POWER FACTOR OF LINE-COMMUTATED GRAETZ CONVERTERS BY CONSIDERING THE COMMUTATION EFFECT

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ABSTRACT - The alternating current (AC) of line commutated converters is non-sinusoidal, generating, therefore, harmonics in the electric system.

Six-pulse Graetz line-commutated converters are widely employed in industry. Twelve-pulse converter can be achieved by associating two six-pulse converters in series or in parallel. However it is necessary to use phase shift transformers. These transformers are connected in such a way that the secondary voltage phase angles are displaced thirty degrees in relation to each other. Lower order characteristic harmonics are eliminated in this case (5°, 7°), rendering these transformers as adequate for the proposed application.

A very good harmonic mitigation can be obtained when 24 or 48 - pulse multiconverters are employed, by associating four or eight Graetz six - pulse converters, respectively. When the converter pulse number is increased there will be also, a system power factor improvement. The commutation effect has influence in the converter power factor, decreasing it in the operation of the bridge as rectifier and increasing it in the operation of the the bridge as inverter, as will be presented in the paper. Experimental results will be presented and discussed.

KEYWORDS

Converter power factor; Commutation; Harmonics.

I. INTRODUCTION

Special transformers delta zig-zag (-15°, 0°, 15°, 30°) or star extended - delta ± (15°) should be used to obtain 15° displacement to achieve 24-pulse multiconverter. In the case of 48-pulse multiconverter, 7.5° displacement is needed and the special transformers mentioned should be designed to obtain the necessary secondary voltage angular displacement. A recent application of these transformers in multiconverter systems is, for instance, in multi-level 48-pulse inverters, to be employed in Static Var Generation (SVG [17]) and in 24-pulse inverters to be used in Adjustable Speed Drives (ASD). These ASD offer significant advantages in fan, pump and process control applications, in terms of high efficiencies and high performance, with major reliability in critical process areas, such as petroleum pumping [18].

The converter power factor will be determined taking into account the influence of the commutation. This effect will provide a reducing in the magnitude of the harmonic currents, because considering the commutation, the AC side current is more approximate of a sinusoidal one. However, the commutation is not responsible by harmonic elimination, being only responsible by harmonic attenuation.

A Matlab routine has been developed for obtaining the converter power factor , taking into account the influence of the commutation effect, as follows.

II - CONVERTER POWER FACTOR

The converter power factor is given by :

$$Pf = \left(\frac{I_1}{I}\right)\cos\phi_1 \tag{1}$$

$$\delta = \alpha + \mu \tag{2}$$

Where:
Pf ⇒ Converter power factor
I_1 ⇒ Rms value of the fundamental phase current
I ⇒ Rms value of the phase current
ϕ_1 ⇒ Phase angle of the fundamental current I_1

Considering the commutation effect, we have [2], [8]:

$$tg\phi_1 = \frac{2\mu + sin2\alpha - sin2\delta}{\cos 2\alpha - \cos 2\delta} \tag{3}$$

Where:
ϕ_1 ⇒Phase angle of the fundamental current
μ ⇒Commutation angle in rad
α ⇒Firing angle
δ ⇒ Auxiliary angle

Neglecting the commutation effect the following relationship can be obtained:

$$\phi_1 = \alpha \tag{4}$$

Also neglecting the commutation effect [8]:

$$I_1 = \frac{\sqrt{6}}{\pi} I_d m \quad (5)$$

Where:
$I_d \Rightarrow$ DC side current
m $\Rightarrow$ Number of bridges connected in series

$$I_n = \frac{I_1}{n} \quad (6)$$

$I_n \Rightarrow$ Rms value of the harmonic current, order n
n $\Rightarrow$ Harmonic order

III - HARMONIC REDUCING BY THE COMMUTATION EFFECT

The commutation is a factor of harmonic reducing. The following expressions allow one to calculated the Harmonic Reduction Factor (HRF) [7].

$$H = \left[\frac{sin(n+1)\mu/2}{n+1} \right] \quad (7)$$

$$K = \left[\frac{sin(n-1)\mu/2}{n-1} \right] \quad (8)$$

$$\frac{I_n}{I_{n0}} = \frac{\sqrt{H^2 + K^2 - 2HK\cos(2\alpha + \mu)}}{(\cos\alpha - \cos\delta)}$$
(9)

Where:
I_{n0} - Rms value of the order n harmonic Current, for the commutation angle $\mu = 0°$.

The expression (9) is not valid for n=1, and according to [2].

$$H_1 = \cos 2\alpha - \cos 2\delta \quad (10)$$

$$K_1 = \sin 2\delta - \sin 2\alpha - 2\mu \quad (11)$$

$$\frac{I_1}{I_{10}} = \frac{\sqrt{H_1^{\ 2} + K_1^{\ 2}}}{4(\cos\alpha - \cos\delta)} \quad (12)$$

Where:
$I_{10} \Rightarrow$ Rms value of the fundamental current for the commutation angle $\mu = 0°$.

IV - POWER FACTOR IMPROVEMENT BY THE CONVERTER PULSE NUMBER INCREASING

Neglecting the commutation effect, we have:

$$Pf = \left(\frac{I_1}{I} \right) \cos\alpha \quad (13)$$

According to expression (6) :

$$I = \sqrt{\sum_{n=1}^{\infty} \left(\frac{I_1}{n} \right)^2} \quad (14)$$

So, for six-pulse operation, one has: (k=0,1,2,3…)
$n=6k \pm 1$ (1,5,7,11,13,...)
$Pf_{6p}=0.9550\cos\alpha$ (15)

For twelve - pulse, the following result comes up:
$n = 12k \pm 1$ (1,11,13,23,25,...)
$Pf_{12p}=0.9901\cos\alpha$ (16)

For twenty four - pulse, yields:
$n = 24k \pm 1$ (1,23,25,47,49,...)
$Pf_{24p}=0.9978\cos\alpha$ (17)

For forty eight - pulse, results:
$n = 48k \pm 1$ (1,47,49,95,97,...)
$Pf_{48p}=0.9996\cos\alpha$ (18)

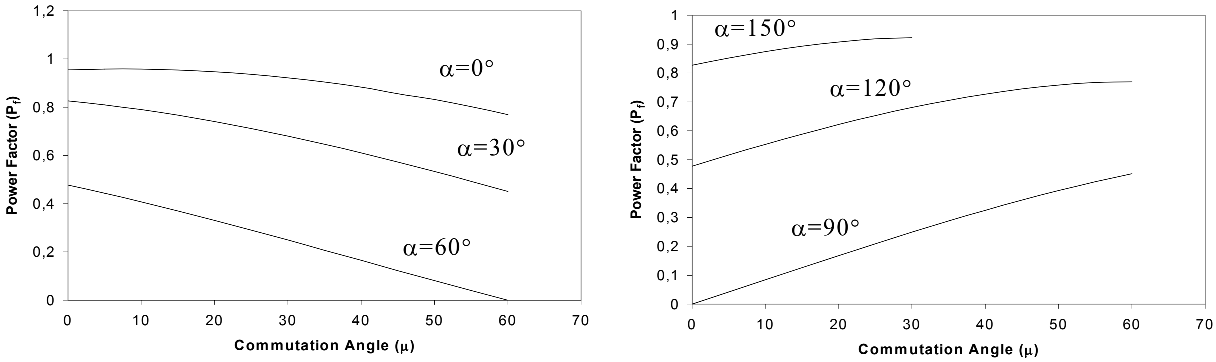
V – SIMULATION RESULTS

A Matlab routine has been developed for obtaining the converter power factor, taking into account the influence of the commutation effect. The input data are the firing angle α, the commutation angle μ and the converter number of pulses. A routine in MATLAB has been developed in order to able the determination of the converter power factor. This routine is presented in the Appendix 1. Also, using EXCEL, students of a graduated course CESE-2002 (Electrical Systems Engineering Course), given in UNIFEI- BRAZIL in 2002, have developed a simulation program, to determine the converter power factor, taking into account the commutation effect. The obtained results match with the ones using the MATLAB routines. The programs are, therefore, corrects.

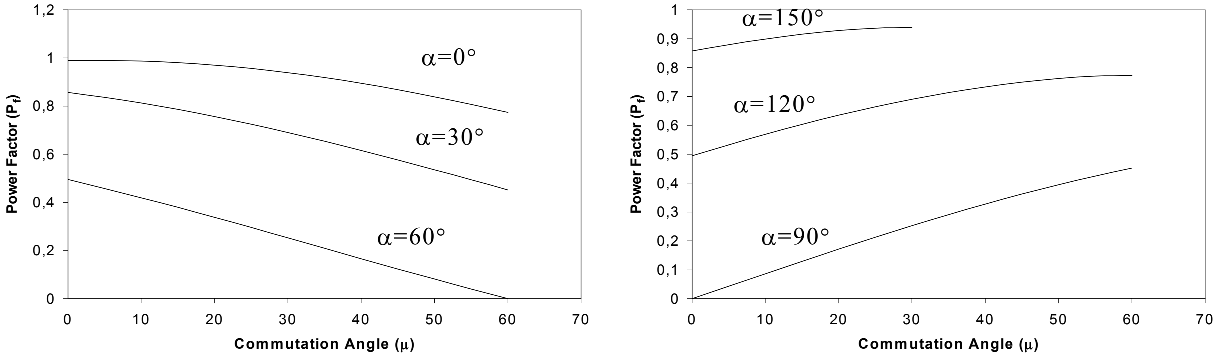
Using the programs and also with the deduction of an algebraic expression, we conclude that the converter power factor is equal zero for the firing angle α in degrees (90 - μ/2 – See Appendix 2). So, for the firing angle α lower of this value, the converter operates as rectifier, with DC output voltage positive, and for the firing angle α higher than this value, the operation of the bridge is as inverter, with DC output voltage negative.

The commutation angle μ has been considered until 60 degrees, maximum theoretical value for this angle. However, for firing angle α equal 150 degrees, the maximum theoretical commutation angle is 30 degrees, in order to have the commutation in the bridge. In practice, the commutation angle have to be lower, due to the necessity of having a commutation margin in the bridge. The obtained theoretical results are presented in figure 1, as follows.

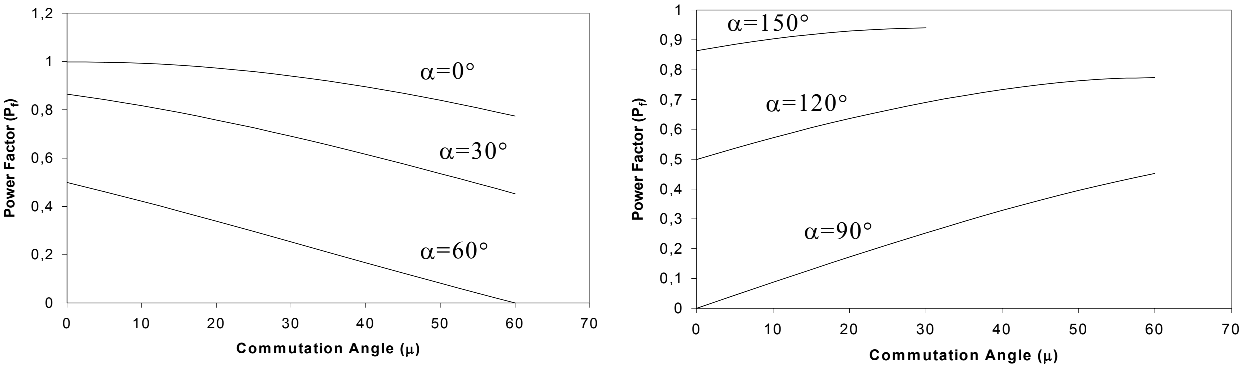
6 pulse



12 pulse



24 pulse



48 pulse

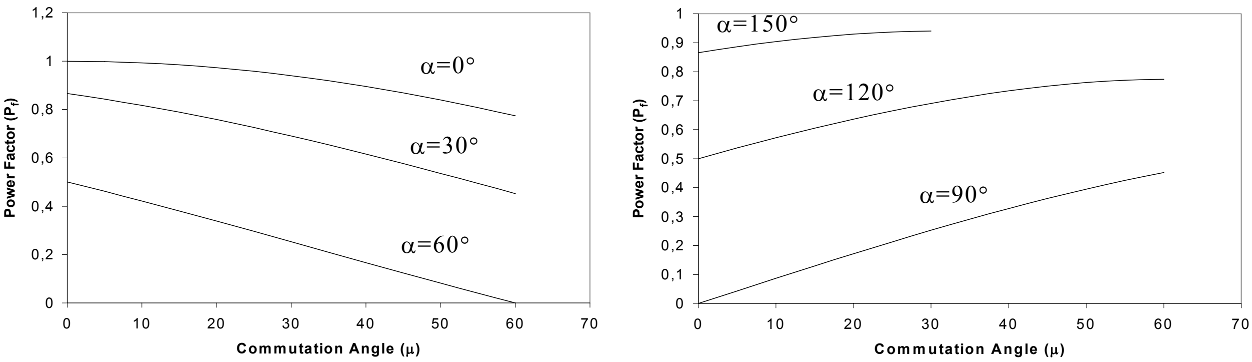


Figure 1: Converter power factors.

VI – EXPERIMENTAL RESULTS

A 6-12-24 pulse multiconverter using diode bridges in series configuration was implemented in laboratory, in order to compare the theoretical results of power factor of expressions (15, 16, 17, 18), with experimental ones. In this case of using diode bridges corresponding to α equal zero degrees, the commutation angle has been also neglected. A resistive load was connected separately to the DC side of the 6-12-24 pulse converter, considering in all cases, the DC output voltage equal 220[V] and the DC output current equal 1[A]. The used instrument to the power factor measurements was the VOLTECH PM 300 (Three phase-power analyser), able to application in circuits with non-sinusoidal current and voltage waveforms. The results are presented in the following expressions:

$$Pf_{6p}=0.9560 \quad (19)$$

$$Pf_{12p}=0.9920 \quad (20)$$

$$Pf_{24p}=0.9980 \quad (21)$$

For another loads, such as resistive-inductive ones, the results was almost the same, with no substantially differences. Figure 2 shows the experimental power factor measurement for 24-pulse operation.

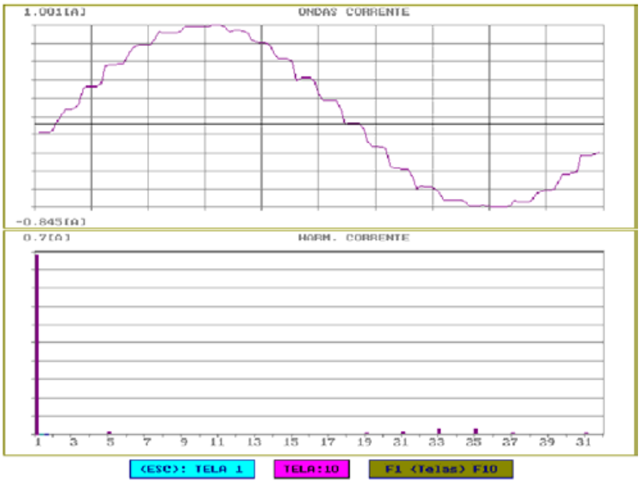


Figure 3: Experimental AC side phase A current and its harmonic spectrum (24 – pulse multiconverter).

VII – CONCLUSION

The commutation effect has influence in the converter power factor, decreasing it in the operation of the bridge as rectifier and increasing it in the operation of the the bridge as inverter. The firing angle α in degrees of transition of the converter operation of rectifier to inverter is equal (90 - μ/2 – See Appendix 2).

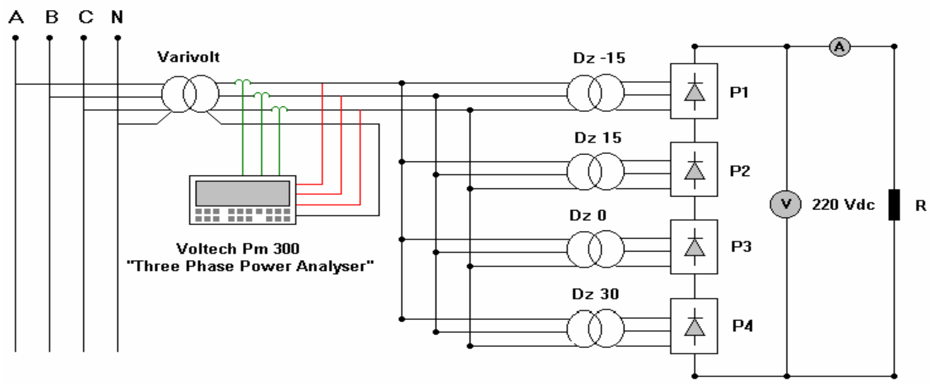


Figure 2: Experimental arrangement –24 pulse operation

Figure 3 shows the experimental qualitative aspect of the AC side phase A current, and its harmonic spectrum, for a 24-pulse multiconverter, using diode bridges.

There is a converter power factor improvement when the converter pulse number is increased, because the Harmonic Distortion Factor, I_1/I, increases.

The developed MATLAB converter power factor simulation program has presented good results which ones have been confirmed using another program, developed using the EXCEL. The commutation is only responsible by harmonic attenuation, but not by harmonic elimination. There is in fact a harmonic distortion factor increasing, but the converter power factor decreases for rectifier converter operation (α<90-μ/2), and increases for inverter operation (α>90-μ/2), because the phase angle ϕ_1 of the fundamental current increases (see expression 1).

Prototypes of 6-12-24-48 pulse converters have been built and tested at our laboratories [1],[2],[4],[6],[9],[11],[12],[13],[14],[15],[16] and experimental results match with simulated ones, as seen comparing the theoretical expressions of multiconverter power factor (expressions 15, 16, 17), with the experimental ones (expressions 19, 20, 21), and also the experimental harmonic spectrum of the AC side phase A current of a 24-pulse arrangement (figure 3), when compared with the theoretical expected harmonics.

The power factor measurement expected for a 48-pulse converter certainly will agree with the theoretical result shown in expression 18.

VIII – REFERENCES

[1]A.J.J.Rezek, "Modelling and implementation of multiconverter systems", (In Portuguese), DS_c Thesis, FEE/UNICAMP, may, 1991.

[2]A.J.J.Rezek, "Permanent and transient condition analysis of an AC/DC electric conversion system" (In Portuguese), $M.S_c$ Thesis, EFEI, june, 1986.

[3]L.Carlsson. "Extended-delta converter transformer for 12 - pulse operation in HVDC projects", *International HVDC Seminar*, Rio de Janeiro, Brasil, 1986.

[4]J.P.G.Abreu; A.J.J.Rezek; A.Candido, "Modelling and implementation of 48-pulse multiconverter", *Proceedings IEEE-ICHPS*, Bologna, Italy, pp 50-54, september ,1994.

[5]J.C.G.Siqueira; G.H.F.Floriano, "Harmonic spectrum of a periodic function by using the Fast Fourrier Transform" (In portuguese), EFEI/CPq/DET, Itajubá, Brasil, 1987.

[6]A.J.J.Rezek; J.P.G.Abreu; V.F.Silva; M.S.Miskulin, "New alternatives for HVDC transmission" (In Portuguese)[1 *Cigré, VI ERLAC*, Foz do Iguaçu, PR, Brasil, may, 1995.

[7]E.Ulmann, "Power transmission by direct current", *Springer-Verlag*, Berlin, Heidelberg, New York, 1975.

[8]E.W.Kimbark, "Direct current transmission", Vol I, *Wiley Intercience*, New York, 1971.

[9]A.J.J.Rezek; J.P.G.Abreu; V.F.Silva; M.S.Miskulin, "Increasing the converter pulse number: Harmonic contents and power factor improvement" (In Portuguese), *Cigré, VII ERLAC*, Puerto Iguazú, Argentina, may, 1997.

[10]J.P.G.Abreu; A.J.J.Rezek; V.F.Silva; L.E.B.Silva; M.S.Miskulin, "Harmonics elimination in multiconverter systems by using a special autotransformer (ADZ)" *Proceedings AMSE Modelling, Simulation & Control*, AMSE Press, vol. 38, n° 4, pp 45-53, France, 1992.

[11]A.J.J.Rezek; M.S.Miskulin; J.P.G.Abreu "Computer aided design applied in power electronics" (In Portuguese), *Proceedings II Power Electronics Seminar*, pp. 102-109, UFSC, Florianopolis, SC, Brasil,1989.

[12]A.J.J.Rezek; J.P.G.Abreu; V.F.Silva; M.S.Miskulin, "Converters for application in HVDC systems", *International Conference on Contribution of Cognition to Modeling, AMSE*, july 6-8, Lyon-Villeurbanne, France, 1998.

[13]O.H.S.Vicentini; A.J.J.Rezek; "Power Factor Improvement and Harmonics Content Analysis of Line Commutated Converters" (In portuguese), *CNPq Scientific Initiation Research*, 2000.

[14] A.J.J. Rezek; J.P.G.Abreu; V. F. Silva; J.M.E. Vicente; J.A. Cortez; W. O. Assis; M. S. Miskulin " Power factor improvement of line-commutated graetz converters by increasing their number of pulses", *V Brazilian Conference of Power Electronics,* COBEP 99, Foz do Iguaçu, PR, Brazil,. Proceedings COBEP'99, v.2. pp 551-556, 1999.

[15]A. J. J. Rezek; J. P. G. Abreu; V. F. Silva; J. M. E. Vicente; J. A. Cortez; O. H..S. Vicentini; A.C. Sá; M. S. Miskulin. " Power factor improvement of line-commutated converters by increasing their number of pulses: modeling and experimental results", proceedings X IEEE ICHQP, International Conference on Harmonics and Quality of Power, Vol I, pp 60-65, Rio de Janeiro, RJ, Brazil, october, 2002.

[16]A. J. J. Rezek; J. P. G. Abreu; V. F. Silva; J. M. E. Vicente; J. A. Cortez; O. H..S. Vicentini; A.C. Sá; A.A. S. Izidoro; M. S. Miskulin. " Power factor improvement of line-commutated Graetz converters by increasing the converter pulse number: modeling and experimental results" (In portuguese) , Revista Eletrônica de Potência (Brazil), SOBRAEP, vol.7 , n. 1, pp 39-45, Novembro de 2002.

[17] S. Mori; K. Matsuno; T. Hasegawa; S. Onnishi; M. Takeda; M. Seto; S. Murakami; F. Isniguro, "Development of a large Static Var Generator using self-commutated inverters for improving power system stability", *IEEE Transactions on Power Systems*, vol. 8, N.1, pp. 371-377, february 1993.

[18]E. Cengelci; P. Enjeti; W. Gray " A new modular motor-modular inverter (MM-MI) concept for medium voltage adjustable speed drive systems", *Proceedings IEEE PESC,* pp. 1972-1979, 1999.

APPENDIX 1

The developed MATLAB routine to obtain the converter power factor is presented as follows.

```
%
%MELHORIA DO FATOR DE POTÊNCIA ATRAVÉS DO
AUMENTO DO NÚMERO DE PULSOS DE ONVERSORES
GRAETZ COMUTADOS PELA REDE
%
%Entrada de Dados
alfgr=input('Entre com o valor do angulo
de disparo alfa em graus = ');
migr=input('Entre com o valor do angulo
de comutação mí em graus = ');
```

```
m=input('Entre com o número de pontes
conectadas em série m (1, 2, 4, 8) = ');
%
%Valor da corrente no lado dc em PU
%
Id=1;
%
%Conversão dos angulos : graus->radianos
alfa=(alfgr*pi)/180;
mi=(migr*pi)/180;
%
%Verificando validade dos dados para o
número de pontes
   while m~=1 & m~=2 & m~=4 & m~=8
      disp('Valor deve ser 1,2,4 ou 8');
      m=input('Entre com o número de
pontes conectadas em série m (1, 2, 4, 8)
= ')
   end
%
if mi==0
%
%Desprezar efeito da comutação
%
fi1=alfa;
I1=((sqrt(6))/pi)*m;
%
%Verificando o número de pontes
conectadas em série
%
if m==1
FP=abs(0.9550*cos(fi1))
elseif m==2
  FP=abs(0.9901*cos(fi1))
elseif m==4
  FP=abs(0.9978*cos(fi1))
else m==8
  FP=abs(0.9996*cos(fi1))
  end
else
   %
   %Considerar Efeito da Comutação
      delta=alfa+mi;
   fi1=atan((2*mi+sin(2*alfa)-
sin(2*delta))/(cos(2*alfa)-
cos(2*delta)));
   %
   %FRH p/ n=1
      H1=cos(2*alfa)-cos(2*delta);
   K1=sin(2*delta)-sin(2*alfa)-2*mi;
   FRH1=(sqrt(H1^2+K1^2))/(4*(cos(alfa)-
cos(delta)));
   if m==1
      pulsos=6;
   elseif m==2
      pulsos=12;
   elseif m==4
      pulsos=24;
   else m=8;
      pulsos=48;
      end
   %Cálculo do número de harmônicos
   for k=1:8
      nneg=abs(pulsos*k-1);

Hneg(k,1)=(sin(((nneg+1)*mi)/2))/(nneg+1)
;
      Kneg(k,1)=(sin(((nneg-
1)*mi)/2))/(nneg-1);

FRHneg(k,1)=(sqrt(Hneg(k,1)^2+Kneg(k,1)^2
-
2*Hneg(k,1)*Kneg(k,1)*cos(2*alfa+mi)))/(c
os(alfa)-cos(delta));
      somaneg(k,1)=(FRHneg(k,1)/nneg)^2;
      npos=pulsos*k+1;

Hpos(k,1)=(sin(((npos+1)*mi)/2))/(npos+1)
;
      Kpos(k,1)=(sin(((npos-
1)*mi)/2))/(npos-1);

FRHpos(k,1)=(sqrt(Hpos(k,1)^2+Kpos(k,1)^2
-
2*Hpos(k,1)*Kpos(k,1)*cos(2*alfa+mi)))/(c
os(alfa)-cos(delta));
      somapos(k,1)=(FRHpos(k,1)/npos)^2;
   end
   fator2=0;
   for y=1:2
   fator1=somaneg(y,1)+somapos(y,1);
   fator2=fator1+fator2;
   end
   fator2;

FP=abs((cos(fi1)/sqrt((FRH1^2)+fator2))*F
RH1)
End
```

APPENDIX 2

Ud = 1.35 x Uff x (cosα + cos(α + μ))/2

Where: Ud : DC output voltage of the bridge

Uff : RMS AC line to line supply voltage of the bridge

For obtaining Ud =0 (transition of the converter operation of rectifier to inverter), one has: $\cos\alpha + \cos(\alpha + \mu) = 0$

By using the trigonometric product transformation, results:

a= α; b=(α + μ)

cos a + cos b = 0 , where a =(A+B) and b = (A-B)

A = (a+b)/2 ; B = (a-b)/2

cos A.cos B – sin A.sin B + cos A.cos B + sin A . sin B=0

2cos A. cos B = 0

$$2\cos\left(\frac{\alpha+\alpha+\mu}{2}\right)\cos\left(\frac{-\mu}{2}\right)=0$$

$$\cos\left(\alpha+\frac{\mu}{2}\right)\cos\left(\frac{\mu}{2}\right)=0$$

$$\left(\alpha+\frac{\mu}{2}\right)=90$$

$$\alpha=90-\frac{\mu}{2}$$