I. Power Factor Correction with an Inductor Placed at the INPUT of a Single-Phase Diode Rectifier with Capacitive Filter at DC Side

1. Introduction

The diode rectifier with capacitive filter at DC side is the most used converter when one desires a CC voltage from the grid. However, they are very harmful to the grid due to their low power factor and high Total harmonic Distortion (THD)
A technique to increase the power factor consists of an inductor placement in the rectifier which results in the mitigation of the impulsive input current behavior. Consequentially, the input current THD is reduced.
In this section, an inductor is placed at the input of the single-phase rectifier. The methodology to dimension the inductor is presented, as well the simulation results. At the end, the new power factor is presented.

2. The Single-Phase Diode Rectifier

The single-phase diode rectifier with an inductor placed at the input is presented in Fig. 1.

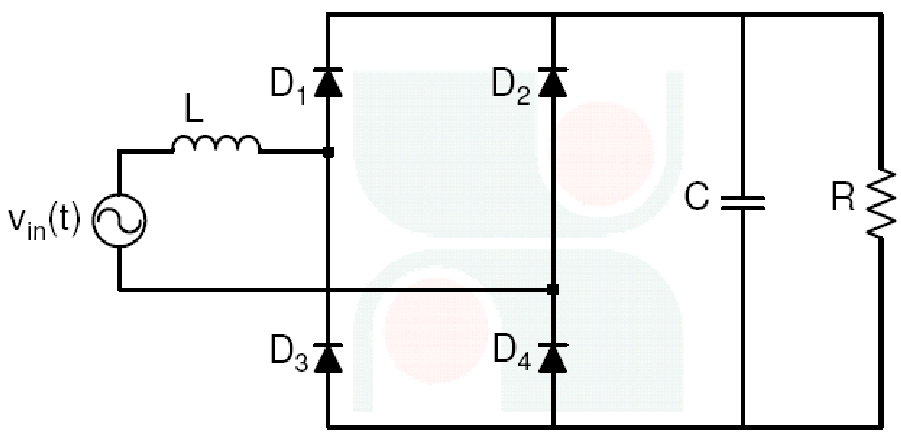

Fig. 1 - single-phase diode rectifier with an inductor placed at the input.

3. Design Methodology

The inductance value is realized based on chart that will be presented soon. The rectifier parameters are presented in Table 1.

Tab. 1 – Rectifier Parameters

Input voltage	V_{in}=311sen(ωt)
Frequency	f = 60Hz
Maximum voltage ripple	ΔV_o=5%$Vo_{máx}$
Output voltage	V_o=280V
Output capacitance	C=2,25mF
Output resistance	R=61,20Ω

Output Power	P_o=1500W

3.1. Voltage Factor

The voltage factor is the converter voltage gain, given by equation (1).

$$FV = \frac{V_o}{\sqrt{2} \cdot Vin_{ef}} \tag{1}$$

Therefore,

$$FV = 0,9 \tag{2}$$

3.2. Normalized Inductance

The normalized inductance is found by using the voltage factor and the chart presented in Figura 2.

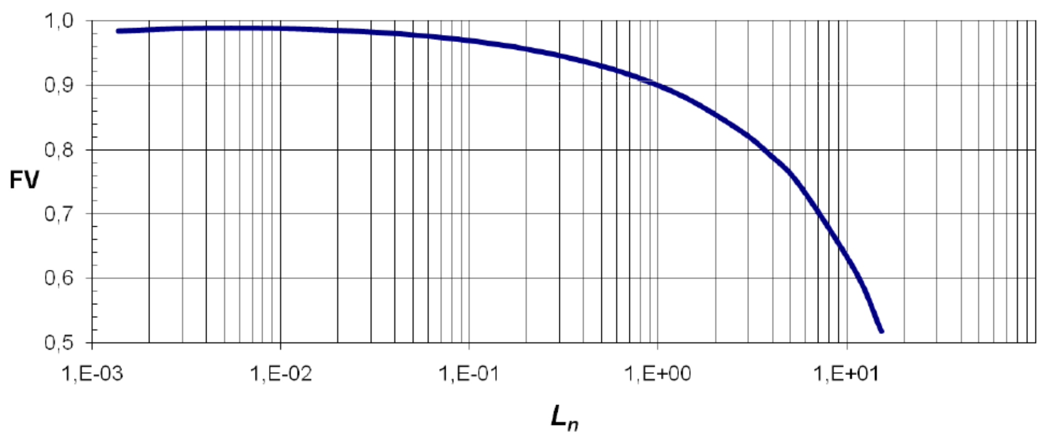

Figura 2 – Chart to find the normalized inductance.

From (2) it reaches:

$$L_n = 1 \tag{3}$$

3.3. Output current

The output current is given by equation (4).

$$I_o = \frac{P_o}{\sqrt{2} \cdot Vin_{ef} \cdot FV} \tag{4}$$

From (2) and from the rectifier parameters it reaches:

$$I_o = 5,36A \tag{5}$$

3.4. The relationship between the output current divided to the average short-circuit current and the voltage factor

The relationship between the output current divided to the average short-circuit current and the voltage factor is found from the chart presented in Figura 3.

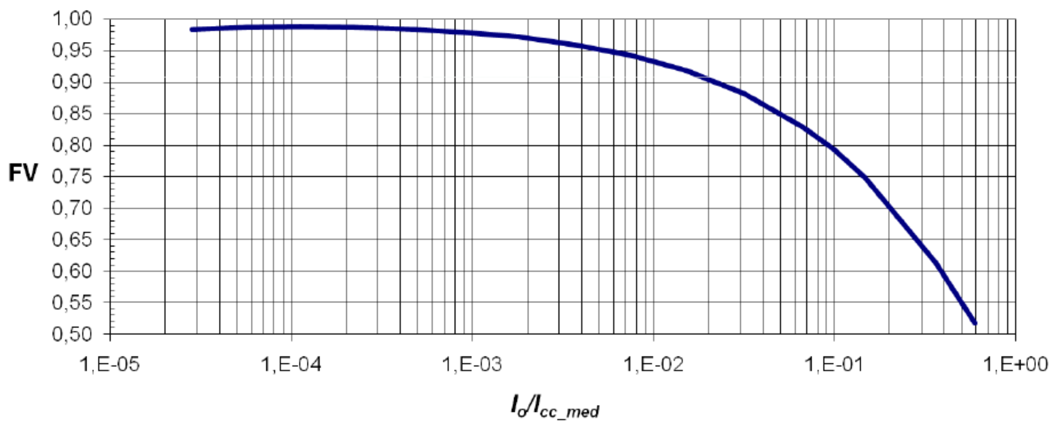

Figura 3 – Chart to find the relationship between the output current and the average short-circuit current.

From (2) it reaches:

$$\frac{I_o}{I_{CC\_med}} = 2,2 \cdot 10^{-2} \tag{6}$$

3.5. Average Short-circuit current

By substituting (5) in (6) it reaches:

$$I_{CC\_med} = 243,64A \tag{7}$$

3.6. Inductance dimensioning

The inductance to be placed in the rectifier input is calculated by means of equation (8).

$$L = \frac{\sqrt{2} \cdot Vin_{ef}}{\pi^2 \cdot f \cdot I_{CC\_med}} \tag{8}$$

Therefore,

$$L = 2,156mH \tag{9}$$

3.7. The new load resistance value

It is mandatory to calculate the new load resistance value to fit the desired power specified in the rectifier parameters. The new value is given by (10).

$$R = \frac{\left(\sqrt{2} \cdot Vin_{ef} \cdot FV\right)^2}{P_o} \tag{10}$$

Therefore,

$$R = 52,27\Omega \tag{11}$$

3.8. The Total Harmonic Distortion

The THD is obtained by means of the normalized inductance and the chart presented in Figura 4.

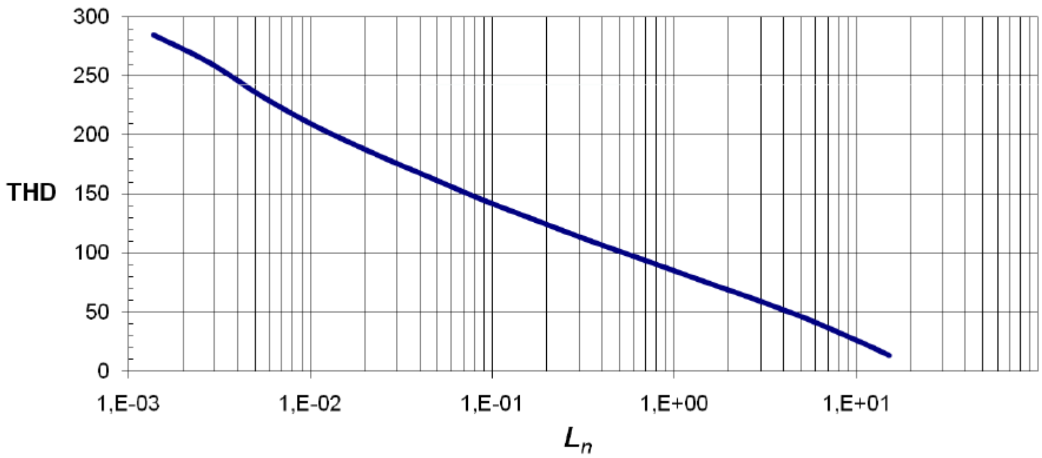

Figura 4 – Chart to obtain the THD from the normalized inductance.

From (3):

$$THD = 83\% \tag{12}$$

3.9. Phase displacement

The phase displacement is found by means of the chart presented in Figura 5.

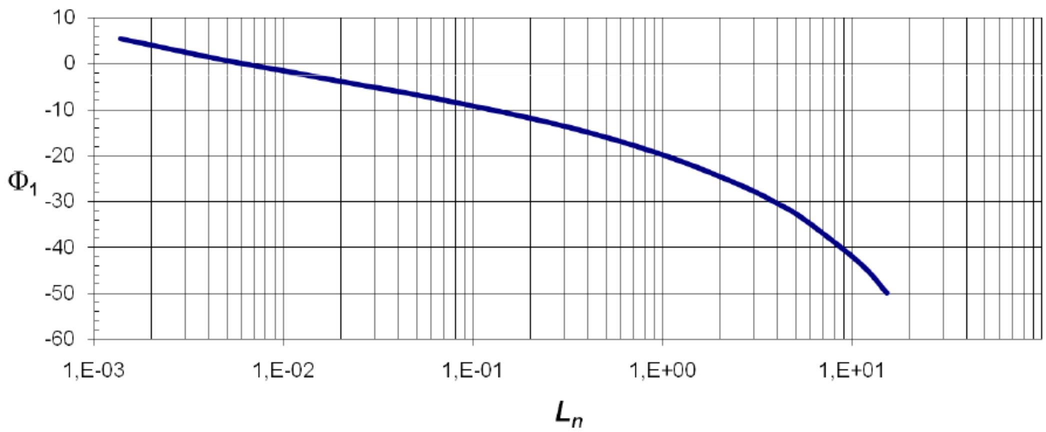

Figura 5 – Chart to find the phase displacement.

From (3):

$$|\phi_1| = 20° \tag{13}$$

3.10. Power Factor

The power factor is found by means of the chart presented in Figura 6.

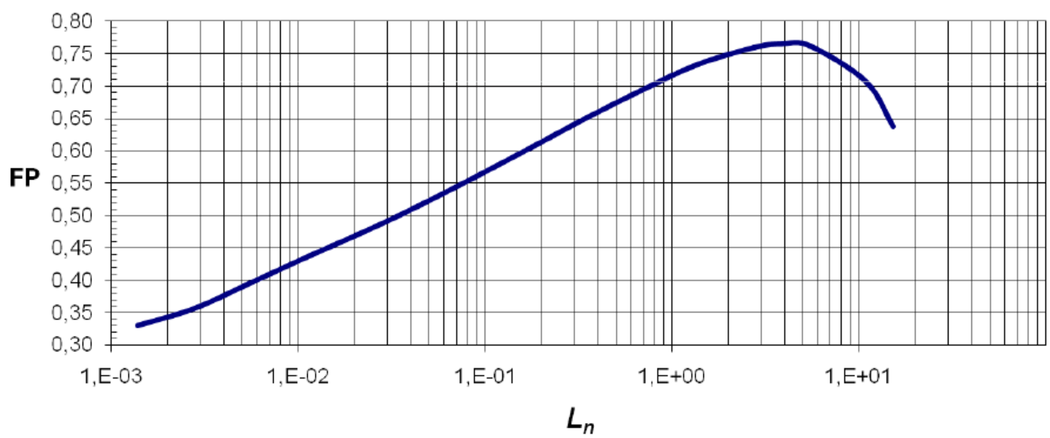

Figura 6 – Chart to find the power factor

From (3):

$$FP = 0,72 \tag{14}$$

4. Simulation Results

The simulated results were obtained in steady-state conditions.

4.1. Output oscillation voltage

The Figura 7 presents the output oscillation voltage. The equation (15) to (18) present the maximum, minimum, average and ripple related to the maximum value. The ripple is inside the rectifier parameters.

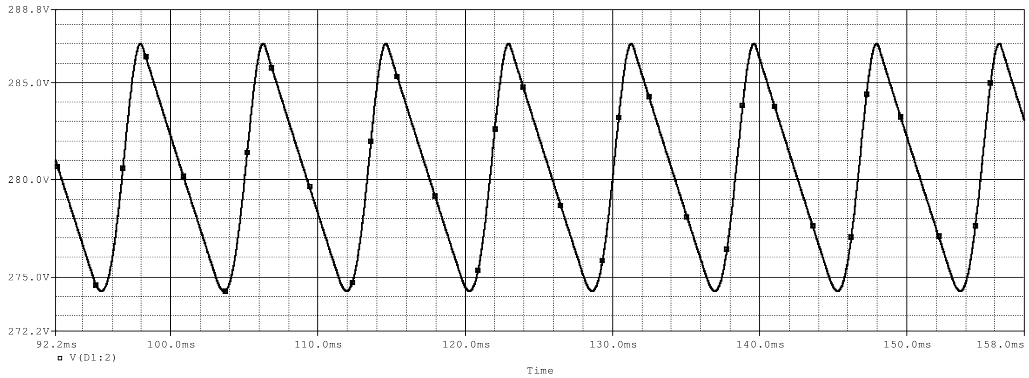

Figura 7 – Output oscillation voltage

$$Vo_{máx} = 287,0V \tag{15}$$

$$Vo_{mín} = 274,25V \tag{16}$$

$$Vo_{med} = 280,63V \tag{17}$$

$$\Delta V_o = 4,54\% Vo_{máx} \tag{18}$$

4.2. Input Voltage, input current and output voltage

The Figura 8 presents the input voltage, input current and output voltage. The input current has presented a softer waveform compared to a rectifier without the input inductor (not shown).

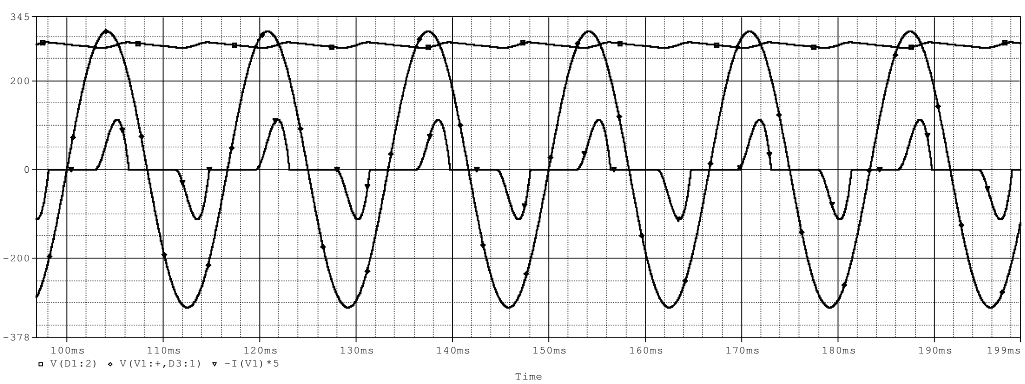

Figura 8 – Input voltage, input current and output voltage

4.3. Load resistor power

The Figura 9 presents the instantaneous load resistor power. Its values is presented in (19), (20) e (21).

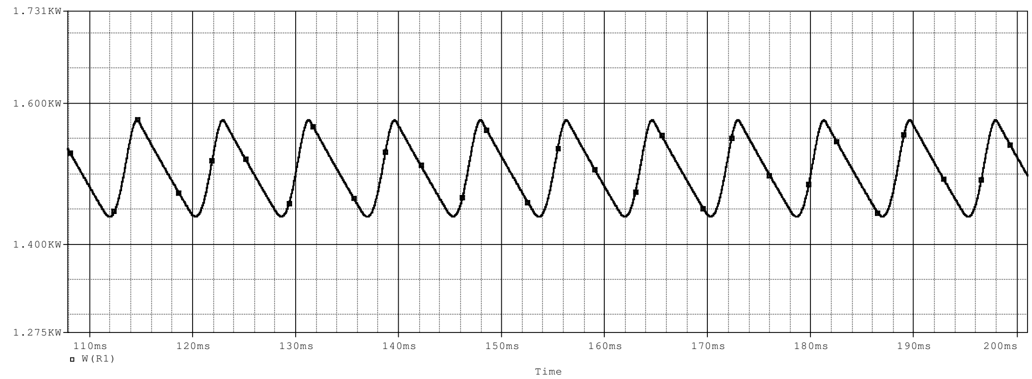

Figura 9 – Instantaneous load resistor power.

$$Po_{máx} = 1576W \quad (19)$$

$$Po_{mín} = 1439W \quad (20)$$

$$Po_{med} = 1507W \quad (21)$$

4.4. Average Output Current

The Figura 10 presents the average output current.

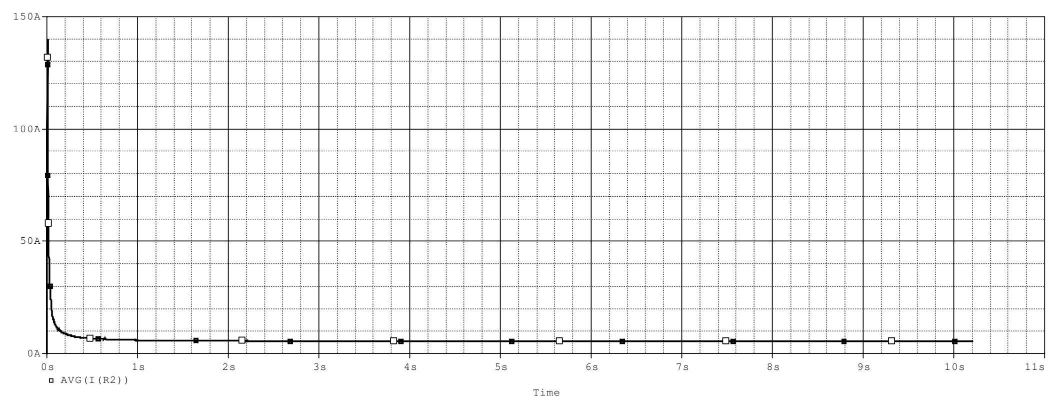

Figura 10 – Average output current.

$$I_o = 5,38A \quad (22)$$

4.5. Average short-circuit current

The Figura 11 presents the average short-circuit current.

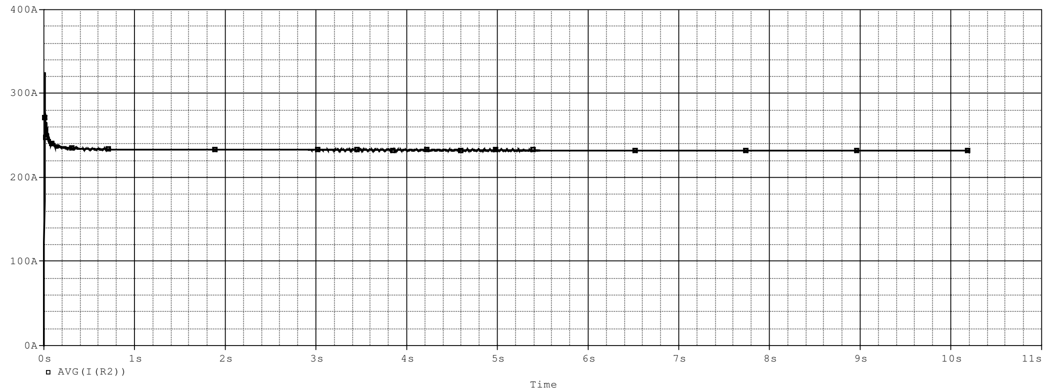

Figura 11 - 4.5. Average short-circuit current

$$I_{CC\_med} = 232,56A \tag{23}$$

4.6. Input current THD

The simulated THD is given by (24). This values is close to the obtained THD.

$$THD = 85,77\% \tag{24}$$

4.7. Phase displacement

The simulated phase displacement is given by (25). Again, its value is close to the obtained.

$$|\Phi_1| = 18° \tag{25}$$

4.8. Power Factor

The simulated power factor is given by (26).

$$FP = 0,76 \tag{26}$$

4.9. Comparative between simulated and calculated values

The Tabela 2 presents a comparison between the simulated and calculated values. They are very close to each other.

Tabela 2 - 4.9. Comparative between simulated and calculated values

Parameter	Acronym	Calculated	Simulated
Output voltage	V_o	280,00V	280,63V
Output voltage ripple	ΔV_o	5%	4,54%
Output power	P_o	1500W	1507W
Average output current	I_o	5,36 A	5,38 A
Average short-circuit current	I_{CC_med}	243,64 A	232,56 A
THD	THD	83%	85,77%
Phase displacement	Φ_1	20	18
Power Factor	FP	0,72	0,76

5. Complementary analysis

In this section will be presented the input current THD, the phase displacement and the power factor for different inductance values. Furthermore, a comparison to the IEC61000-3-2 regulamentation will be done. The Tabela 3 presents the referred values.

Tabela 3 – Complementary analysis

Inductance Value (L)	Phase Displacement (Φ_1)	(THD)	Power Factor (FP)
2,156mH	18°	85,77%	0,76
5mH	24°	68%	0,755
10mH	28,8°	54,52%	0,769
20mH	34,5°	41,05	0,762

It is possible to verify the increasing inductance value makes the phase displacement to increase and the THD to reduce. The power factor is almost kept unchanged. The TDH gets lower as the inductance increases. Thus, for project aiming a low THD a high inductance value is required. Nevertheless, a high inductance value makes the inductor voltage drop to be high. Consequentially, the output voltage is reduced. Additionally, the physical project of inductors may become this solution infeasible due to its final volume.

The Figura 12 presents the harmonic content for the input current for different inductance values as well the IEC regulamentaion limits. Approximately, from L=10mH the content fits the regulamentaion limits.

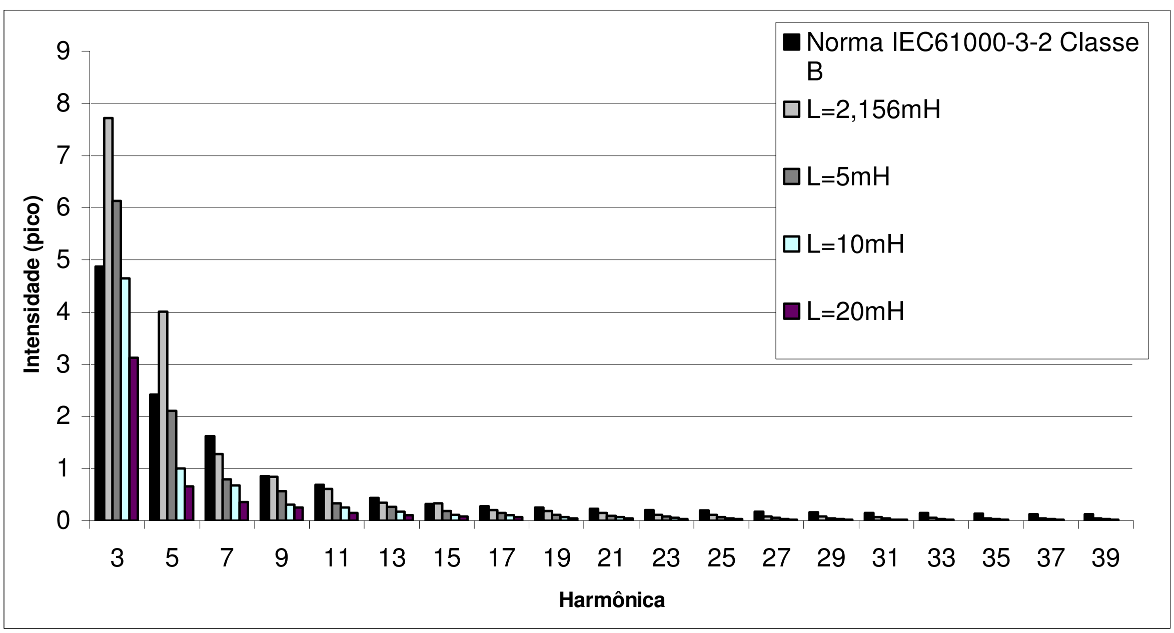

Figura 12 – Harmonic content for the input current and the IEC61000-3-2 Class B

6. Conclusions

The power factor correction by means of the inductor placement has improved the power factor in a limited range. Depending on the applications, the resulted value is still low.

II. Power Factor Correction with an Inductor Placed at the OUTPUT of a Single-Phase Diode Rectifier with Capacitive Filter at DC Side

7. Introduction

Another way to improve de power factor in a single-phase diode rectifier is to place an inductor to its output. In this section the methodology to dimension its inductance will be presented.

8. The Circuit

The single-phase diode rectifier with a capacitive filter at the DC side and an inductor placed at the output is presents in Figura 13. There are two possible operation mode: the continuous conduction mode and the discontinuous conduction mode. In the firs the inductor current never reaches the zero value in steady-state conditions. In the second, there are some intervals in which the inductor current keeps in zero. In the continuous conduction mode the inductor behaves like a current source.

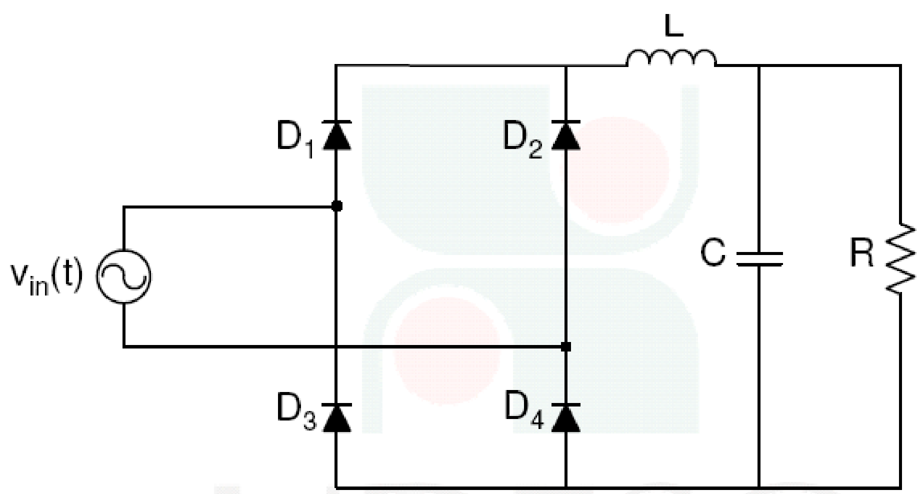

Figura 13 - Single-phase diode rectifier with a capacitive filter at the DC side and an inductor placed at the output

9. Design Methodology

The methodology to calculate the inductance is the same used in the previous section. Therefore, the methodology won't be presented. The calculated inductance now is just placed at the output.

10. Simulated Results

10.1. Output voltage, input current during the start-up

The output voltage and the input current during the start-up is presented in Figura 14.

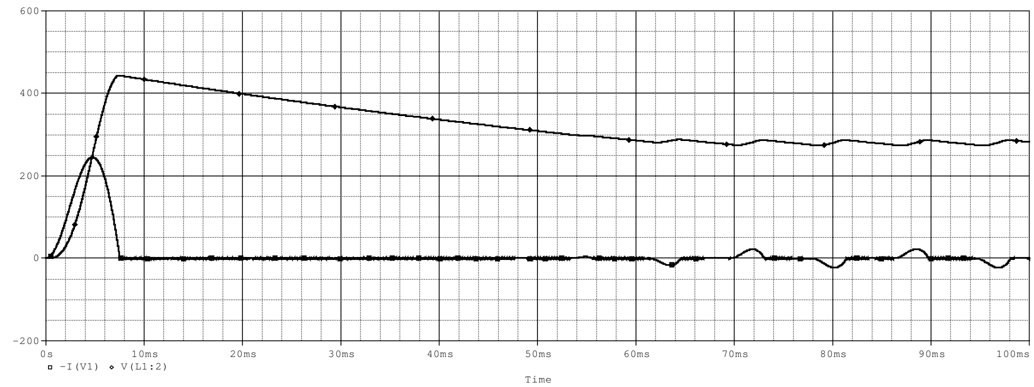

Figura 14 - output voltage and the input current during the start-up.

10.2. Output oscillating voltage

The Figura 15 presents the output oscillating voltage and equations (27) to (30) some important values. These values are inside the rectifier parameters.

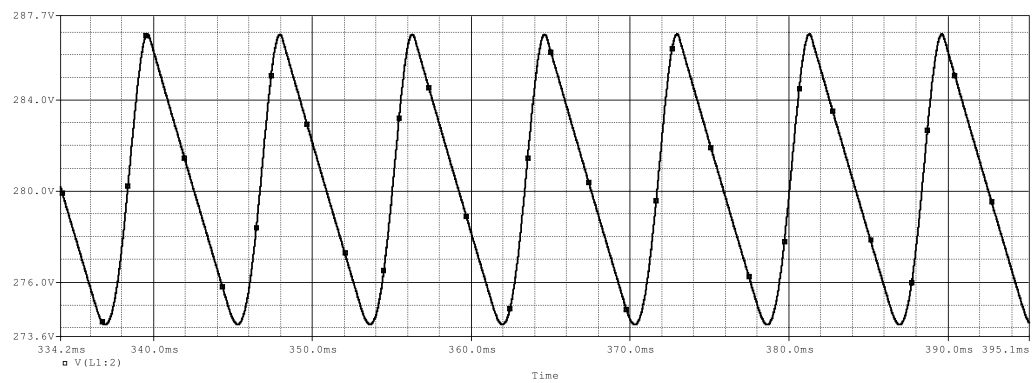

Figura 15 – Output oscillating voltage.

$$Vo_{máx} = 286,89V \quad (27)$$

$$Vo_{mín} = 274,14V \quad (28)$$

$$Vo_{med} = 280,51V \quad (29)$$

$$\Delta V_o = 4,43\% Vo_{máx} \quad (30)$$

10.3. Input Voltage, input current and output voltage

The Figura 16 presents the input voltage, the input current and the output voltage. The waveforms are quite de same as the previous technique.

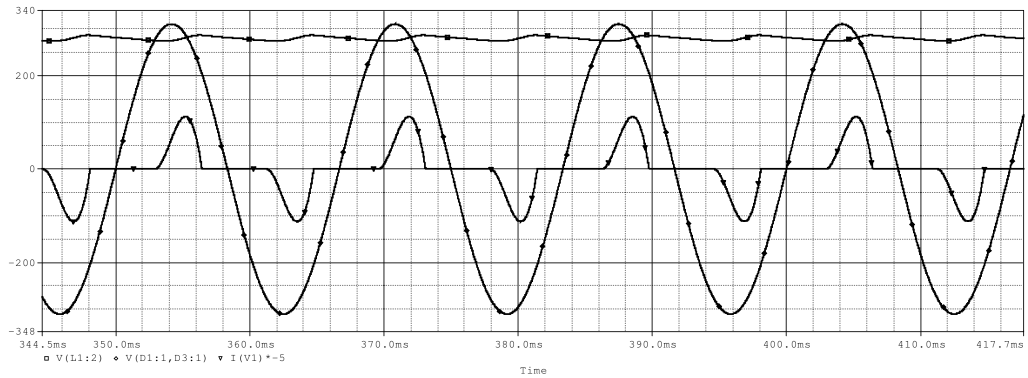

Figura 16 – Output voltage, input voltage and input current.

10.4. Instantaneous Load resistor power

The presents the instantaneous load resistor power. Its values is presented in (31) to (33).

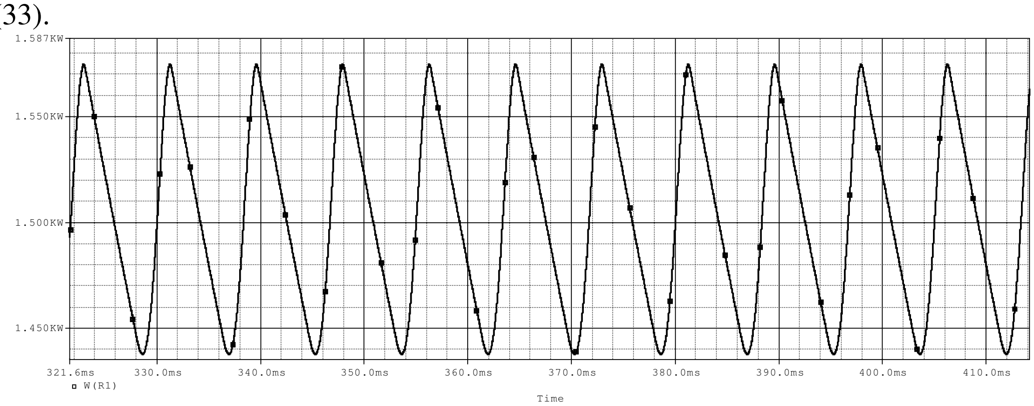

Figura 17 - Instantaneous load resistor power

$$Po_{máx} = 1574W \quad (31)$$

$$Po_{mín} = 1437W \quad (32)$$

$$Po_{med} = 1505W \quad (33)$$

10.5. Average Output Current

The Figura 18 presents the average output current measured in the inductor.

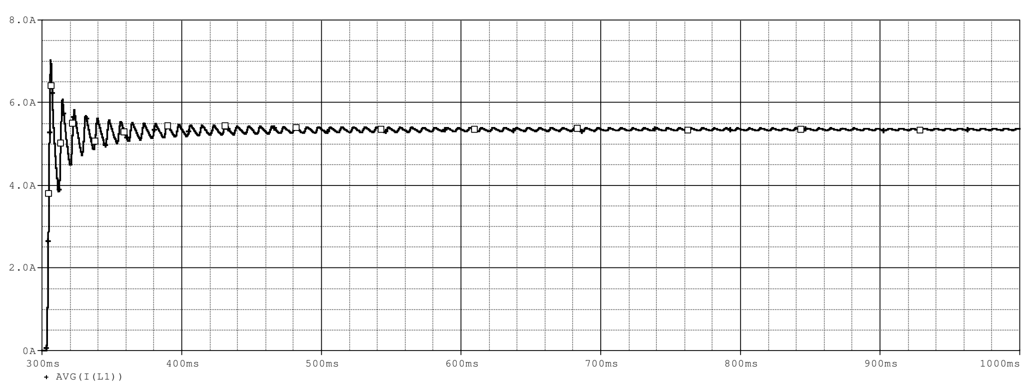

Figura 18 – Average output current

$$I_o = 5,34A \quad (34)$$

10.6. Average short-circuit current

The Figura 19 presents the average short-circuit current.

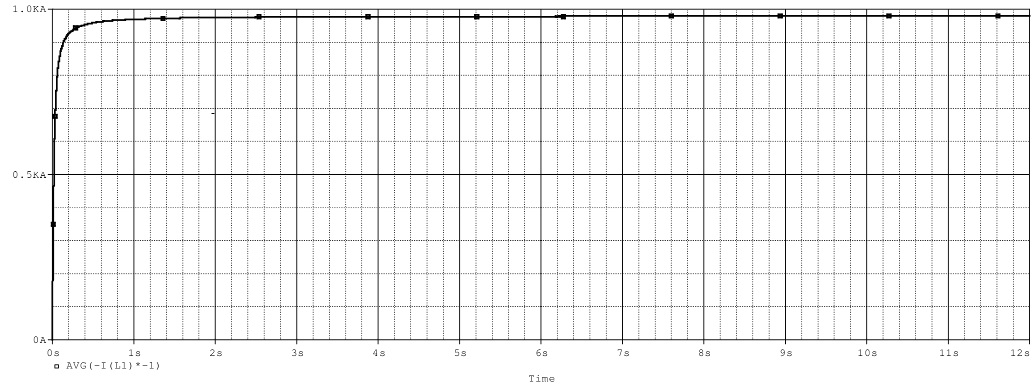

Figura 19 - average short-circuit current

$$I_{CC\_med} = 978,5A \quad (35)$$

10.7. Input current THD

The simulated input current THD is given by (36). Its value is very close to the calculated one.

$$THD = 85,78\% \quad (36)$$

10.8. Phase displacement

The simulated phase displacement is given by (37).

$$\left|\Phi_1\right| = 18,1° \quad (37)$$

10.9. Power Factor

The simulated power factor is given by (38).

$$FP = 0,72 \quad (38)$$

10.1. Comparative between simulated and calculated values

The Table 4 presents a comparison between the simulated and calculated values. They are very close to each other.

Tabela 4 - 10.1. Comparative between simulated and calculated values

Parameter	Acronym	Calculated	Simulated
Output voltage	V_o	280,00V	280,51V
Output voltage ripple	ΔV_o	5%	4,43%
Output power	P_o	1500W	1505W
Average output current	I_o	5,36 A	5,34 A
Average short-circuit current	I_{CC_med}	243,64 A	987,5 A

THD	THD	83%	85,78%
Phase displacement	Φ_1	20	18,1
Power Factor	FP	0,72	0,72

11. Complementary analysis

In a similar way to the previous technique, it will be present an analysis of the interested values as the inductance increases.

Tabela 5 – Complementary analysis

Inductance value (L)	Phase displacement (Φ_1)	(THD)	Power Factor (FP)
2,156mH	18,1°	85,78%	0,72
5mH	24,8°	67,98%	0,75
10mH	29,9°	54,88%	0,76
20mH	35,5°	40,76%	0,76
100mH	19°	46,85%	0,86
500mH	3,7°	47,56%	0,90

As the inductance increases the power factor also increases. Furthermore, the THD decreases. However, high values of the inductance makes the output voltage to be lower. The Figura 20 presents the input current and voltage for an inductance value of 500mH

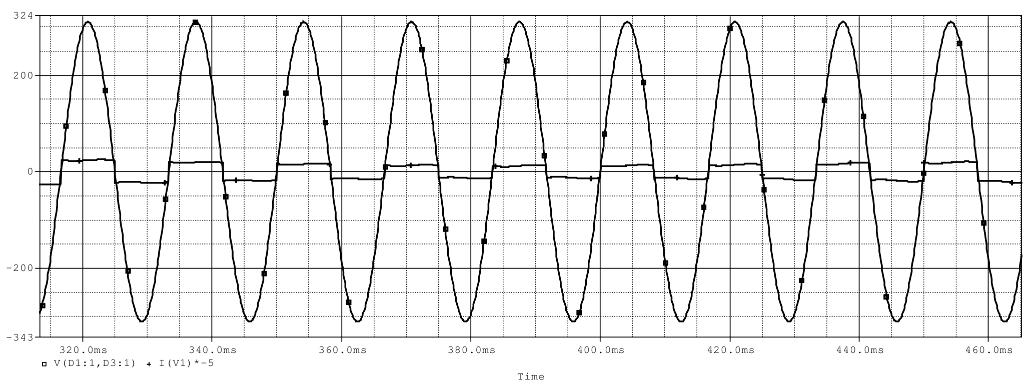

Figura 20 – Input voltage and current.

The Figura 21 the input current harmonic content for some values of inductance and the IEC regulamentation.

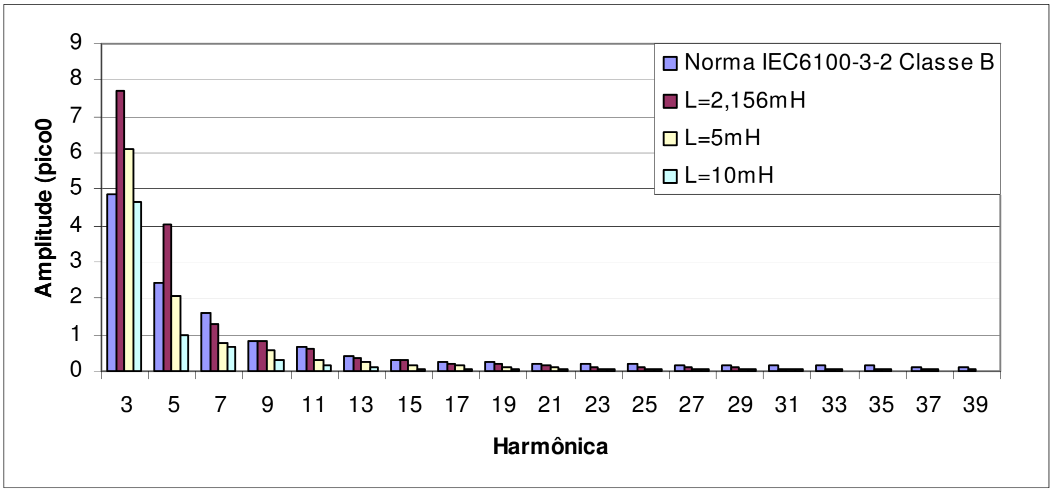

Figura 21 - input current harmonic content for some values of inductance and the IEC regulamentation.

12. Conclusions

This case has shown better values compared to the previous analysis. The power factor is improved by increasing the inductance value.

III. Power Factor Correction with an Inductor Placed at the INPUT of a Three-Phase Diode Rectifier with Capacitive Filter at DC Side

13. Introduction

Three-phase diode rectifiers are usually used in high power applications. The technique to place an inductor at the output is used in three-phase diode rectifiers. In this section, it will be shown how to dimension the inductance.

14. The Three-phase diode rectifier

The three-phase diode rectifier with capacitive filter at the DC side is presented in Figura 22.

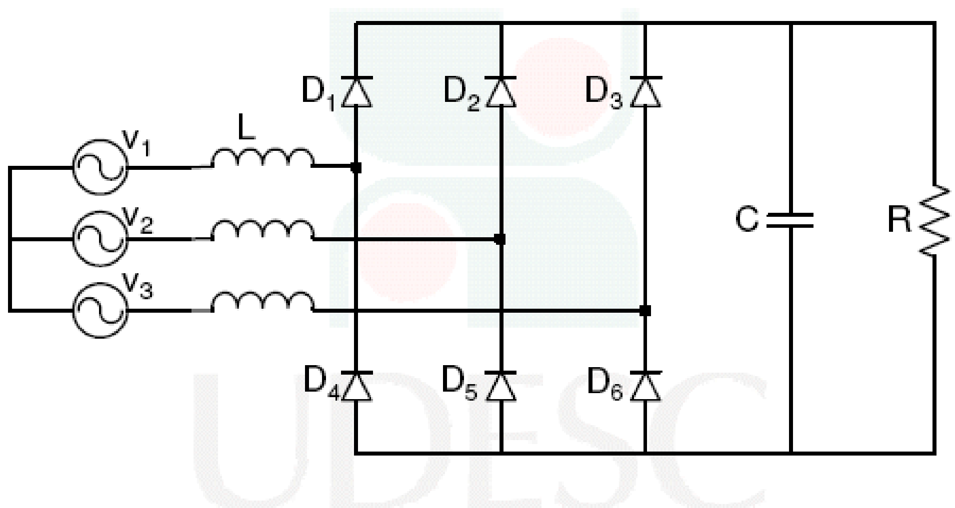

Figura 22 – Three-phase diode rectifier with an input inductor.

15. Design methodology

The inductance value is realized based on chart that will be presented soon. The rectifier parameters are presented in Table 6.

Tabela 6 – Rectifier Parameters

Input voltage	V_{in}=311sen(ωt)
Frequency	f = 60Hz
Maximum output voltage ripple	ΔV_o=10%$Vo_{máx}$
Output voltage	V_o=500V
Output capacitance	C=188,32uF
Output resistance	R=87,33Ω
Output power	P_o=3000W

15.1. Voltage Factor

The voltage factor is the converter voltage gain, given by equation (1).

$$FV = \frac{V_o}{\sqrt{3} \cdot \sqrt{2} \cdot Vin_{ef}} \tag{1}$$

therefore,

$$FV = 0{,}928 \tag{2}$$

15.2. Normalized inductance

The normalized inductance is found by using the voltage factor and the chart presented in Figura 23.

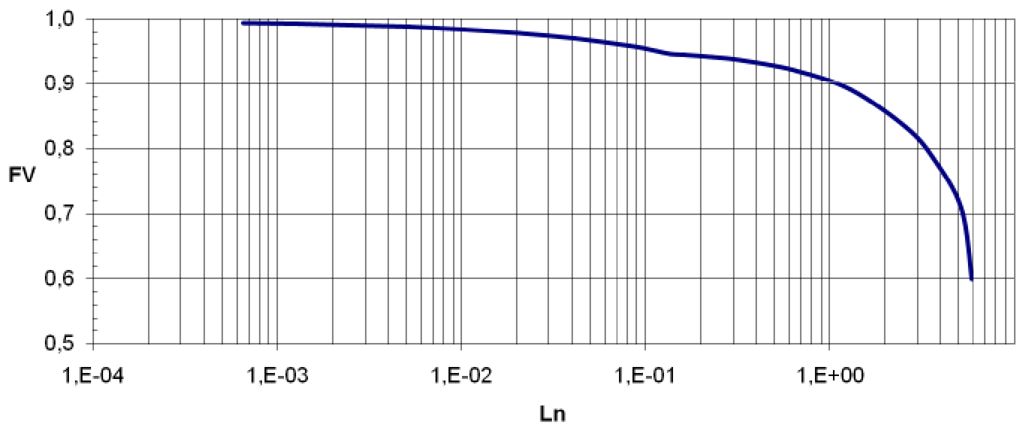

Figura 23 - Chart to find the normalized inductance.

From (2):

$$L_n = 0{,}6 \tag{3}$$

15.3. Output current

The output current is given by equation (4).

$$I_o = \frac{P_o}{\sqrt{2} \cdot \sqrt{3} \cdot Vin_{ef} \cdot FV} \tag{4}$$

From (2) and from the rectifier parameters it reaches:

$$I_o = 6{,}00A \tag{5}$$

15.4. The relationship between the output current divided to the average short-circuit current and the voltage factor

The relationship between the output current divided to the average short-circuit current and the voltage factor is found from the chart presented in Figura 24.

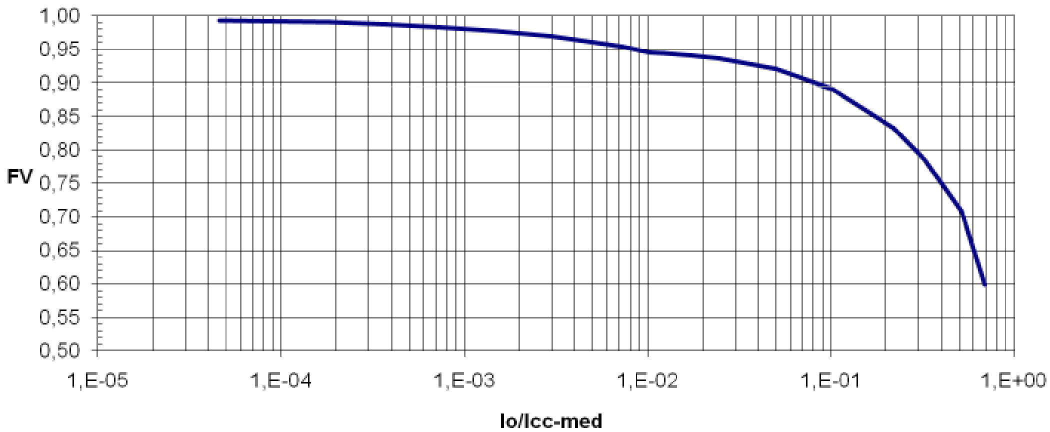

Figura 24 - Chart to find the relationship between the output current and the average short-circuit current.

From (2) it reaches:

$$\frac{I_o}{I_{CC\_med}} = 4 \cdot 10^{-2} \tag{6}$$

15.1. Average Short-circuit current

By substituting (5) in (6) it reaches:

$$I_{CC\_med} = 150A \tag{7}$$

15.1. Inductance dimensioning

The inductance to be placed in the rectifier input is calculated by means of equation (8).

$$L = \frac{3\sqrt{2} \cdot Vin_{ef}}{2\pi^2 \cdot f \cdot I_{CC\_med}} \tag{8}$$

Therefore,

$$L = 5,25mH \tag{9}$$

15.1. The new load resistance value

It is mandatory to calculate the new load resistance value to fit the desired power specified in the rectifier parameters. The new value is given by (10).

$$R = \frac{\left(\sqrt{2} \cdot \sqrt{3} \cdot Vin_{ef} \cdot FV\right)^2}{P_o} \tag{10}$$

therefore,

$$R = 83,36\Omega \tag{11}$$

15.1. The Total Harmonic Distortion

The THD is obtained by means of the normalized inductance and the chart presented in Figura 25.

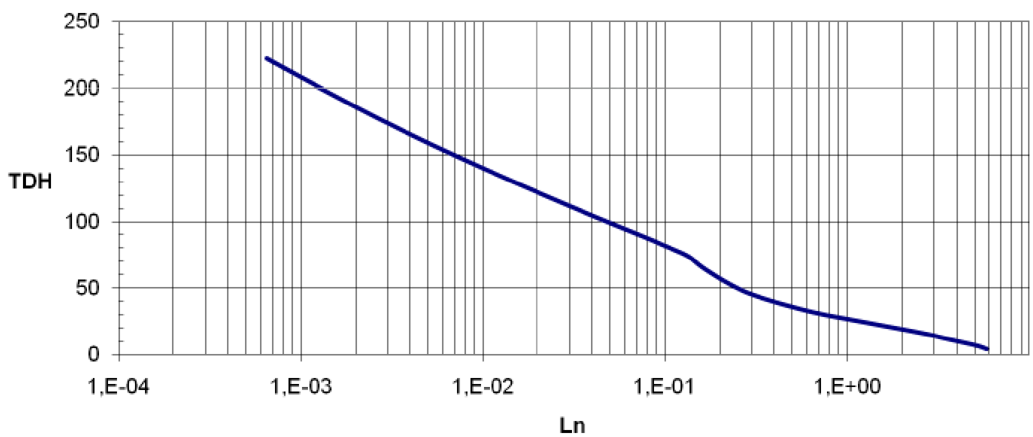

Figura 25 - Chart to obtain the THD from the normalized inductance.

From (3):

$$THD = 30\% \tag{12}$$

15.1. Phase displacement

The phase displacement is found by means of the chart presented in Figura 26.

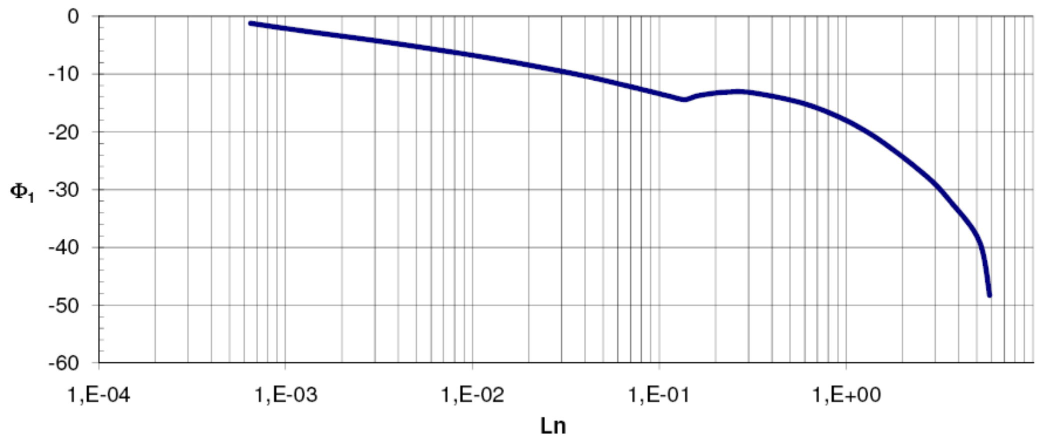

Figura 26 - Chart to find the phase displacement.

From (3):

$$|\phi_1| = 15° \tag{13}$$

15.1. Power Factor

The power factor is found by means of the chart presented in Figura 27.

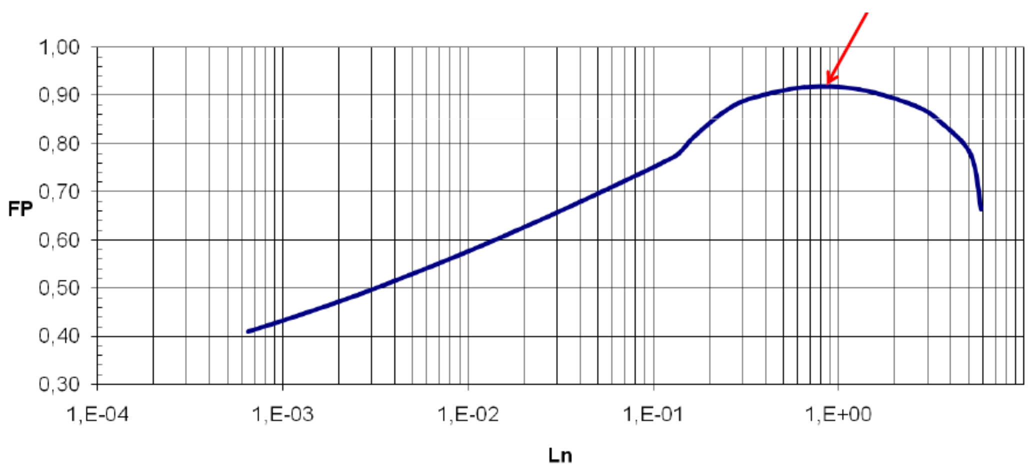

Figura 27 - Chart to find the power factor

From (3):

$$FP = 0,92 \tag{14}$$

1. Simulation Results

The simulated results were obtained in steady-state conditions.

1.1. Output oscillation voltage

The Figura 28 presents the output oscillation voltage. The equation (15) to (18) present the maximum, minimum, average and ripple related to the maximum value. The ripple is inside the rectifier parameters.

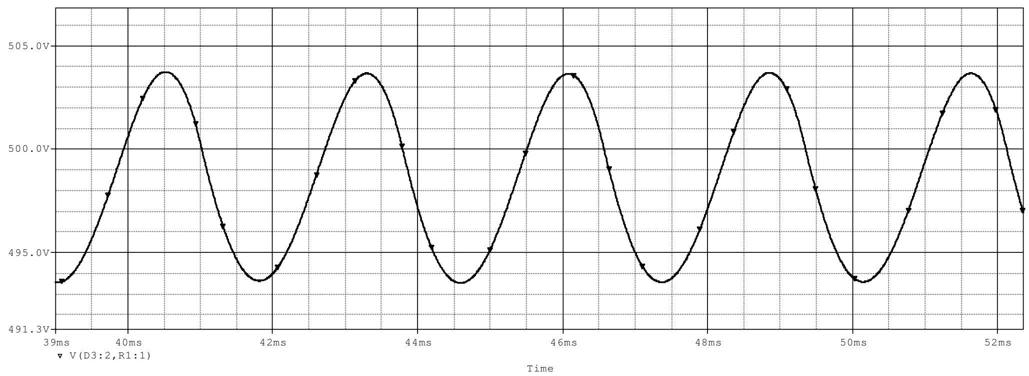

Figura 28 - Output oscillating voltage

$$Vo_{máx} = 503,6V \quad (15)$$

$$Vo_{mín} = 493,6V \quad (16)$$

$$Vo_{med} = 498,6V \quad (17)$$

$$\Delta V_o = 1,98\% Vo_{máx} \quad (18)$$

1.1. Input Voltage, input current and output voltage

The Figura 29 presents the input voltage, input current and output voltage. The input current has presented a softer waveform compared to a rectifier without the input inductor (not shown).

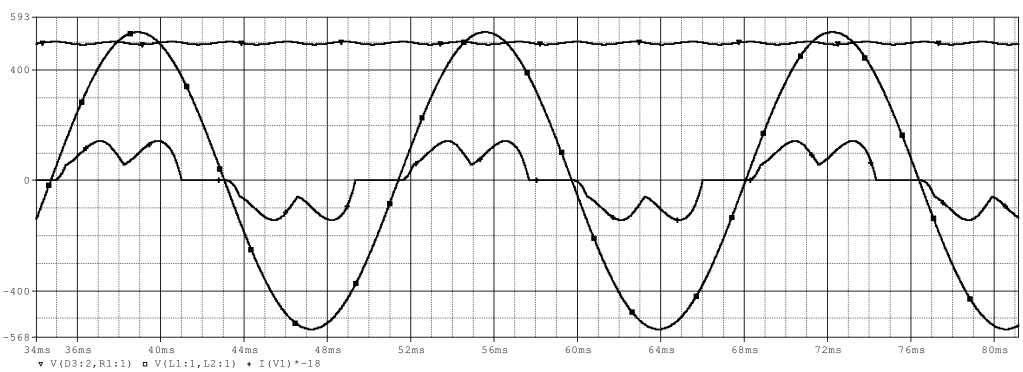

Figura 29 - Input voltage, input current and output voltage

1.1. Load resistor power

The Figura 30 presents the instantaneous load resistor power. Its values is presented in (19), (20) e (21).

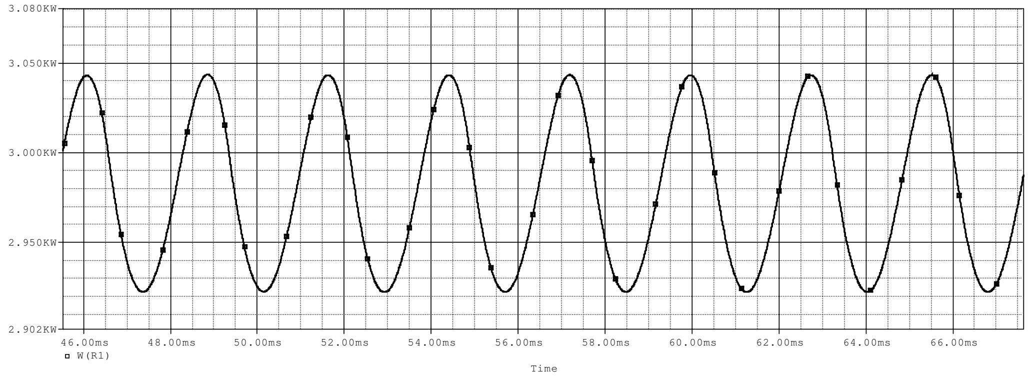

Figura 30 - Instantaneous load resistor power.

$$Po_{máx} = 3043W \quad (19)$$

$$Po_{mín} = 2922W \quad (20)$$

$$Po_{med} = 2982,5W \quad (21)$$

1.1. Average Output Current

The Figura 10 presents the average output current.

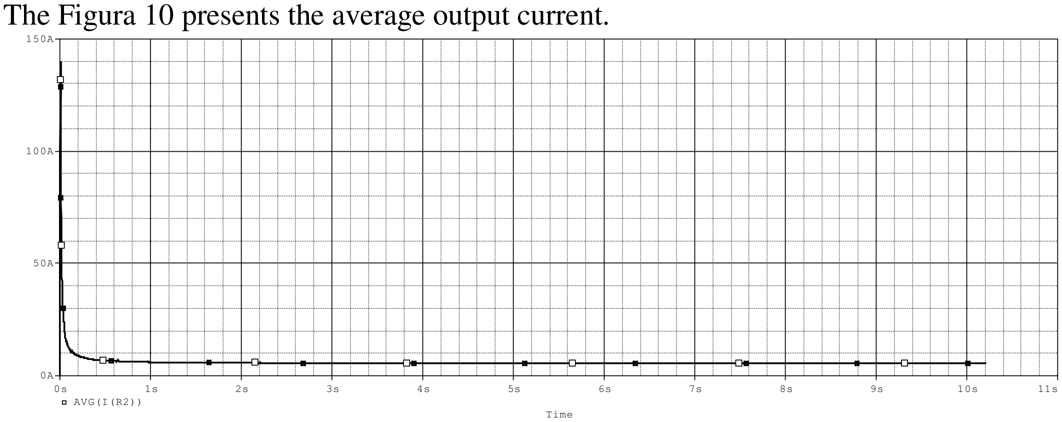

Figura 31 - Average output current

$$I_o = 5,95A \quad (22)$$

1.2. Average short-circuit current

The Figura 32 presents the average short-circuit current.

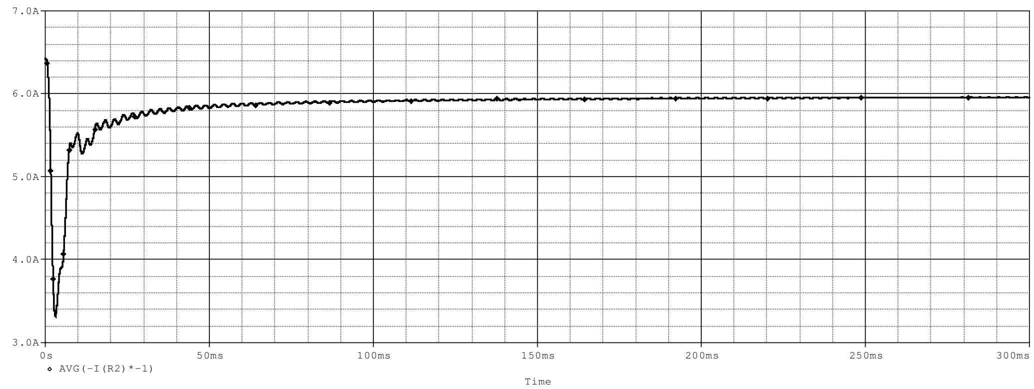

Figura 32 - Average short-circuit current

$$I_{CC\_med} = 232,56A \quad (23)$$

1.1. Input current THD

The simulated THD is given by (24). This values is close to the obtained THD.

$$THD = 36,9\% \quad (24)$$

1.1. Phase displacement

The simulated phase displacement is given by (25). Again, its value is close to the obtained.

$$|\Phi_1| = 14,2° \quad (25)$$

1.1. Power Factor

The simulated power factor is given by (26).

$$FP = 0,91 \quad (26)$$

1.1. Comparative between simulated and calculated values

The 7 presents a comparison between the simulated and calculated values. They are very close to each other

Tabela 7 - Comparative between simulated and calculated values

Parameter	Acronym	Calculated	Simulated
Output voltage	V_o	500V	498,6V
Output voltage ripple	ΔV_o	10%	1,98%
Output power	P_o	3000W	2982,5W
Average output current	I_o	6 A	5,95 A
Average short-circuit current	THD	30%	36,9%
THD	Φ_1	15°	14,2°
Phase displacement	FP	0,92	0,91

1. Complementary analysis

In this section will be presented the input current THD, the phase displacement and the power factor for different inductance values. The Table 8 presents the referred values.

Tabela 8 - Complementary analysis

Inductance Value (L)	**Phase Displacement (Φ_1)**	**(THD)**	**Power Factor (FP)**
5,25mH	14,2˚	36,9%	0,91
10mH	13,8˚	28,02%	0,94
50mH	31,9˚	11,91%	0,84
100mH	41,3˚	6,8%	0,75

IV. Power Factor Correction with an Inductor Placed at the OUTPUT of a Three-Phase Diode Rectifier with Capacitive Filter at DC Side

2. Introduction

Another way to improve de power factor in a three-phase diode rectifier is to place an inductor to its output. In this section the methodology to dimension its inductance will be presented.

3. The Circuit

The single-phase diode rectifier with a capacitive filter at the DC side and an inductor placed at the output is presented in Figura 33. There are two possible operation mode: the continuous conduction mode and the discontinuous conduction mode. In the firs the inductor current never reaches the zero value in steady-state conditions. In the second, there are some intervals in which the inductor current keeps in zero. In the continuous conduction mode the inductor behaves like a current source.

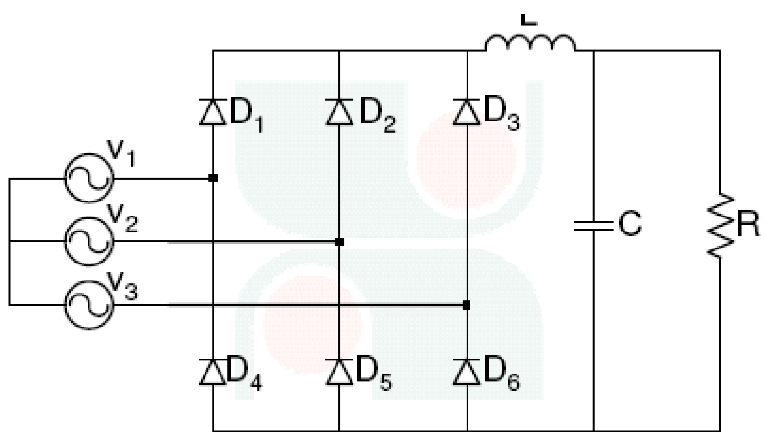

Figura 33 - Single-phase diode rectifier with a capacitive filter at the DC side and an inductor placed at the output

1. Design Methodology

The methodology to calculate the inductance is the same used in the previous section. Therefore, the methodology won't be presented. The calculated inductance now is just placed at the output.

1. Simulated Results

1.1. Output oscillating voltage

The Figura 34 presents the output oscillating voltage and equations (27) to (30) some important values. These values are inside the rectifier parameters.

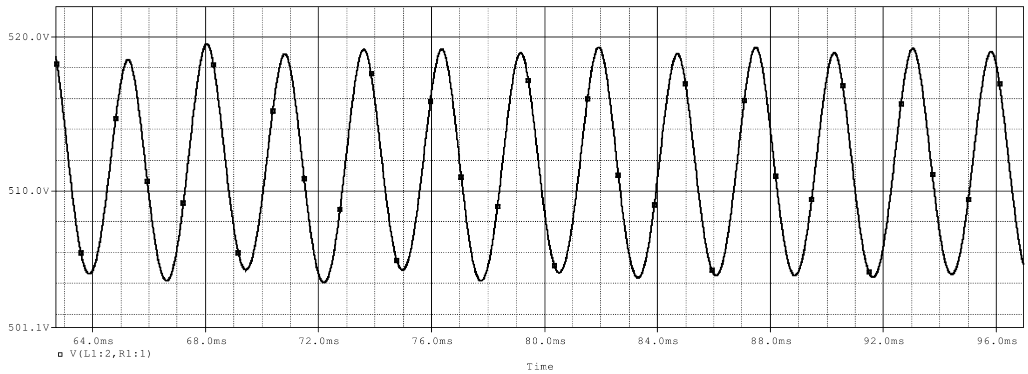

Figura 34 - Output oscillating voltage

$$Vo_{máx} = 519,3V \quad (27)$$

$$Vo_{mín} = 504,36V \quad (28)$$

$$Vo_{med} = 511,83V \quad (29)$$

$$\Delta V_o = 2,87\% Vo_{máx} \quad (30)$$

1.1. Input Voltage, input current and output voltage

The Figura 35 presents the input voltage, the input current and the output voltage. The waveforms are quite de same as the previous technique

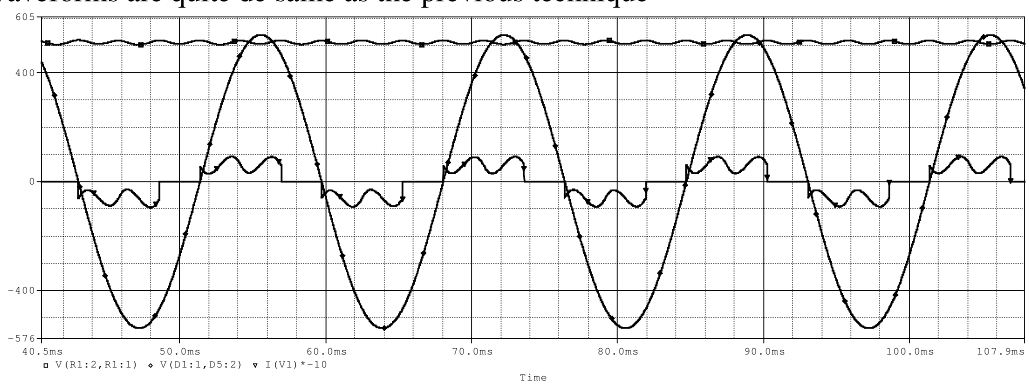

Figura 35 - Output voltage, input voltage and input current

1.1. Instantaneous Load resistor power

The Figure 36 presents the instantaneous load resistor power. Its values is presented in (31) to (33).

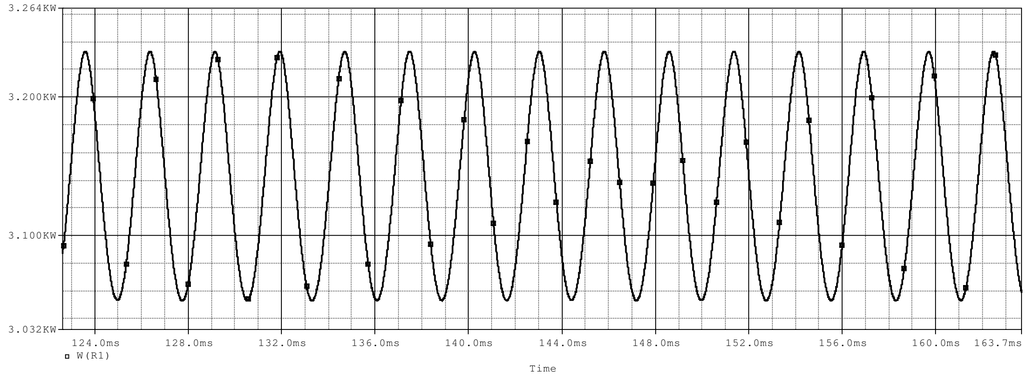

Figura 36 - Load resistance power

$$Po_{máx} = 3232W \quad (31)$$

$$Po_{mín} = 3053W \quad (32)$$

$$Po_{med} = 3142,5W \quad (33)$$

1.1. Average Output Current

The Figura 37 presents the average output current measured in the inductor..

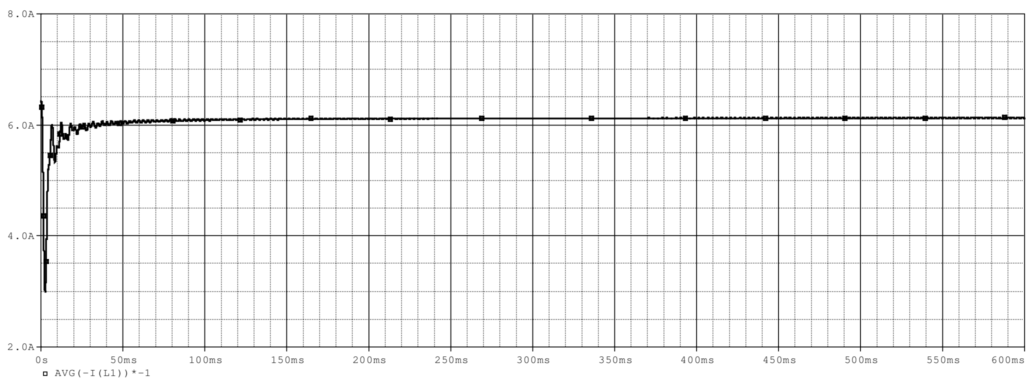

Figura 37 - Average output current

$$I_o = 6,12A \quad (34)$$

1.1. Input current THD

The simulated input current THD is given by (35). Its value is very close to the calculated one.

$$THD = 46,8\% \quad (35)$$

1.1. Phase displacement

The simulated phase displacement is given by (36).

.

$$|\Phi_1| = 5,3° \quad (36)$$

1.1. Power Factor

The simulated power factor is given by (37).

$$FP = 0,9 \tag{37}$$

1.1. Comparative between simulated and calculated values

The Table 9 presents a comparison between the simulated and calculated values. They are very close to each other.

Tabela 9 - Comparative between simulated and calculated values

Parameter	Acronym	Calculated	Simulated
Output voltage	V_o	500V	511,83
Output voltage ripple	ΔV_o	10%	2,87%
Output power	P_o	3000W	3142W
Average output current	I_o	6 A	6,12 A
THD	THD	30%	46,8%
Phase displacement	Φ_1	15°	5,3°
Power Factor	FP	0,92	0,9