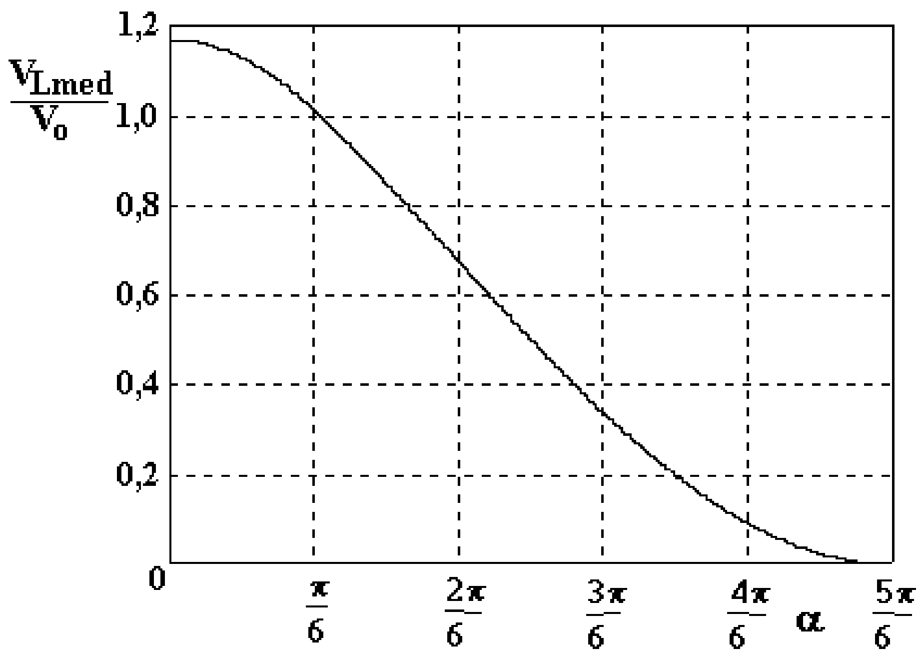
$v_1(\omega t) = \sqrt{2}\, V_o \,\text{sen}(\omega t)$

$v_2(\omega t) = \sqrt{2}\, V_o \,\text{sen}(\omega t - 120^o)$

$v_3(\omega t) = \sqrt{2}\, V_o \,\text{sen}(\omega t + 120^o)$

$\alpha = 60^o$



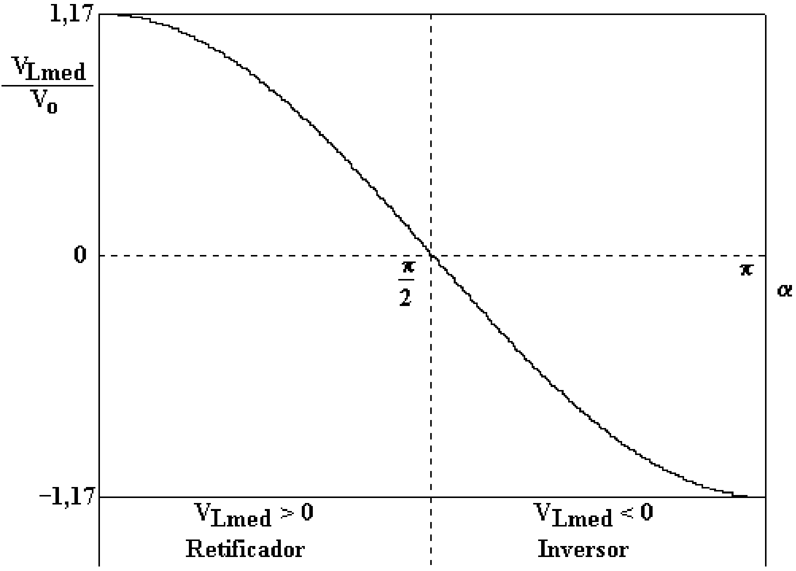


$$V_{Lmed} = \frac{3}{2\pi}\int_{\frac{\pi}{6}+\alpha}^{\pi} \sqrt{2}\, V_o \,\text{sen}(\omega t)\, d(\omega t)$$

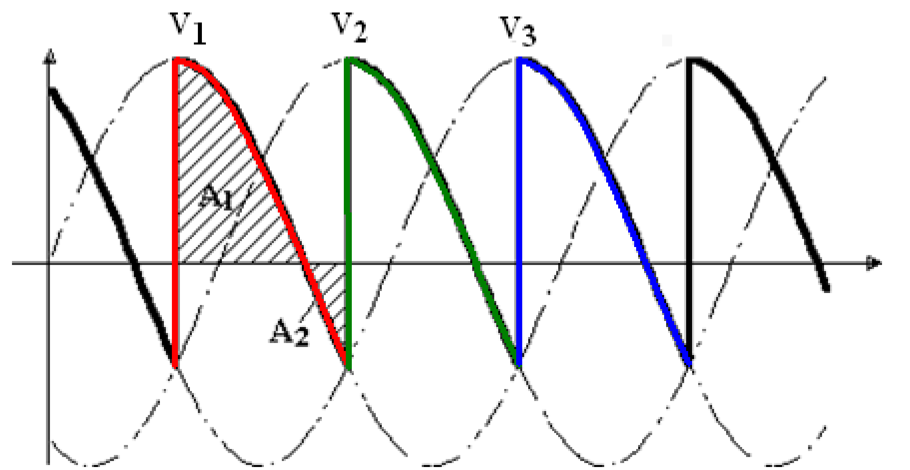
$$V_{LMED} = \frac{3\sqrt{2}}{2\pi} V_o \left[1 + cos\left(\frac{\pi}{6} + \alpha\right)\right]$$

Retificador Trifásico a Ponto Médio com Tiristor com Carga Indutiva

Vamos considerar o caso em que a condução é contínua



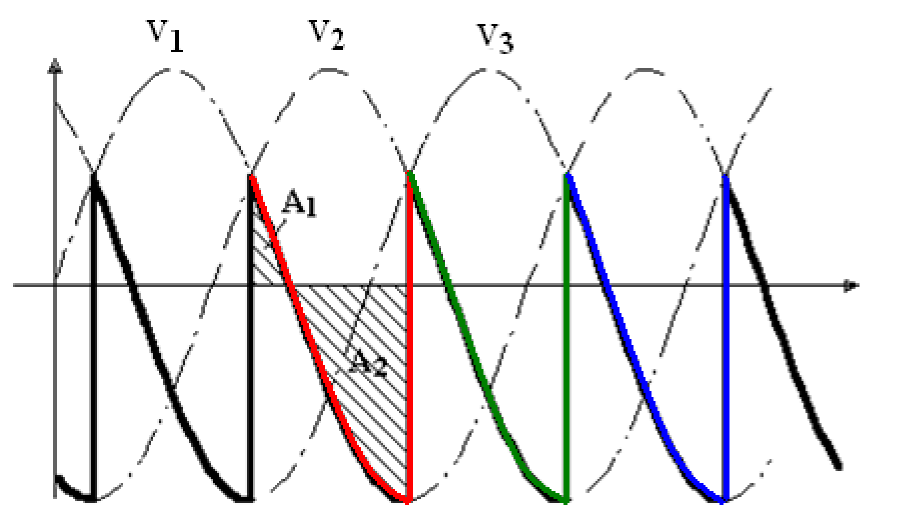
$$V_{Lmed} = 1{,}17\, V_o \cos\alpha$$



Nº de pulsos	$\beta_{crítico}$
1	$\beta_c = 2\pi + \alpha_1$
2	$\beta_c = \pi + \alpha_1$
3	$\beta_c = \dfrac{2\pi}{3} + \alpha_1$
6	$\beta_c = \dfrac{2\pi}{6} + \alpha_1$

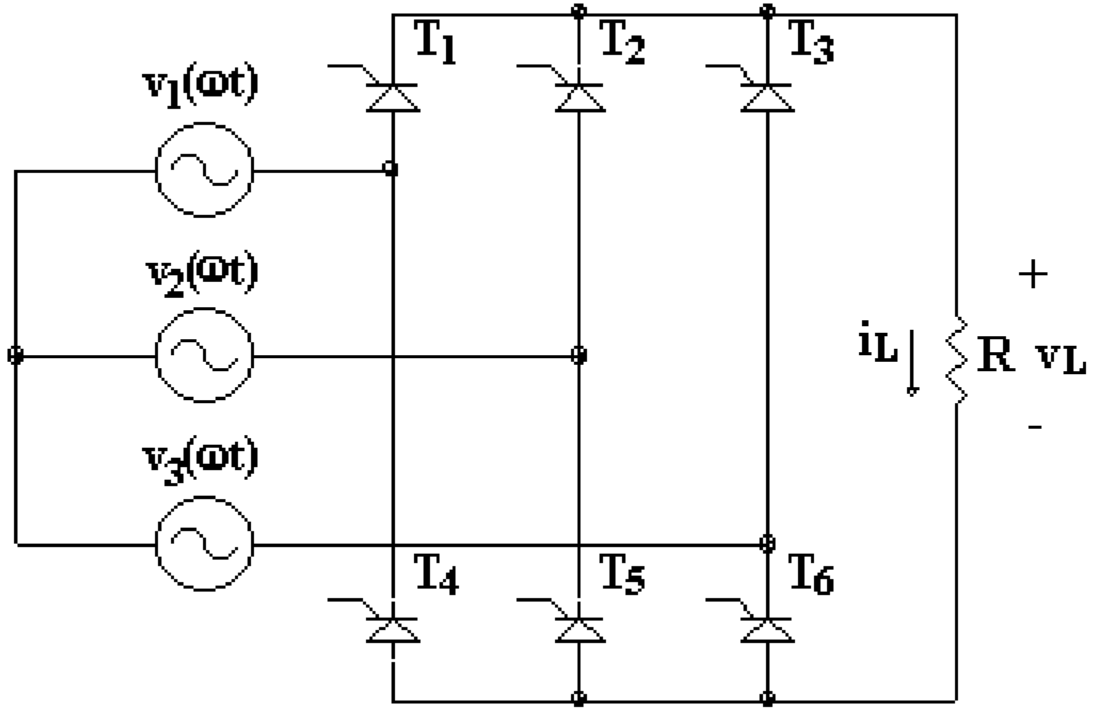
$$\beta_c = \frac{2\pi}{m} + \alpha_1$$

$$\alpha_1 = \alpha + 30^o$$



Retificador Trifásico Ponte de Graez com Tiristor, Carga R

TOPOLOGIA



O ângulo α é contado a partir do ponto da interceptação de duas tensões da fonte, e não do cruzamento por zero

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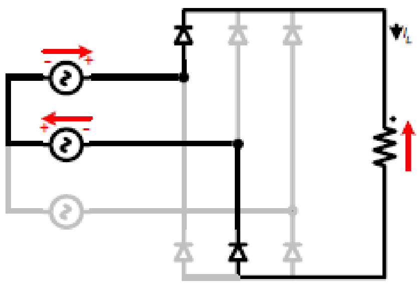
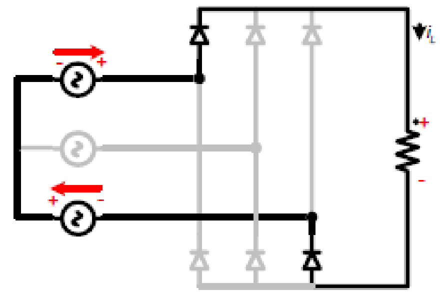
Retificador Trifásico Ponte de Graez com Tiristor, Carga R

Modo de condução contínua ($0° < \alpha < 60°$)

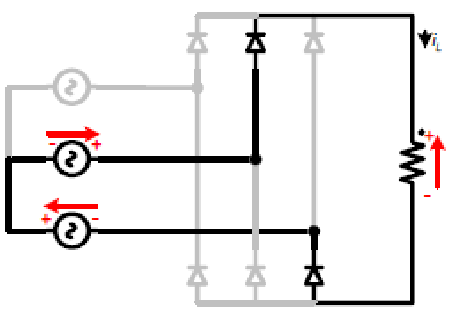
Etapa 1 $\alpha \leq \omega t < \alpha + \pi/3$



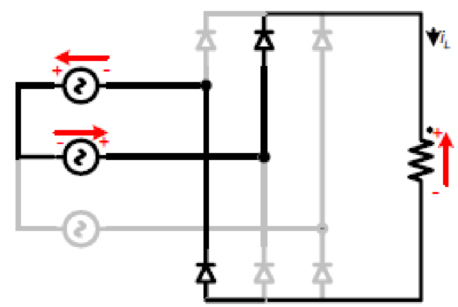
Etapa 2 $\alpha + \pi/3 \leq \omega t < \alpha + 2\pi/3$



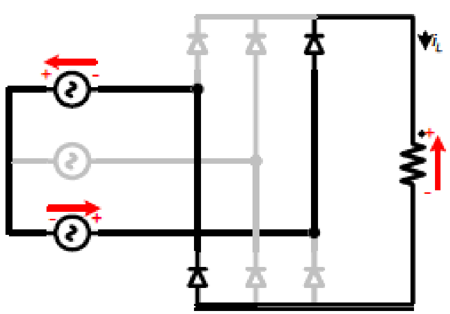
Etapa 3 $\alpha + 2\pi/3 \leq \omega t < \alpha + \pi$



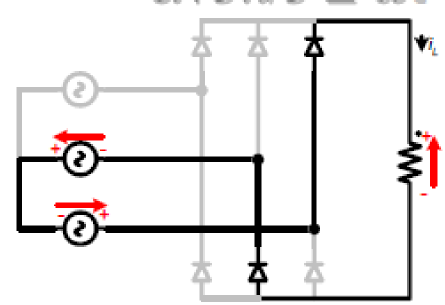
Etapa 4 $\alpha + \pi \leq \omega t < \alpha + 4\pi/3$



Etapa 5 $\alpha + 4\pi/3 \leq \omega t < \alpha + 5\pi/3$



Etapa 6 $\alpha + 3\pi/3 \leq \omega t < \alpha + 2\pi$



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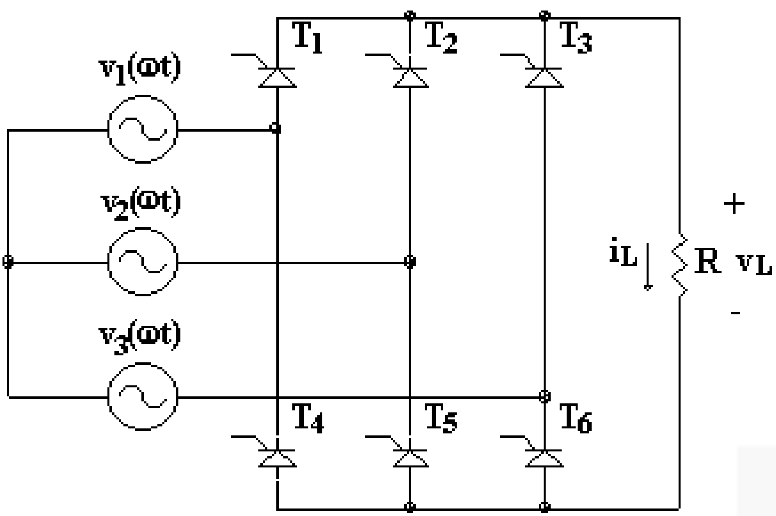
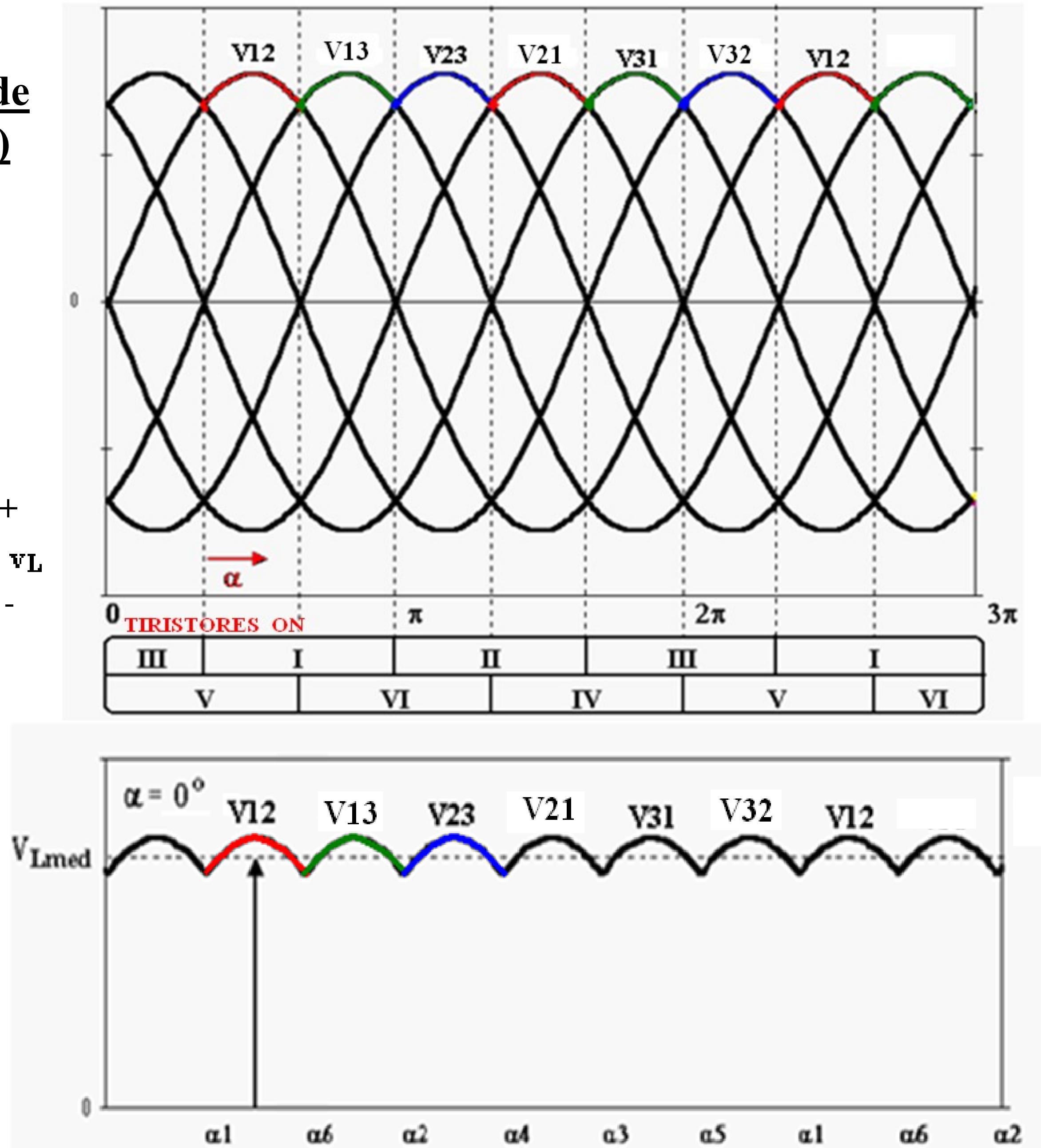
Retificador Trifásico Ponte de Graez com Tiristor, Carga R

FORMAS DE ONDAS – Modo de Condução Contínua ($0 < \alpha < \pi/3$)

Ângulo de disparo $\alpha = 0°$



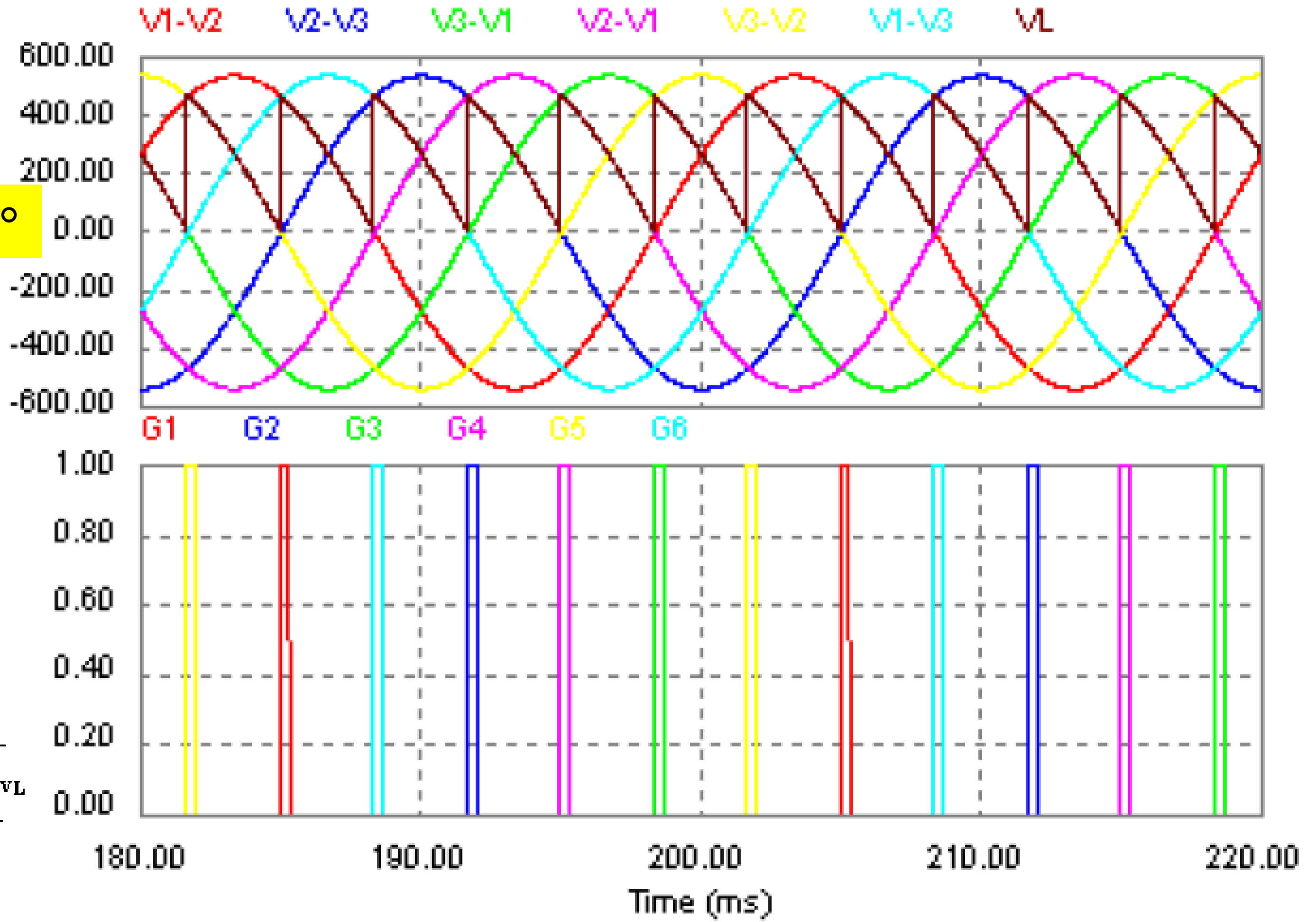


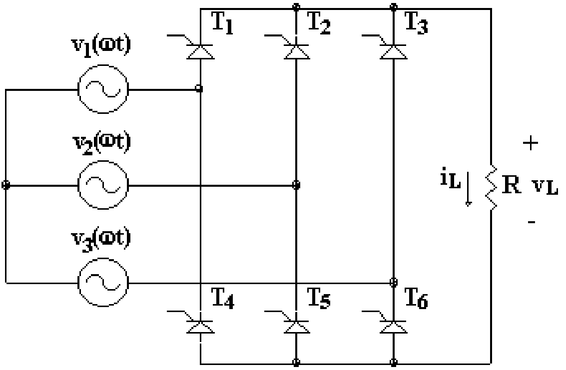
Retificador Trifásico Ponte de Graez com Tiristor, Carga R

FORMAS DE ONDAS – Modo de Condução Contínua

$R=10\Omega$
$V_o=380V_{ef}$(linha)
$f=50Hz$

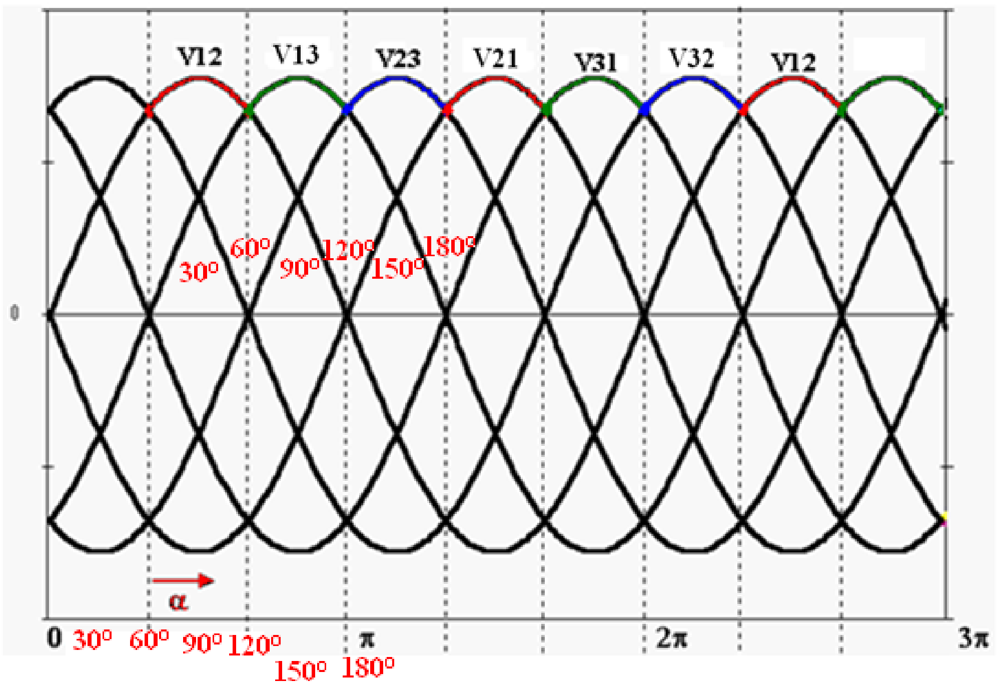
Ângulo de disparo α = 60°





Retificador Trifásico Ponte de Graez com Tiristor, Carga R

TENSÃO NA CARGA – Condução Contínua (0 < α < π/3)



MÉDIO

$$\boxed{V_{Lmed} = \frac{6}{2\pi}\int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}+\alpha} \sqrt{2}\,V_{OL}\,\mathrm{sen}(\omega t)\,d(\omega t)}$$

$$\boxed{V_{Lmed} = 2{,}34\,V_o\cos\alpha}$$

EFICAZ

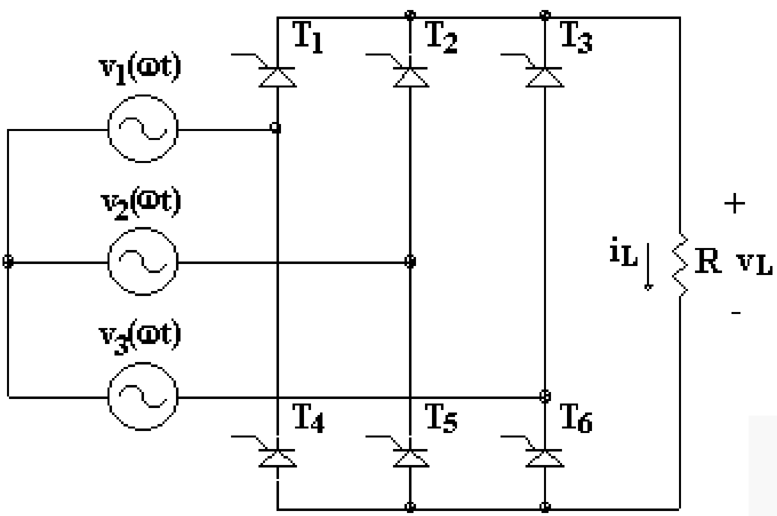
$$V_{Lef} = \sqrt{\frac{1}{2\pi/6}\int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}+\alpha}\left[\sqrt{2}\sqrt{3}V_o\,\mathrm{sen}(\omega t)\right]^2 d(\omega t)}$$

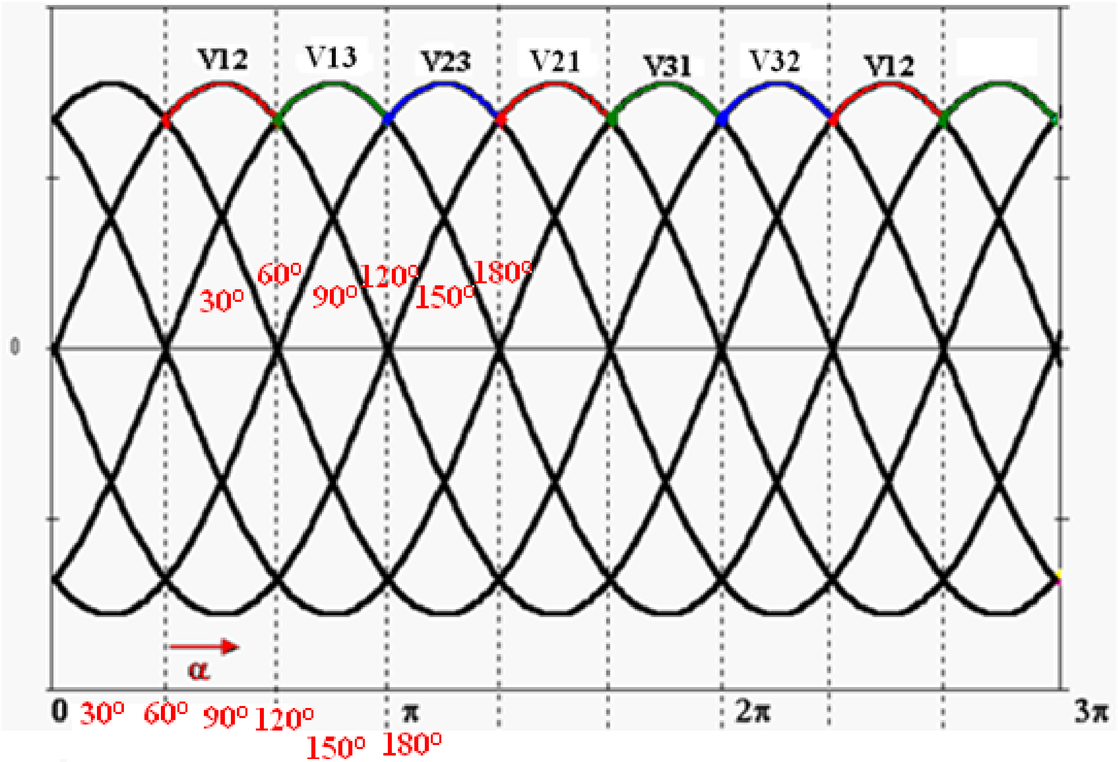
$$\boxed{V_{Lef} = V_o\sqrt{\frac{18}{3}+\frac{9}{2\pi}\mathrm{sen}\left(\frac{2\pi}{3}+2\alpha\right)}}$$

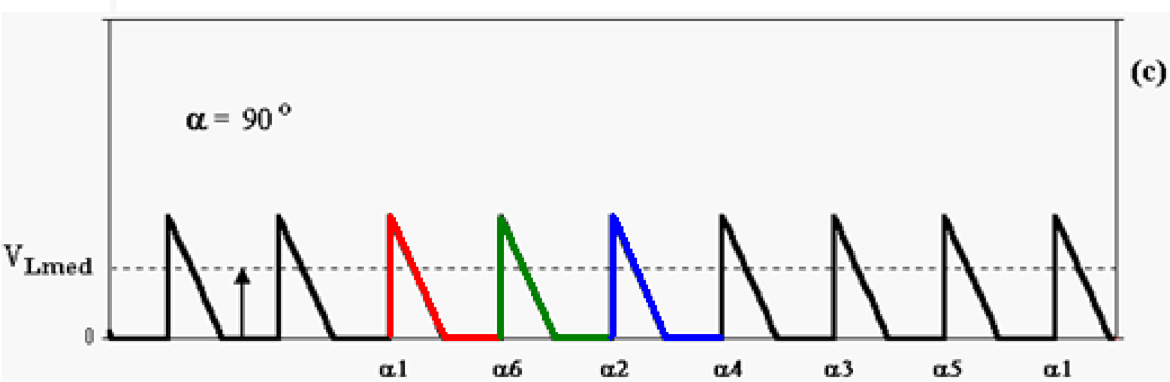
Retificador Trifásico Ponte de Graez com Tiristor, Carga R

FORMAS DE ONDAS – Modo de Condução Descontínua ($\pi/3 < \alpha < 2\pi/3$)

Ângulo de disparo $\alpha = 90°$







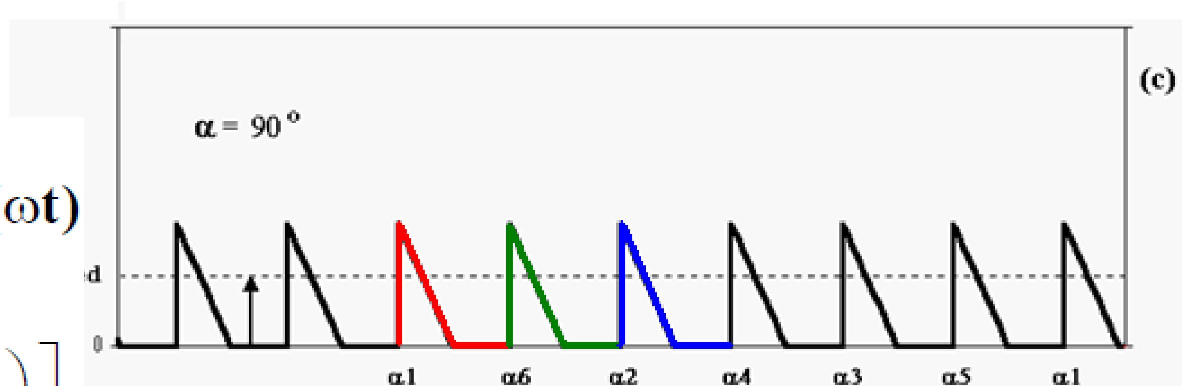
Retificador Trifásico Ponte de Graez com Tiristor, Carga R

TENSÃO NA CARGA – Condução Descontínua ($\pi/3 < \alpha < 2\pi/3$)

MÉDIO

$$V_{Lmed} = \frac{6}{2\pi} \int_{\frac{\pi}{3}+\alpha}^{\pi} \sqrt{2}\, V_{OL}\, \mathrm{sen}(\omega t)\, d(\omega t)$$

$$V_{Lmed} = 2{,}34\, V_{OL} \left[1 + \cos\left(\frac{\pi}{3} + \alpha \right) \right]$$



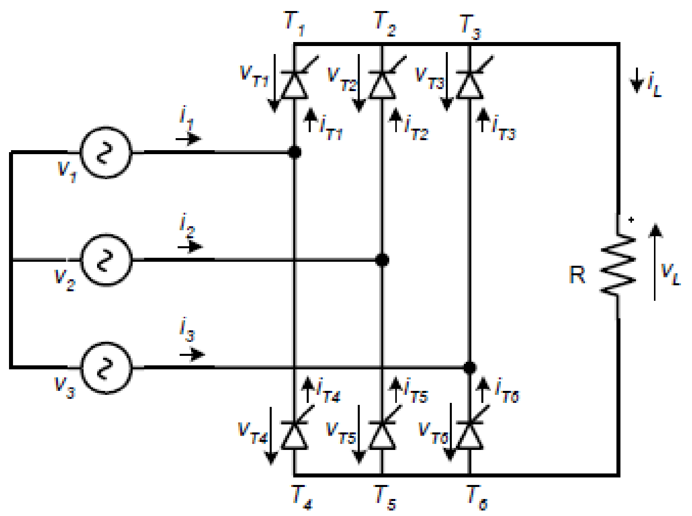
EFICAZ

$$V_{Lef} = \sqrt{\frac{1}{2\pi/6} \int_{\frac{\pi}{3}+\alpha}^{\pi} \left[\sqrt{2}\sqrt{3} V_o\, \mathrm{sen}(\omega t) \right]^2 d(\omega t)}$$

COMPORTAMENTO DA TENSÃO MÉDIA NA CARGA

Retificador Trifásico Ponte de Graez com Tiristor, Carga R

Corrente na carga



Médio

$$\boxed{I_{Lmed} = \frac{V_{Lmed}}{R}}$$

Eficaz

$$\boxed{I_{Lef} = \frac{V_{Lef}}{R}}$$

Corrente na entrada (em cada fase)

Médio

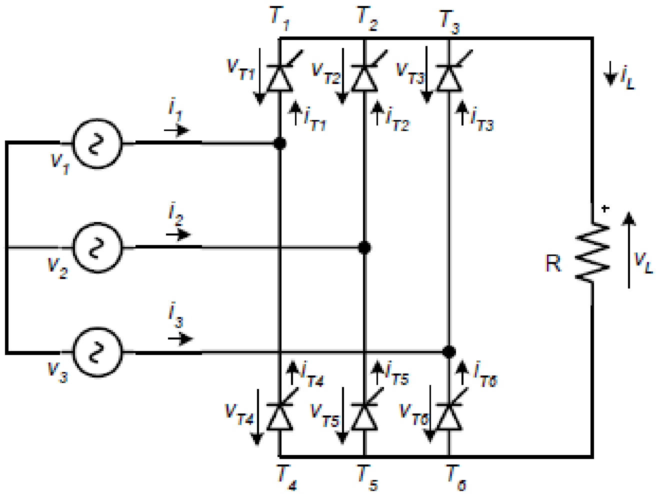
$$\boxed{I_{1med} = 0}$$

Eficaz

$$\boxed{I_{1ef} = \sqrt{\frac{2}{3}} I_{Lef}}$$

Retificador Trifásico Ponte de Graez com Tiristor, Carga R

Esforços nos tiristores



Tensão direta e reversa

$$\boxed{V_{T\max} = \sqrt{3}\sqrt{2}V_o}$$

Corrente de pico

$$\boxed{I_{T\max} = \sqrt{2}\sqrt{3}\frac{V_o}{R}}$$

Corrente média

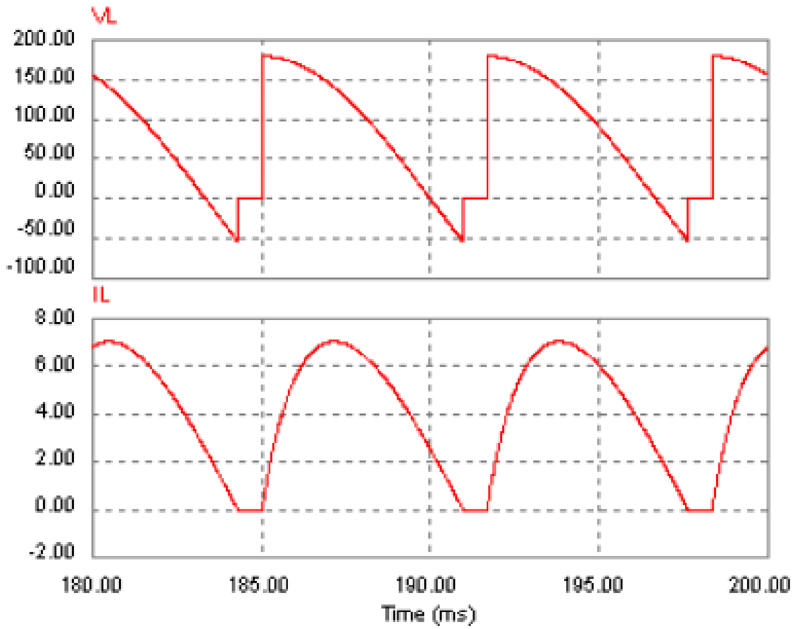
$$\boxed{I_{Tmed} = \frac{I_{1med}}{3}}$$

Corrente eficaz

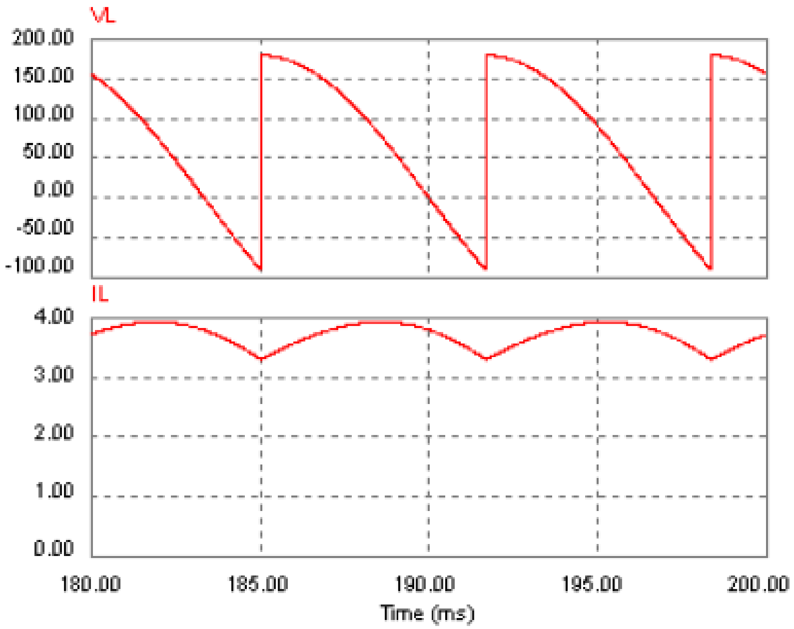
$$\boxed{I_{Tef} = \frac{I_{1ef}}{\sqrt{3}}}$$

Modos de condução

1) Condução descontínua



2) Condução contínua



Retificador Trifásico Ponte de Graez com Tiristor, Carga RL

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$$\cos\phi = \frac{R}{\sqrt{R^2 + \omega^2 L^2}}$$

Ábaco de Puschlowski

$\alpha_1 = \alpha + 60^o$

Ângulo crítico

$\beta_c = 60^o + \alpha_1$

$$\beta_c = \frac{2\pi}{m} + \alpha_1$$

Nº de pulsos	$\beta_{crítico}$
1	$\beta_c = 2\pi + \alpha_1$
2	$\beta_c = \pi + \alpha_1$
3	$\beta_c = \frac{2\pi}{3} + \alpha_1$
6	$\beta_c = \frac{2\pi}{6} + \alpha_1$

Exemplo:

$\alpha=30^o$

$\alpha_1=90^o$

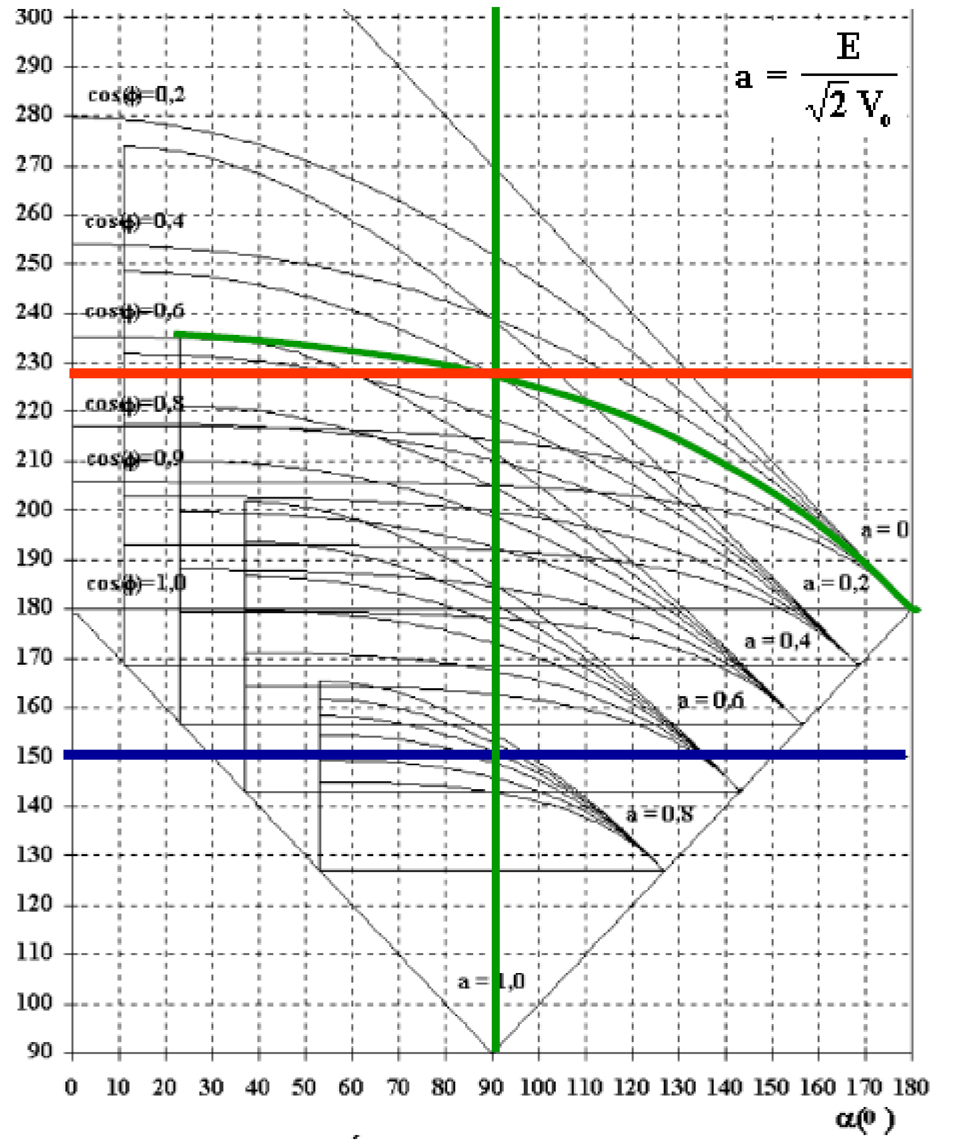
$\cos\phi=0.6$

$a=0$

$\beta_c=150^o$

Resultado:

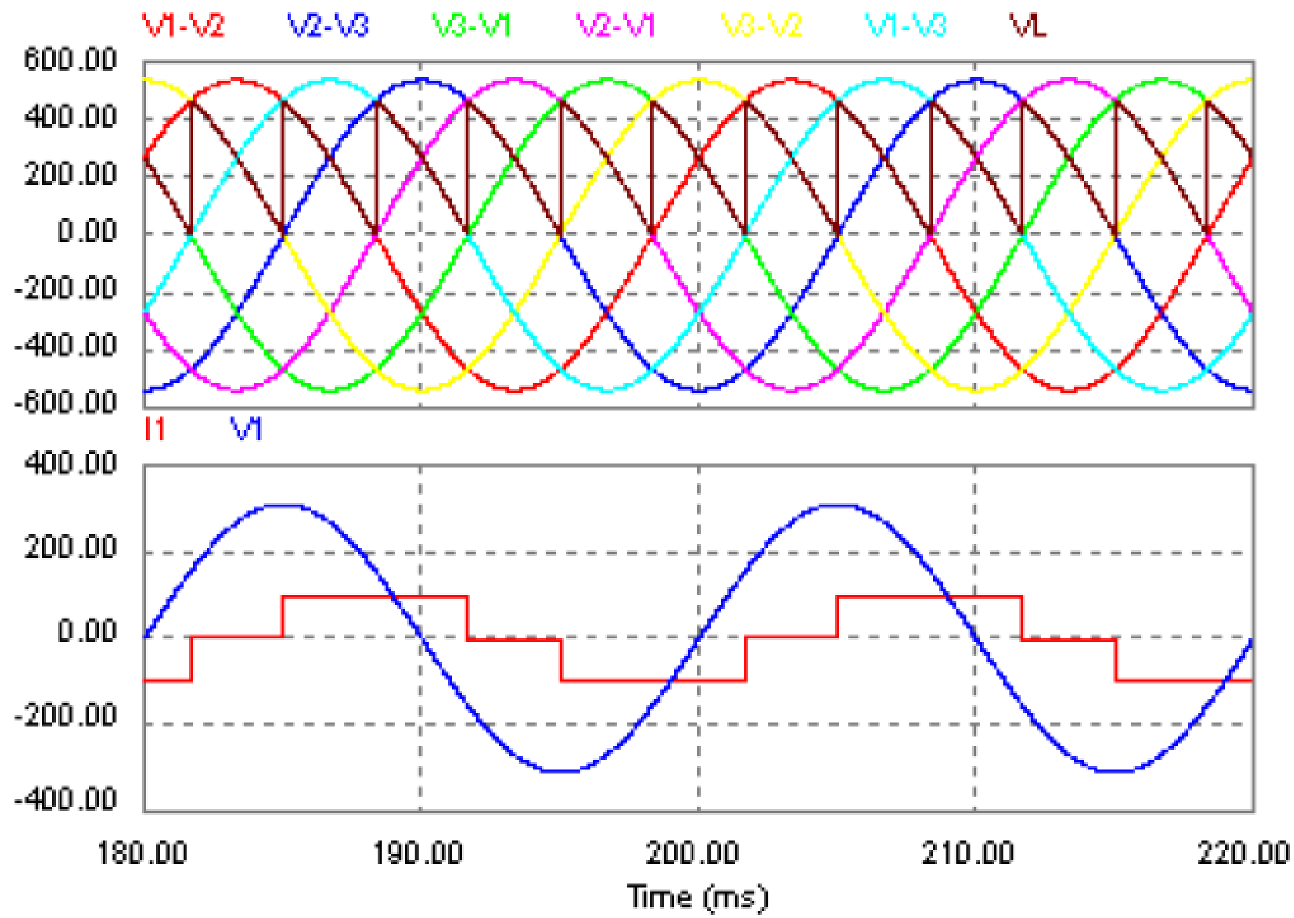
$\beta = 228^\circ$ (condução contínua)

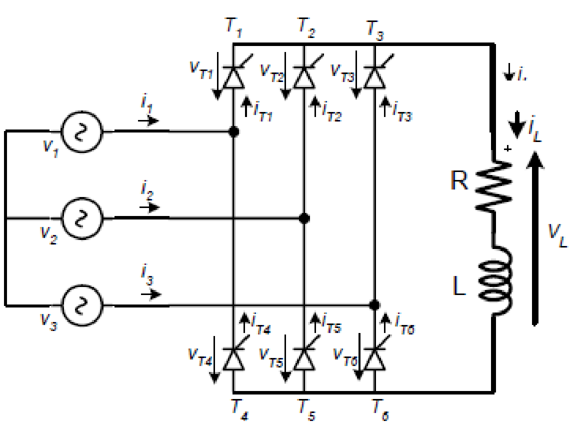


Retificador Trifásico Ponte de Graez com Tiristor, Carga RL

Formas de onda → condução contínua

I_L=100A
V_o=380V_{ef}(linha)
f=50Hz
α=60º

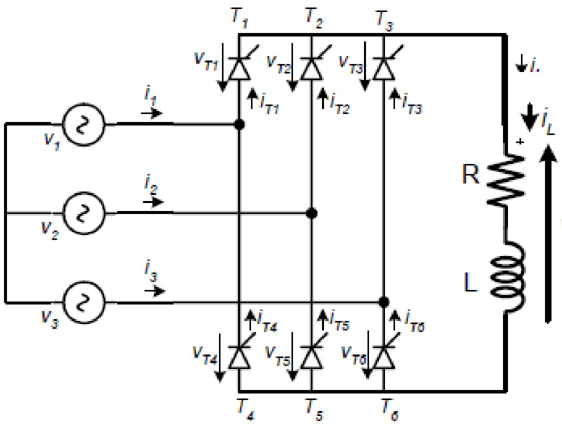


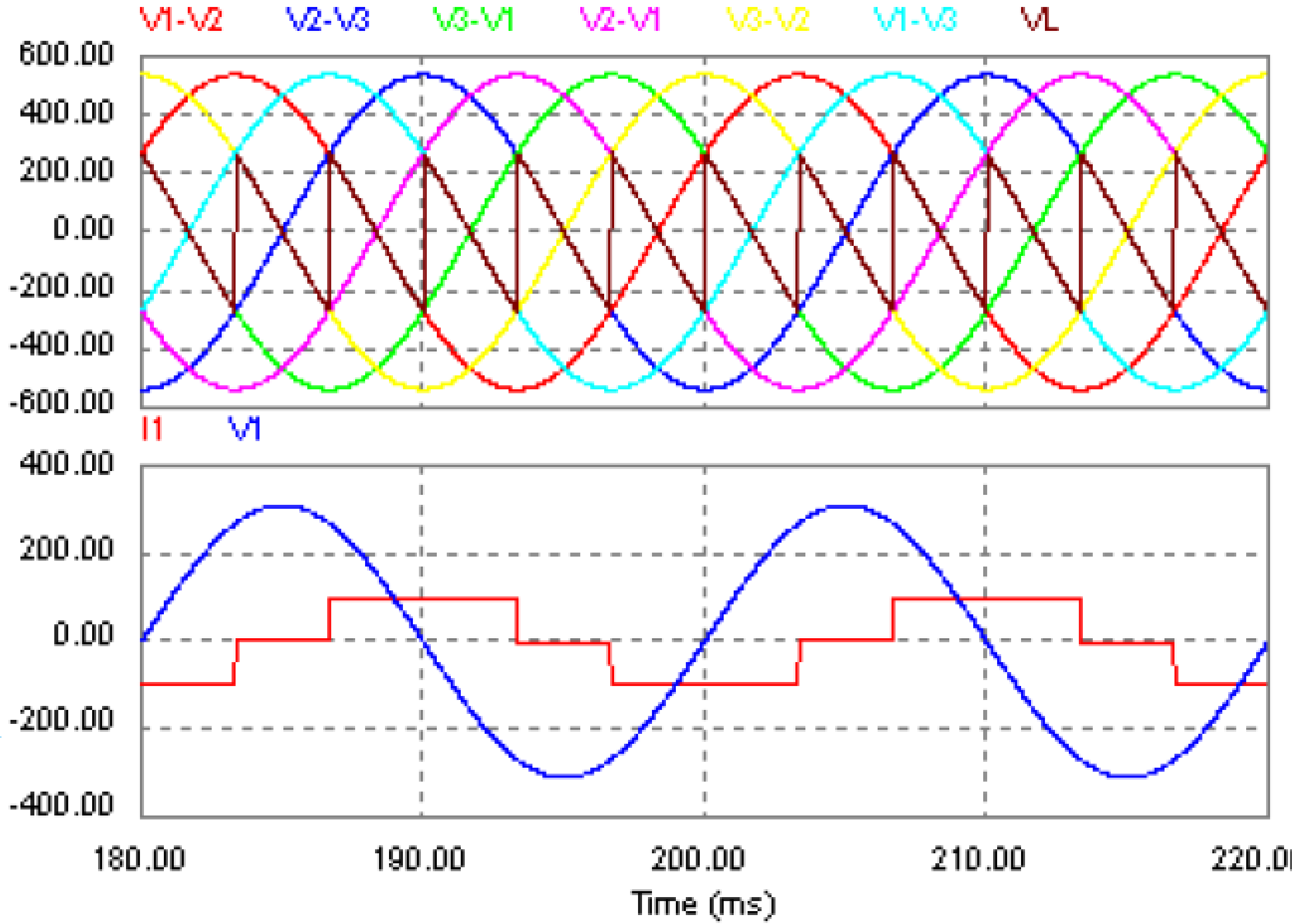


Retificador Trifásico Ponte de Graez com Tiristor, Carga RL

Formas de onda → condução contínua

I_L=100A
Vo=380V_{ef}(linha)
f=50Hz
α=90°

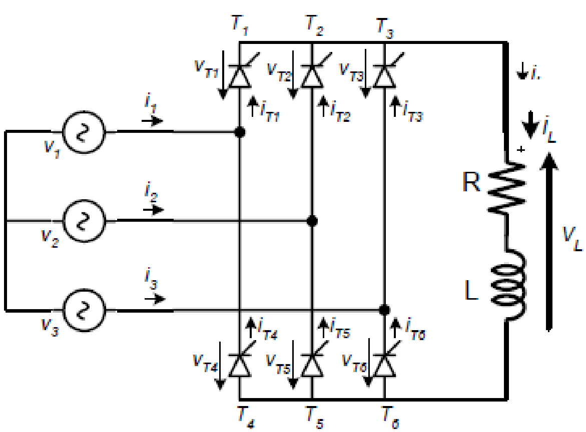


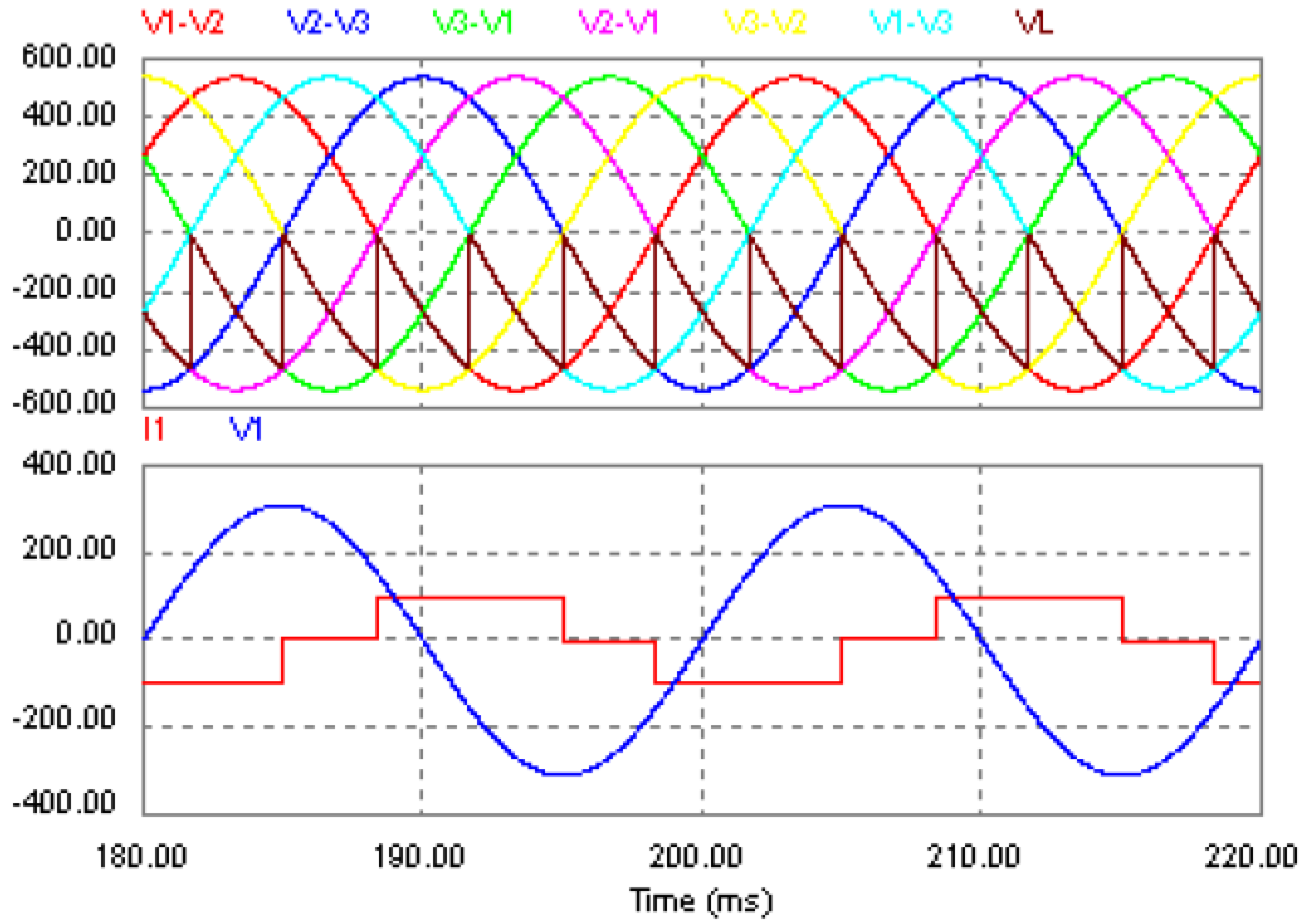


Retificador Trifásico Ponte de Graez com Tiristor, Carga RL

Formas de onda → condução contínua

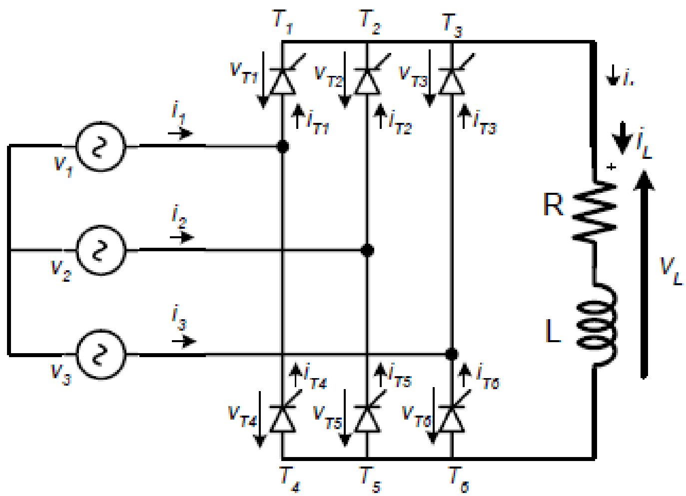
I_L=100A
Vo=380V_{ef}(linha)
f=50Hz
α=120°





Retificador Trifásico Ponte de Graez com Tiristor, Carga RL

Tensão na carga



Médio

$$V_{Lmed} = \frac{1}{2\pi/6} \int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}+\alpha} \sqrt{2}\sqrt{3}V_o \operatorname{sen}(\omega t)\, d(\omega t)$$

$$\boxed{V_{Lmed} \cong 2.34 V_o \cos(\alpha)}$$

Eficaz

$$V_{Lef} = \sqrt{\frac{1}{2\pi/6} \int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}+\alpha} \left[\sqrt{2}\sqrt{3}V_o \operatorname{sen}(\omega t)\right]^2 d(\omega t)}$$

$$\boxed{V_{Lef} = V_o \sqrt{3 + \frac{9}{2\pi}\left[\operatorname{sen}\left(\frac{2\pi}{3}+2\alpha\right) - \operatorname{sen}\left(\frac{4\pi}{3}+2\alpha\right)\right]}}$$

Retificador Trifásico Ponte de Graez com Tiristor Carga Indutiva (RL)

$$0 \leq \alpha < \frac{\pi}{2} \Rightarrow V_{Lmed} > 0$$

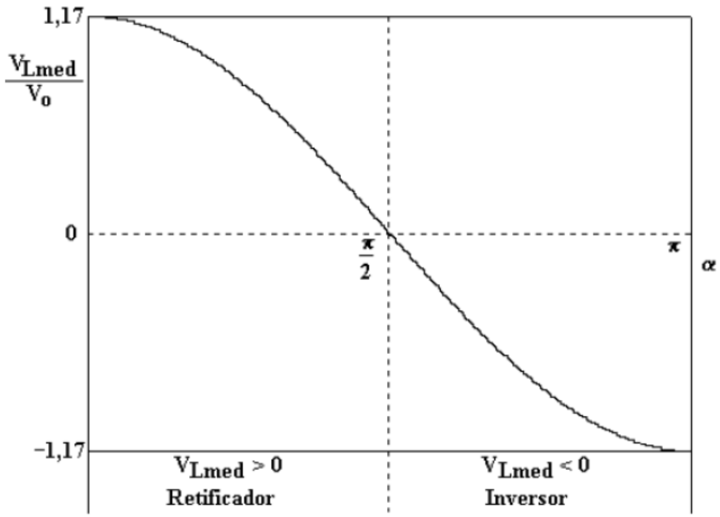
-Operação como retificador;

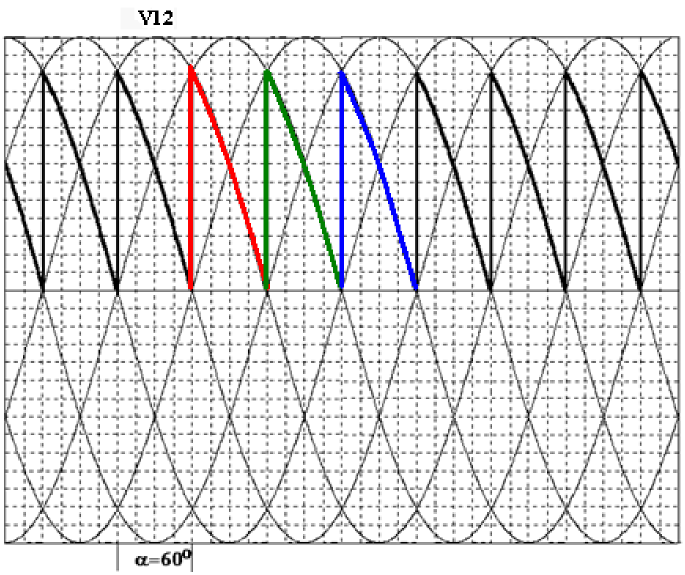
$$\frac{\pi}{2} < \alpha \leq \pi \Rightarrow V_{Lmed} < 0$$

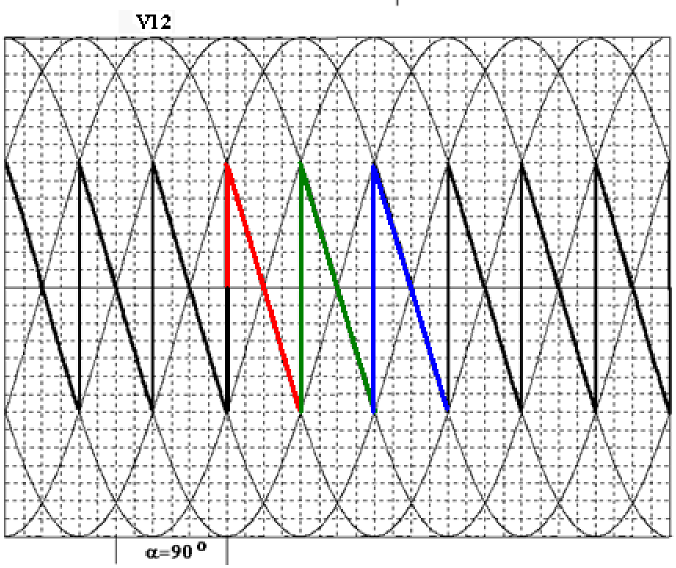
-Operação como inversor não-autônomo

$$\alpha = \frac{\pi}{2} \Rightarrow V_{Lmed} = 0$$

Tensão média na carga





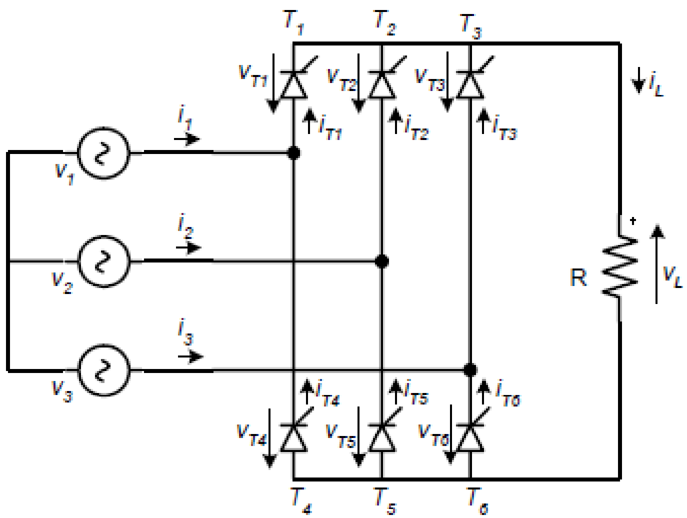


Retificador Trifásico Ponte de Graez com Tiristor, Carga RL

Corrente na carga

Médio

$$I_{Lmed} = \frac{V_{Lmed}}{R}$$



Eficaz

$$I_{Lef} = I_{Lmed}$$

Corrente na entrada (em cada fase)

Médio

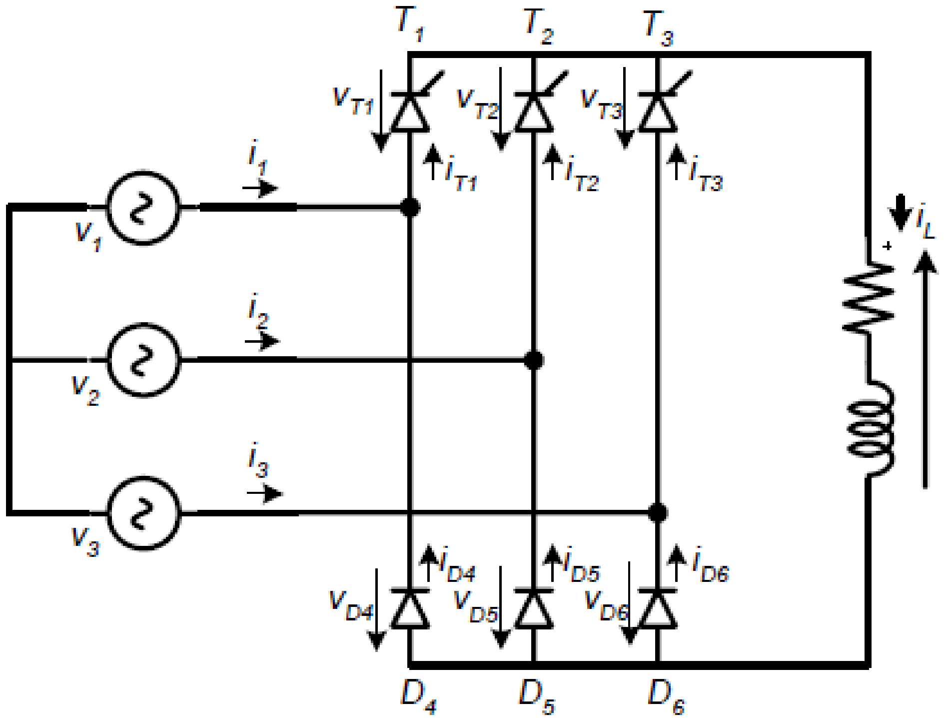
$$I_{1med} = 0$$

Eficaz

$$I_{1ef} = \sqrt{\frac{2}{3}} I_{Lef}$$

Retificador Trifásico Semicontrolado, Carga RL

TOPOLOGIA

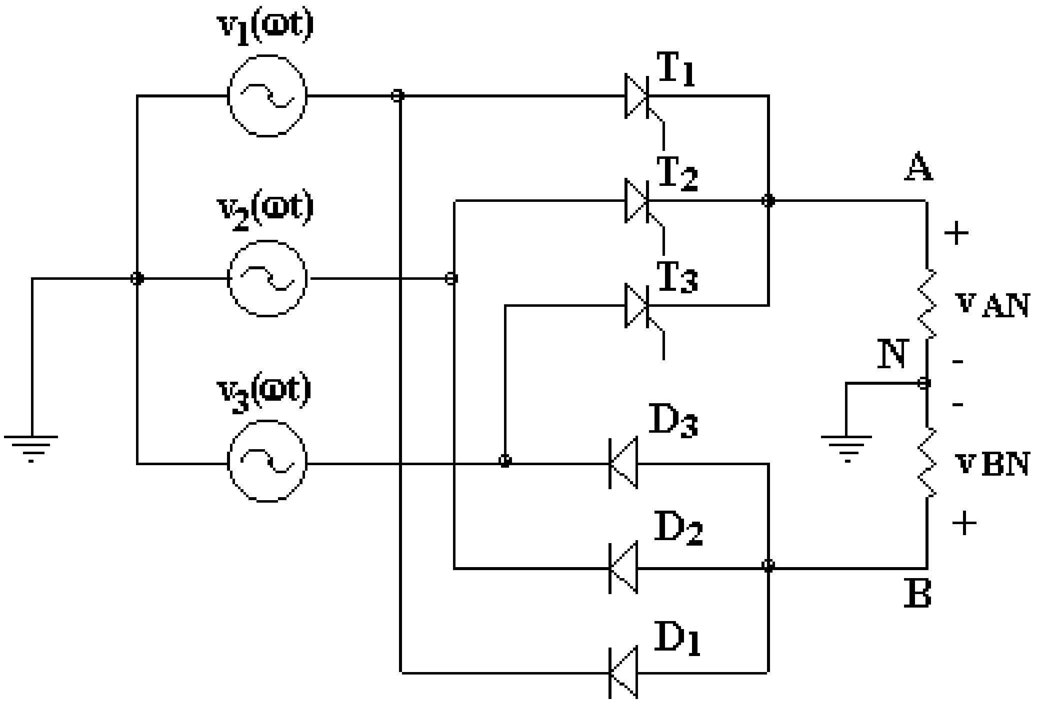


O ângulo α é contado a partir do ponto da interceptação de duas tensões da fonte, e não do cruzamento por zero

Retificador Trifásico Semicontrolado, Carga RL

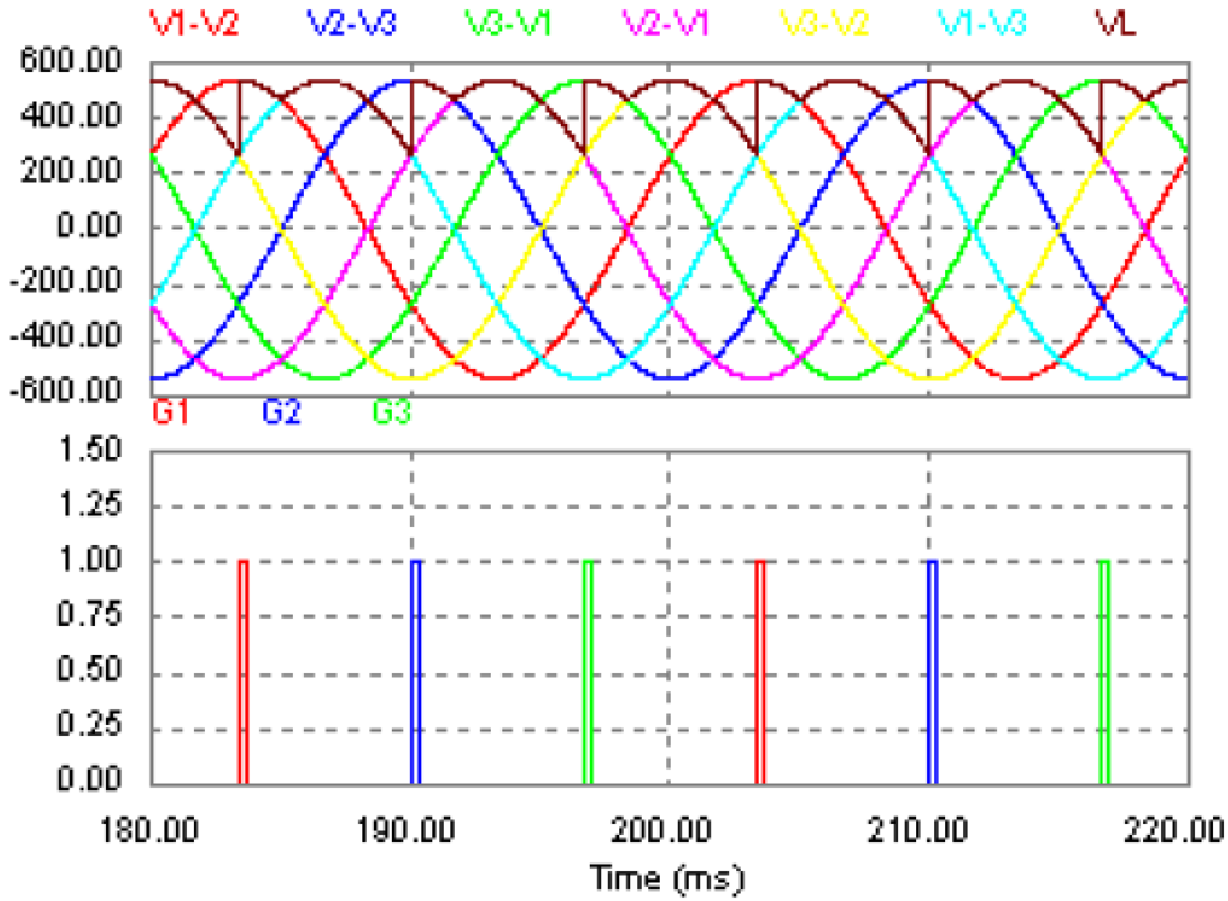
PRINCIPAIS CARACTERÍSTICAS:

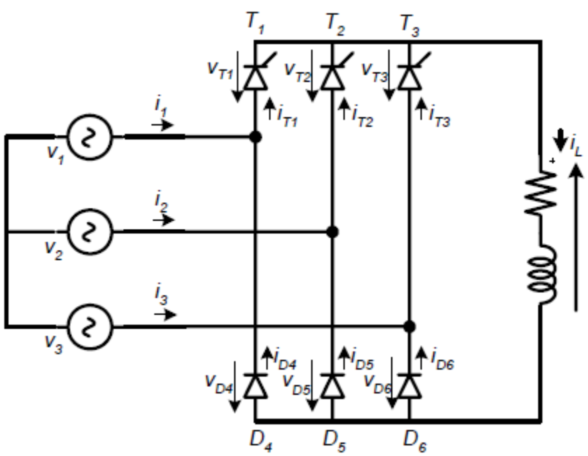
- Operação somente em um quadrante (retificadores);
- Circuitos de comandos mais simples;
- Emprego de apenas 3 tiristores.



Formas de onda → condução contínua

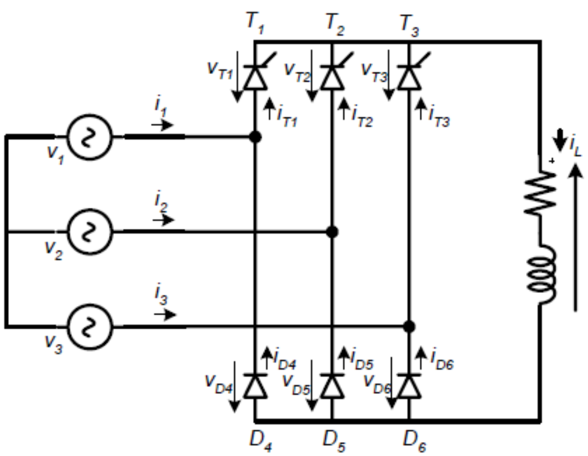
I_L=100A
Vo=380V_{ef}(linha)
f=50Hz
α=30°

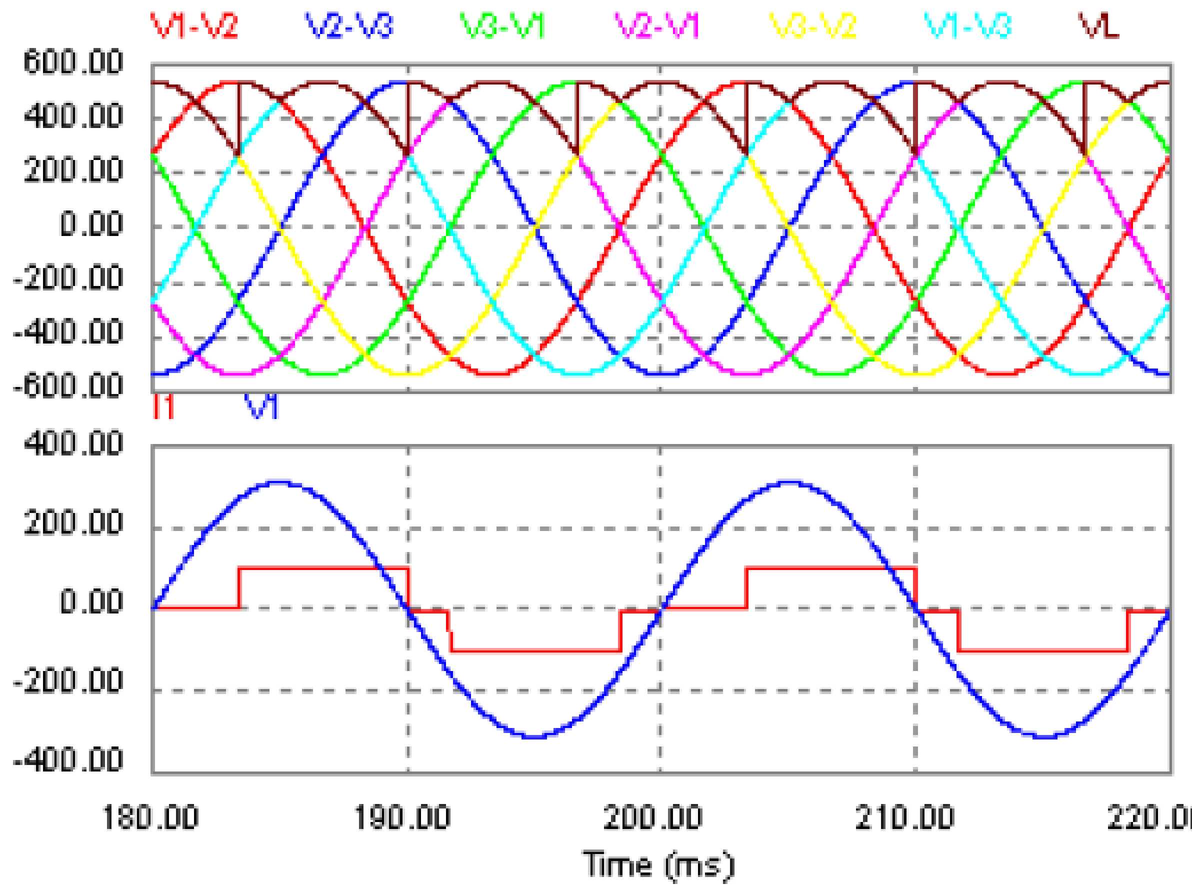




Formas de onda → condução contínua

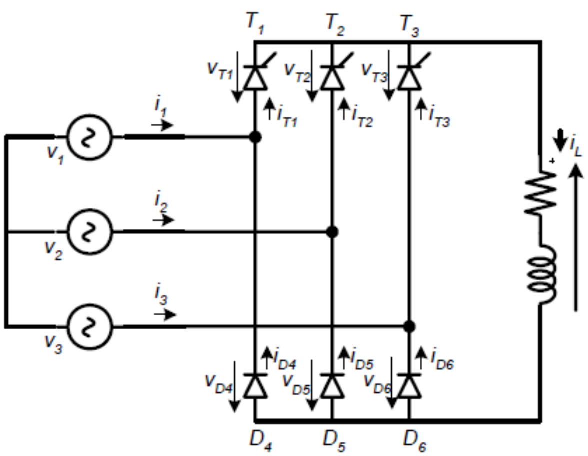
I_L=100A
Vo=380V_{ef}(linha)
f=50Hz
α=30º

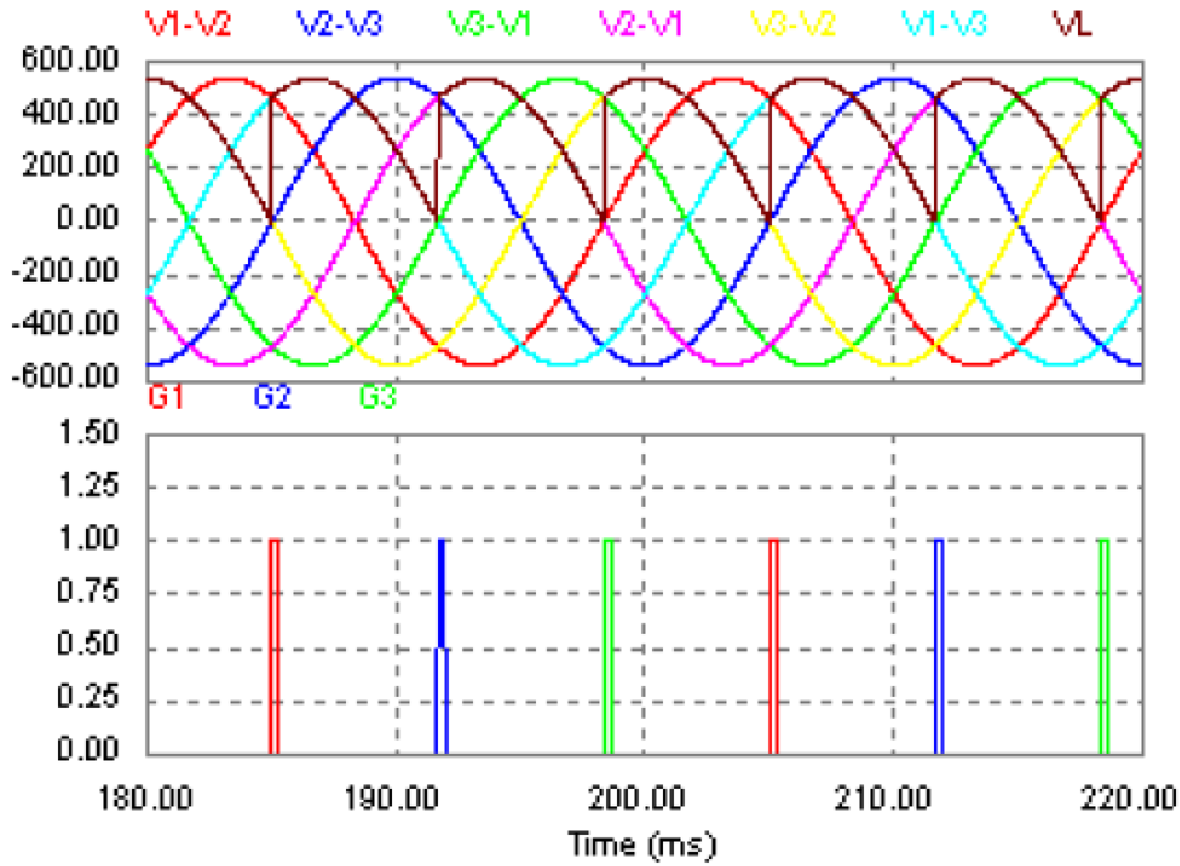




Formas de onda → condução contínua

I_L=100A
Vo=380V_{ef}(linha)
f=50Hz
α=60°

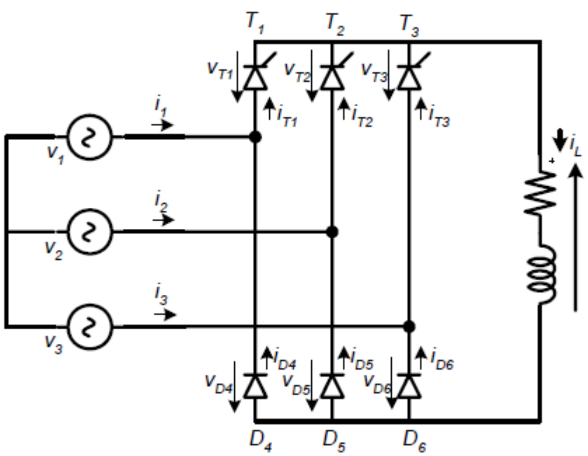


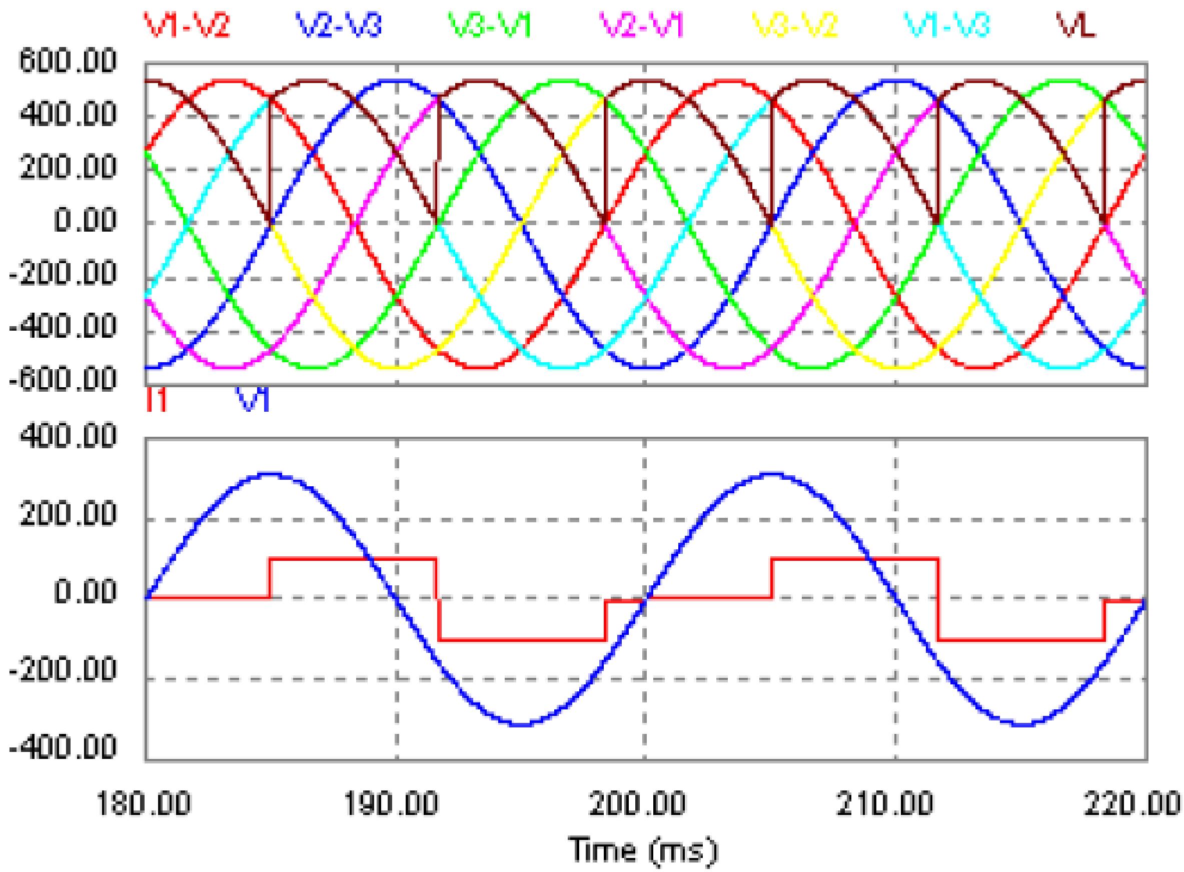


Retificador Trifásico Semicontrolado, Carga RL

Formas de onda → condução contínua

I_L=100A
Vo=380V_{ef}(linha)
f=50Hz
α=60°

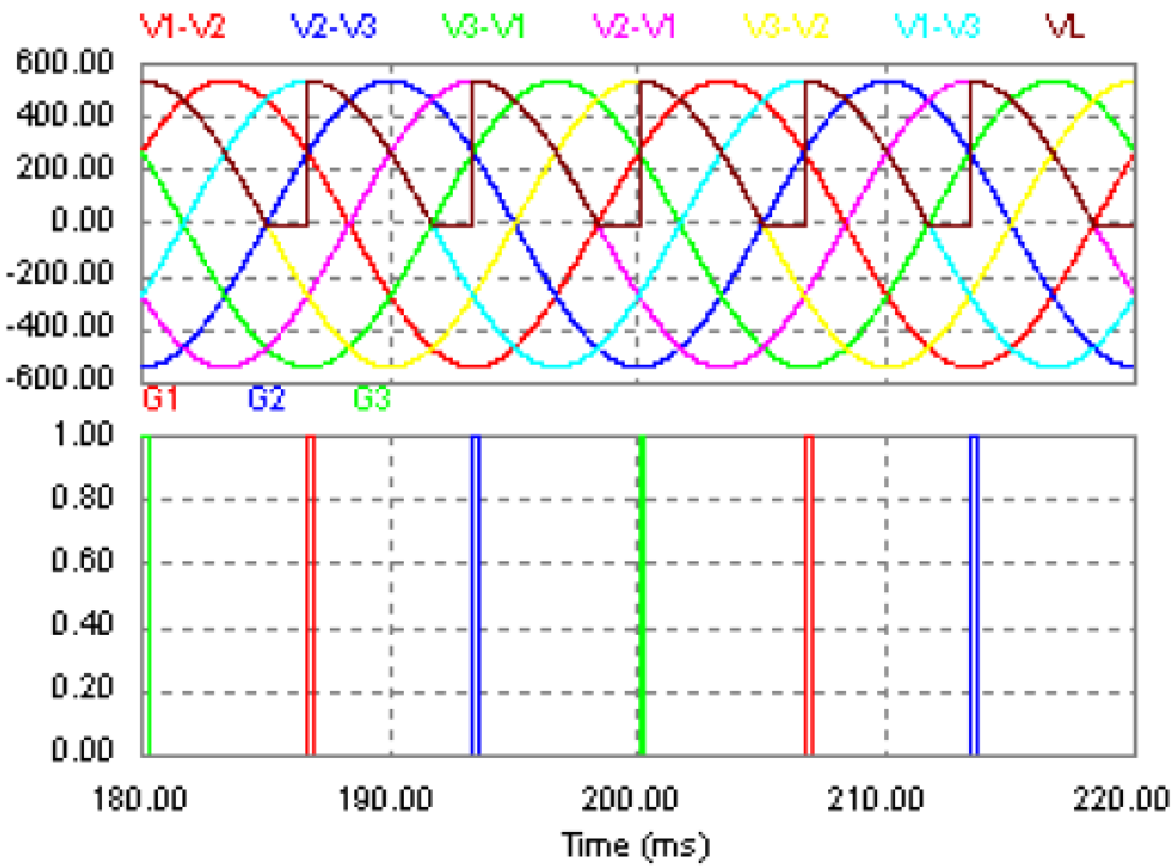


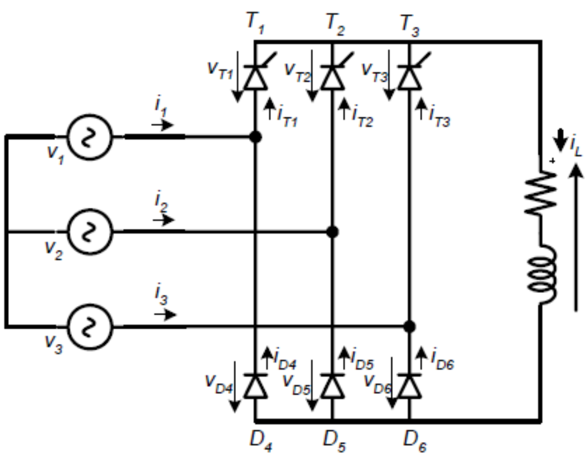


Retificador Trifásico Semicontrolado, Carga RL

Formas de onda → condução contínua

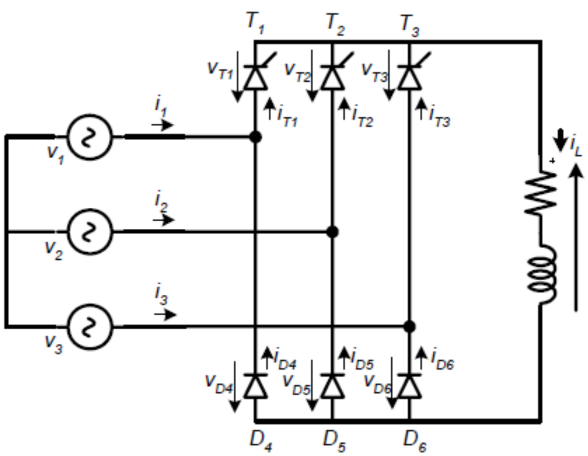
I_L=100A
Vo=380V_{ef}(linha)
f=50Hz
α=90°

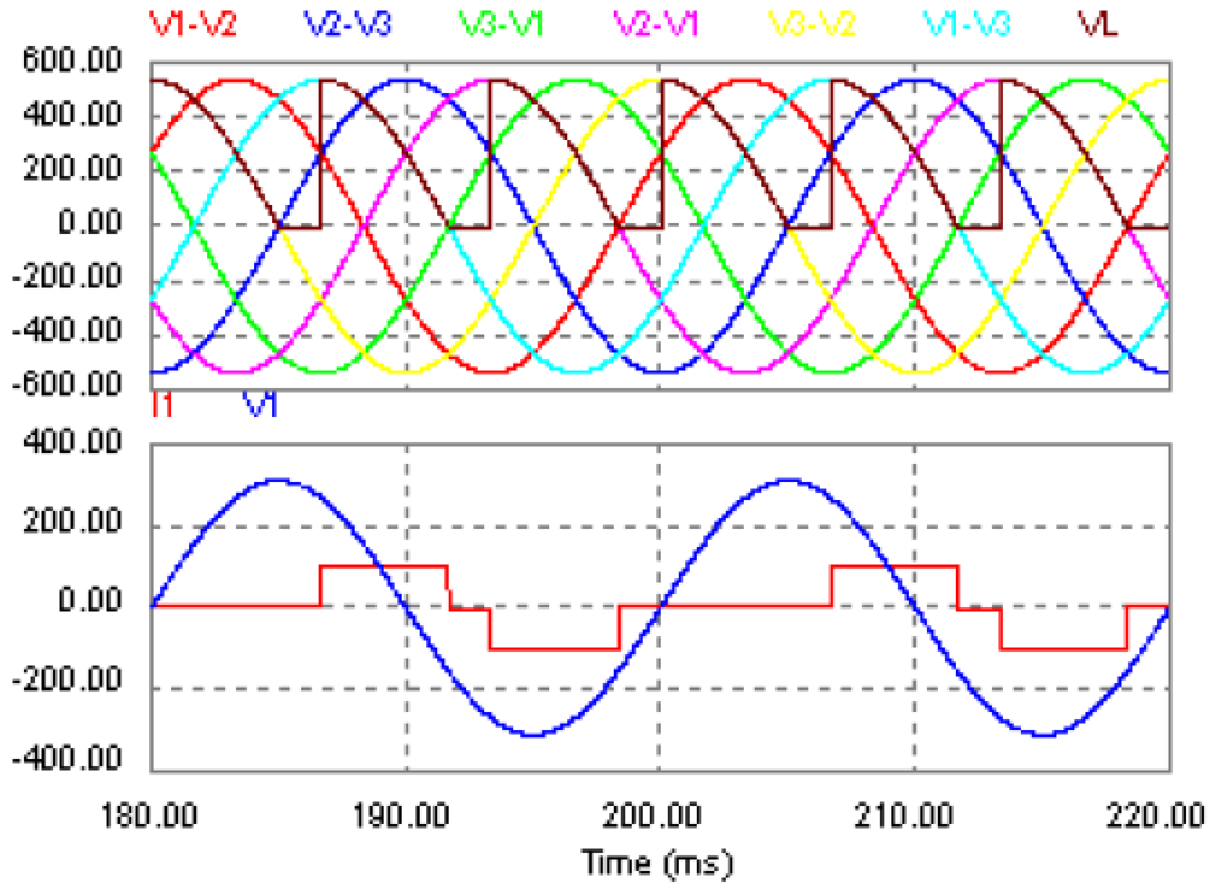




Formas de onda → condução contínua

I_L=100A
Vo=380V_{ef}(linha)
f=50Hz
α=90º





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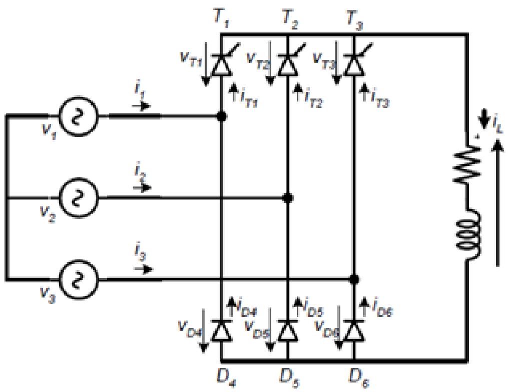
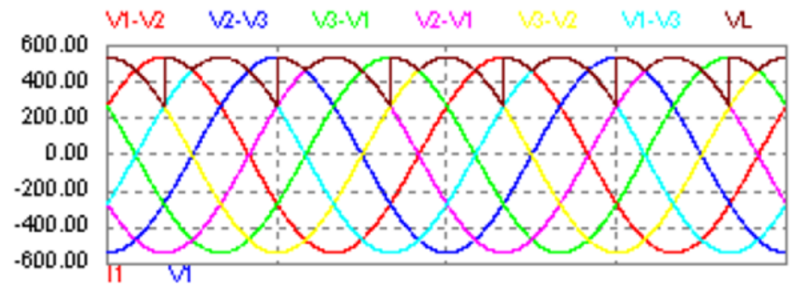
Retificador Trifásico Semicontrolado, Carga RL

Tensão na carga



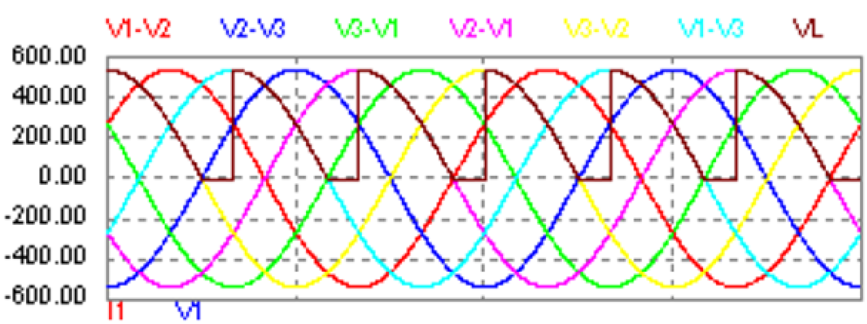
Médio

Para α < 60°



$$V_{LMED} = \frac{3}{2\pi}\int_{\frac{\pi}{3}+\alpha}^{\frac{2\pi}{3}} \sqrt{2}V_{OL}.sen(\omega t).d\omega t + \frac{3}{2\pi}\int_{\frac{\pi}{3}}^{\frac{2\pi}{3}+\alpha} \sqrt{2}V_{OL}.sen(\omega t).d\omega t$$

Para α > 60°

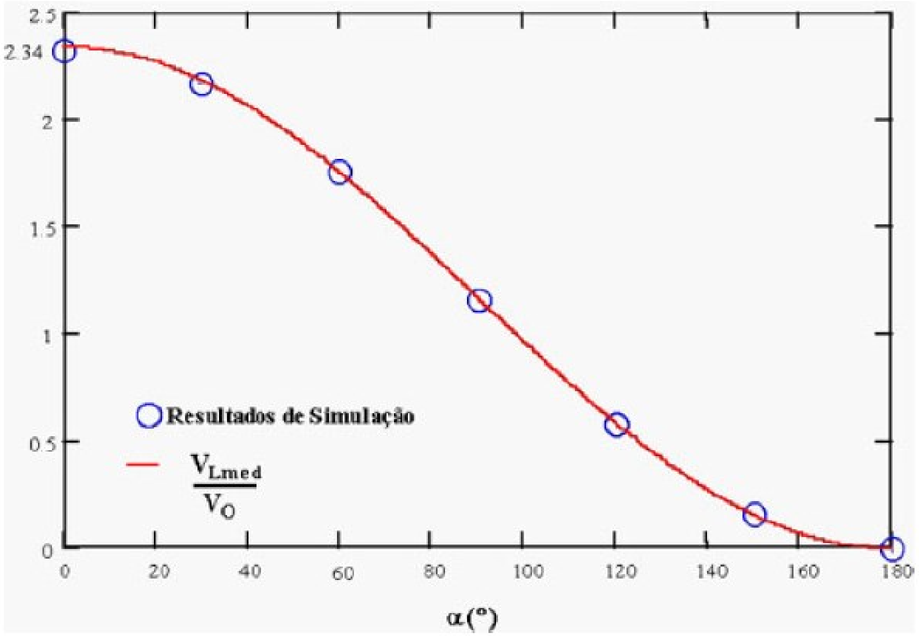


$$V_{LMED} = \frac{3}{2\pi}\int_{\alpha}^{\pi} \sqrt{2}V_{OL}.sen(\omega t).d\omega t$$

$$V_{LMED} = 0{,}675.V_{OL}\left[1+\cos(\alpha)\right]$$

Retificador Trifásico Ponte Mista com Tiristor

Tensão média na carga



É comum o emprego de um diodo de circulação em paralelo com a carga. Com isto diminuem-se as correntes nos tiristores.