# Study Case: Problems with power quality in DC drives

F. N. Bertolotti , H. E. Tacca , *Member, IEEE* , E.A. Cano Plata, *Member, IEEE*

*Abstract*— **This work presents two cases dealing with power quality when dc drives are used. First, the problems found are presented. Then the possible solutions are analyzed, determining which of them are the most adequate to implement. The selected options selected were simulated in ATPDraw.**

*Index Terms*— **DC Drives, Filters, Power Factor, Harmonics, Power Quality.**

## I. INTRODUCTION

T He first case that it is analyzed arise with the problems that occurred with the actuation of automatic reactive power compensators in a factory. When the compensator faults the power factor becomes deficient and the distribution company can penalize for this deficiency. Following a request from a factory, inspections and measurements were done at the electric grid into the factory to design suitable filters.

The second case surges as a study to energize the excitation circuit of synchronic machine. The regulation of excitation is done by thyristor controlled rectifiers. It is mandatory to eliminate the harmonics of the rectifier line current while keeping $\cos \varphi \geq 0,8$ at the connection point of the grid.

The detailed study of the proposal were simulated using ATPDRaw.

## II. STUDY CASE I

A plot of the grid can see in Fig. 1. The factory has a three-phase transformer to reduce the voltage from 3 x 13, 2 kV to 3 x 380 V. The automatic compensator was installed in the secondary side of the transformer and has two electric boards with protection equipment and capacitors bank. At the moment of inspection, the equipment was out of use. Measurements of the rms and the harmonic distortion of voltages and line currents were done. In the command and protection electric board of the production line pointed T1 (see the Fig. 1) also the same measurements were done, plus the estimation of power factor and the active and reactive power consumed.

F. N. Bertolotti, Departamento de Electrónica, Facultad de Ingeniería, Universidad de Buenos Aires, CABA, Argentina (e-mail: fbertol@fi.uba.ar).

H. E. Tacca, Departamento de Electrónica, Facultad de Ingeniería, Universidad de Buenos Aires, CABA, Argentina (e-mail: htacca@fi.uba.ar).

E. A. Cano Plata. Departamento de ingeniería Eléctrica, Electrónica y Computación, Facultad de Ingeniería y Arquitectura. Universidad Nacional de Colombia. Manizales (e-mail: ecano@ieee.org).
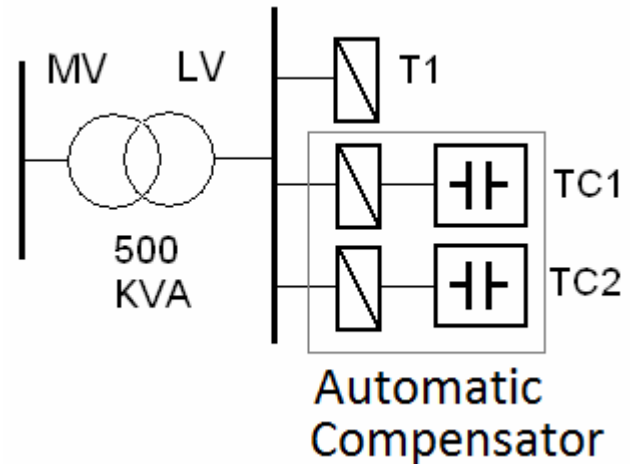


Fig. 1 .Electric distribution network. T1 is the electric board for protection and command at the production line 2. TC1 and TC2 are automatic electric board compensators.

The measurements showed high value in the harmonics components of voltages and currents. The shift between voltage and current was quite high, near of 63°. The distortion index THD was higher than 6%.

### A. Information about the dc drive

Rectifier with six thyristors. Nominal values: Un=0-440 V (dc), In= 225 A(dc). Work values: U=200 - 400 V (dc), Idc=170 A (dc).

### B. Information about the dc motor

Pn=89 kW, Un=440 V, In=220 A (rotor), Un=190 V, In =7.5 A (Field). Motor inductance La=3.6 mH.

### C. Information about the Transformer

Sn=500 kVA, Un=13.2 kV/380V.

## III. STUDY CASE II

The goal is to regulate the voltage of the excitation coil of a synchronic machine. The electric grid at which the rectifier is connected is 3x380 V.

### A. Information about the excitation circuit of the synchronic machine

Rectifier with six thyristors. Nominal values: Un=0-440 V (dc), In= 225 A (dc). Work values: U=130 V (dc), I=100 A (dc).

## IV.  STUDY AND SIMULATION OF SOLUTIONS FOR CASE  I

The solution proposal must reduce the currents harmonics and improve the $\cos\varphi$.

The load is the dc motor with the parameters given in the paragraph II B, and the dc voltage $V_d$ may change from 200 V to 400 V with a main dc current of $I_0 = 170A$.

### A.  Proposal I

It consists of filters placed at the rectifier input (dc drive) to reduce the harmonics current components. Also a capacitor bank is placed in order to compensate $\cos\varphi$. The automatic compensator changes $\cos\varphi$ at values higher that 0.9. This solution is showed in Fig. 2. The main dc voltage is calculated with equation (1) where $V_{d0} = \dfrac{3}{\pi}\hat{V}_L$ and $\hat{V}_L$ is the line peak voltage and $\alpha$ the command angle of conduction in the thyristor.

$$V_d = V_{d0}\cos\alpha \tag{1}$$

As $V_{d0} = \dfrac{3}{\pi}\hat{V}_{Linea} = 514.16V$ there are angle variations from $\alpha = 38.986º$ when $V_d = 400V$ to $\alpha = 67.129º$ when $V_d = 200V$.

#### 1)  Filter designs

##### a)  Aperiodic filter

This filter must reduce the amplitude of current harmonics bigger than the cut frequency $\omega_C$. It is an LC filter with the capacitors in delta. The frequency is selected $\omega_C = 4\omega$. The capacity is choose to compensate the reactive power consumed by the rectifier when $V_d = 400V$ that corresponds to $\alpha = 38.986°$, for a dc current value of $I_0 = 170A$. That reactive power can be calculated with equation (2) where $P$ is the active power consumed by the rectifier and $\alpha$ is the conduction angle.

$$Q = P*tg\alpha \tag{2}$$

Being $P = P_d = 68000W$ and $\alpha = 38.986º$, it results $Q = Q_2 = 55037.219VAR$.

The capacity in delta connection $C_{f\Delta}$ is calculated with equation (3) where $Q$ is the reactive power, $\omega = 2\pi f$, $f$ is the grid frequency and $U_L$ is the line voltage.
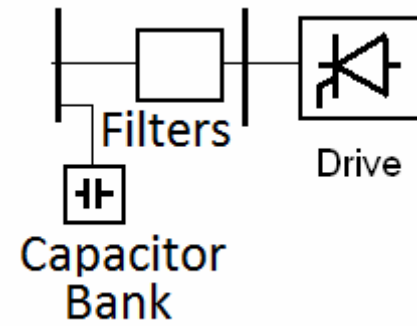


Fig. 2. Diagram of proposal I.

$$C_f = \frac{Q}{\omega(3U_L{}^2)} \tag{3}$$

How $Q = Q_2 = 55037.219VAR$, $\omega = 314.16rad/s$ y $U_L = 381.051V$ it results $C_{f\Delta} = 402.178\mu F$

La inductance $L_f$ is calculated with equation (4) where $\omega_C = 4\omega$, $\omega = 2\pi f$ and $C_f = C_{f\lambda} = 3C_{f\Delta}$.

$$L_f = \frac{1}{(\omega_C)^2 C_f} \tag{4}$$

If $\omega = 314.16rad/s$, $\omega_C = 1256.64rad/s$ and $C_f = C_{f\lambda} = 1206\mu F$ it results $L_f = 0.525mH$.

##### b)  5th and 7th harmonics filter

This stage is composed by two LC series filters placed in shunt with the rectifier. It must filter the $5^{th}$ and $7^{th}$ current harmonic.

To filter the 5th current harmonic component, the inductance is calculated by equation (4) with $\omega_C = 5\omega$. Adopting $C_{f5} = 33\mu F$ and $\omega_C = 1570.8rad/s$ yields $L_{f5} = 12.28mH$.

To filter the 7th current harmonic component, the inductance is calculated by equation (4) with $\omega_C = 7\omega$. Stating $C_{f7} = 33\mu F$ and $\omega_C = 2199.12rad/s$ one obtains $L_{f7} = 6.26mH$.

#### 2)  Capacitors for reactive power compensation

As the dc voltage varies from $V_d = 200V$ to

$V_d = 400V$ the compensation task needs a variable capacity and an automatic compensator or one static compensator should be used.

The maximum capacity of the capacitor bank is required when the rectifier operates with $V_d = V_{d1} = 200V$, then the reactive power is maximum and may be calculated by equation (2) where $P = P_{d1} = 34000W$ and $\alpha = 67.129º$. It results $Q = Q_1 = 80603.06VAR$.

The reactive power was compensated for $V_d = V_{d2} = 400V$ and the capacitors must compensate the remaining $Q_1 - Q_2 = 25565.84VAR$. Also, the reactive power $Q_F$ consumed by the aperiodic filter inductance $L_f$ must be compensated. $L_f$ may be calculated using equation (5) where $X_{Lf} = \omega L_f$ is the filter reactance and $I_F$ is the rms currents that flow through $X_{Lf}$. Therefore:

$$Q_F = 3 * (I_F)^2 X_{Lf} \tag{5}$$

As $I_F = 138.804A$, and $X_{Lf} = 0.1649\Omega$ it results $Q_F = 9531.22VAR$

The capacity is calculated by equation (3) with $Q = (Q_1 - Q_2) + Q_F = 35097.06VAR$ and $U_L = 381.051V$, thus yielding $C_{C\Delta} = 256.46\mu F$.

### 3)　Power lost and efficiency

The power loss is mainly the power dissipated by Joule effect in the filter damping resistors. For the aperiodic filter the current may be obtained using equation (6) where $R_S$ is the resistance and $X_{Cf}$ the reactance of the aperiodic filter.

$$I_f = \frac{U_L}{\sqrt{R_S^2 + X_{Cf}^2}} \tag{6}$$

As $R_S = 0.1\Omega$, $U_L = 381.051V$ and $X_{Cf} = 7.918\Omega$ it results $I_f = 48.12A$. The power loss is calculated by equation (7) where $I_f$ is the rms current passing through the resistor $R_S$.

$$P_f = 3 * I_f^2 * R_S \tag{7}$$

It results $P_f = 694.66W$.

In reference to the power lost in the 5th harmonic filter this power is calculated using equation (7) for two limits which corresponds to voltages from 200V to 400 V. With $R_{S5} = 0.1\Omega$ and for 200V, and the rms current obtained by simulation $I_{f5} = 50.47A$, it results $P_{f5} = 764.17W$. Also, for 400V and $I_{f5} = 56.45A$ one obtains $P_{f5} = 955.98W$.

For the 7th harmonic filter, the equation (7) may be also applied to calculate the power losses. With $R_{S7} = 0.1\Omega$, for 200V and the rms current obtained by simulation $I_{f7} = 16.578A$ it results $P_{f7} = 82.45W$, while for 400V if $I_{f7} = 27.914A$ one obtains $P_{f7} = 233.757W$.

The efficiency is calculated by equation (8), where $P_d$ is the power consumed by the rectifier and $P_{Loss}$ is the power lost in the filters: $P_{Loss} = P_f + P_{f5} + P_{f7}$.

$$\eta = \frac{P_d}{P_d + P_{Loss}} \tag{8}$$

There are two values of efficiency calculated for 200V and 400V. As the power consumed by the rectifier for 200V is $P_d = 34000W$ one obtains $\eta = 0.956$. For 400V the power consumed is $P_d = 68000W$ and the efficiency becomes $\eta = 0.973$.

### 4)　Performance with frequency changes

The simulations done for 50Hz and 49Hz show that the dc voltage maintains its harmonic spectrum when the frequency changes. The line current also maintains the spectrum, but in this case, the harmonics 5th y 7th become bigger than the others when the frequency varies.

There are usually low variations in the line currents and the filters currents, so the efficiency does not change a lot respect its value at 50 Hz.

The shift between voltage and current keeps $\cos\varphi \geq 0.96$ when the frequency changes.

### 5)　Performance with asymmetrical voltages

By means of simulations the performance with asymmetrical voltages was assessed. Two types of asymmetry were studied, one of them named (+15%, 0%, 0%) has the phase R risen up 15%, letting both remaining phases at the nominal values. The other case, named (+10%,-5%, 0%), has the phase R increased 10%, while the phase S drops 5% and T remains at the nominal value. Some results are shown in tables I, II, III, y IV. When voltage asymmetries occur, the 3th harmonic component appears in the line current (added to the other harmonics components). This 3th component is not

present in the 5th and 7th harmonics filters. It should be pointed that this 3th harmonic component is in direct sequence. The dc voltage changes its spectrum and all even harmonics components appear. However, the efficiency does not get worse when there are voltage asymmetries.

### B. Proposal II

It consists in placing a transformer feeding the rectifier (drive) to have α zero so the reactive power consumed Q be null too. Also, one must place filters. The proposal is depicted in Fig.7. Using equation (1) the necessary line voltage can be calculated for $V_d = 400V$ with $\alpha = 0$, this results in

$$\hat{V}_L = \frac{\pi}{3}V_d = \frac{\pi}{3}400 = 418.88V \ .$$

#### 1)    Transformer design

The transformer relation is calculated by equation (9), where $n_1$ and $n_2$ are the number of turns of the primary and secondary transformer coils, while $U_1$ y $U_2$ are the primary and secondary voltages.

$$\frac{n_1}{n_2} = \frac{U_1}{U_2} \tag{9}$$

The voltage can change in 10% maximum, then the worst case to design the transformer occurs when the voltage is 198V. As $V_F = \dfrac{\hat{V}_L}{\sqrt{3}\sqrt{2}}$ the transformer relation becomes

$$\frac{n_1}{n_2} = \frac{198}{171} = 1.157 \ .$$

It must note that when the phase rms voltage is 220V the conduction angle necessary to obtain a dc voltage of 400V is $\alpha = 25.92°$. Then the secondary rms voltage is $U_2 = \dfrac{n_2}{n_1}U_1 = \dfrac{1}{1.157}220 = 209V$. Therefore, when the dc voltage is 200V the conduction angle is $\alpha = 63.277°$.

#### 2)    Filter design

##### a)    Aperiodic filter design

When the dc voltage is 400V, the reactive power consumed has the lowest value. It can be calculated by equation (2). If $P = P_d = 68000W$ one obtains $Q = 33048.36VAR$.

The capacity necessary to compensate the reactive power is calculated using equation (3). As $U_L = 329.34V$ it results

$$C_{f\Delta} = 323.28\mu F \ .$$

The inductance is calculated by (4). If $\omega_C = 4\omega$ and

TABLE I
LINE CURRENTS-VOLTAGE ASYMMETRY (+10%,-5%,0%)

| RMS-A | | R | S | T |
|---|---|---|---|---|
| I | 200[V] | 74.77 | 74.22 | 71.59 |
| | 400[V] | 134.87 | 132.82 | 132.67 |
| I 5 | 200[V] | 37.04 | 38.4 | 37.38 |
| | 400[V] | 38.95 | 40.09 | 38.73 |
| I 7 | 200[V] | 12.37 | 13.18 | 12.58 |
| | 400[V] | 19.11 | 19.57 | 18.77 |
| Asym +10%,-5%,0% | | | | |

TABLE II
DC VOLTAGE-VOLTAGE ASYMMETRY (+10%,-5%,0%)

| Vd | 200[V] | 400[V] |
|---|---|---|
| 0 | 205.9 | 410.8 |
| 2do | 18.13 | 18.2 |
| 4to | 5.43 | 5.47 |
| 6to | 158.4 | 109.5 |
| 8vo | 3.22 | 3.47 |
| 12do | 69.59 | 46.27 |
| 18vo | 43.47 | 24.86 |
| 24to | 31.89 | 16.94 |
| Asym +10%,-5%,0% | | |

TABLE III
FILTER CURRENTS VOLTAGE-ASYMMETRY (+15%,0%,0%)

| | | R | S | T |
|---|---|---|---|---|
| I | 200[V] | 74.77 | 74.22 | 71.59 |
| | 400[V] | 162.89 | 160.76 | 159.39 |
| I 5 | 200[V] | 37.04 | 38.4 | 37.38 |
| | 400[V] | 45.87 | 47.51 | 46.56 |
| I 7 | 200[V] | 12.37 | 13.18 | 12.58 |
| | 400[V] | 24.27 | 24.85 | 23.86 |
| Asym +15%,0%,0% | | | | |

TABLE IV
DC VOLTAGES-VOLTAGE ASYMMETRY (+15%,0%,0%)

| Vd | 200[V] | 400[V] |
|---|---|---|
| 0 | 210 | 419.1 |
| 2do | 20.55 | 20.75 |
| 3ro | 0.06 | 0.049 |
| 4to | 6.16 | 6.17 |
| 6to | 162.7 | 112 |
| 8vo | 3.67 | 4.43 |
| 12do | 71.26 | 46.48 |
| 18vo | 43.88 | 23.07 |
| 24to | 32.01 | 15.24 |
| Asym +15%,0%,0% | | |

$C_{f\lambda} = 3C_{f\Delta}$ it results $L_f = 0.653mH$ .



Fig. 7. Diagram of proposal II.

### b)　　5th y 7th harmonics filter design

The design procedure is similar to the one done in the proposal I.

### 3)　　Capacitors for compensation of reactive power

It was seen that when dc voltage is 400V the reactive power consumed has the lowest value. Because the voltage varies form 200V to 400V, the highest reactive power appears when the dc voltage is 200V . It should be calculated using (2).

Being $P = P_d = 34000W$ and $\alpha = 63.277°$ it results $Q = 67533.92VAR$ .

Also the reactive power in the aperiodic filter inductance $L_f$ must be compensated. The inductance can be calculated by equation (5). If $I_F = 138.804A$ and $X_{Lf} = 0.2051\Omega$ one obtains $Q_F = 11854.78Var$

The highest capacity is required to compensate the difference of reactive power lost for 200V and 400V plus the reactive power $Q_F$ of the aperiodic filter. Therefore, using (3) with $Q = 46340.34VAR$ , one obtains $C_{f\Delta} = 453.31\mu F$ .

In the practice it is necessary a variable capacity, for this purpose, an automatic compensator bank or a static compensator can be used.

### 4)　　Power loss and efficiency
The power losses are power dissipated by Joule effect in the filter resistances. For the aperiodic filter the current is calculated using equation (1). If $R_S = 0.1\Omega$ , $U_L = 381.051V$ , $X_{Lf} = 9.8547\Omega$ it results $I_f = 38.665A$ . Then the power loss is calculated by equation (7), resulting $P_{fA} = 448.49W$ .

For the 5$^{th}$ harmonic filter the power loss for the dc voltages 200V and 400V can be obtained using equation (7). If $R_{S5} = 0.1\Omega$ , with the rms currents obtained by simulation $I_{f5} = 45.26A$ for 200V , and $I_{f5} = 56.356A$ for 400V, it results $P_{f5} = 614.54W$ for 200V and $P_{f5} = 952.79W$ for 400V.

For the 7$^{th}$ harmonic filter the power loss for the dc voltages 200V and 400V may be calculated using equation (7). If $R_{S7} = 0.1\Omega$ , with the rms currents obtained by simulation $I_{f7} = 16.637A$ for 200V and $I_{f7} = 35.269A$ for 400V it
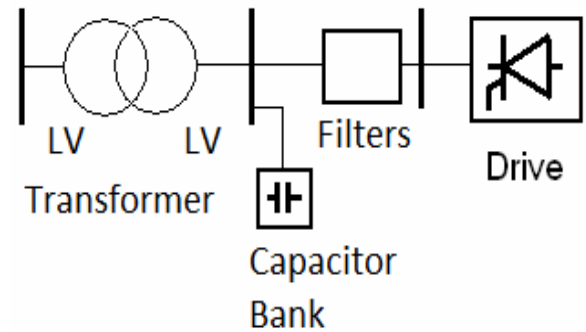
results $P_{f7} = 83.037W$ for 200V and $P_{f7} = 373.17W$ for 400V.

The efficiency is computed using equation (8), for dc voltages 200V and 400V. As the active power consumed is $P_d = 34000W$ for 200V and $P_d = 68000W$ for 400V, it results $\eta = 0.967$ for 200V and $\eta = 0.974$ for 400V.

### 5)　　Performance with frequency change

From the simulations done by introducing frequency changes, one gets the same conclusions obtained when considering the proposal I of the study case I, because similar results were obtained.

### 6)　　Performance with asymmetrical voltages

With the simulations in which asymmetrical voltages are considered, two types of asymmetry were defined, one of them named (+15%, 0%, 0%) where only phase R rises 15% while keeping both others at nominal value, and other one named (+10%,-5%, 0%) where phase R rises 10% while S is reduced 5% and the remaining phase T keeps the nominal value. The performance with asymmetrical voltages is similar to the one presented in the proposal I of study case I, because the results obtained were quite similar.

## V. STUDY AND SIMULATIONS OF SOLUTIONS FOR STUDY CASE II

In this case the load is an excitation coil of a synchronic machine. The information about the excitation coil was presented in III A, which must work with a dc voltage of 130V and a dc current of 100A. Similarly to study case I, the solutions must reduce the current harmonics components and improve the $\cos\varphi$ .

### A. Proposal I

This proposal is presented in Fig.8. The filters in the front of the rectifier must reduce the current harmonics components. Also capacitors to compensate el $\cos\varphi$ to 0.8 are included.

The automatic compensator rises the $\cos\varphi$ to a level higher that 0, 9.

The dc voltage it calculated with equation (1). If $V_{d0} = 514.16V$ and $V_d = 130V$ it results $\alpha = 75.32°$. Therefore, it is possible to use a free wheel diode. When using a free wheel diode, the negative part of the output voltage is eliminated and the line current improves its power spectrum.

The average output voltage with a free wheel diode is given by equation (9)

$$V_0 = V_{d0}\left[1 + \cos\left(\alpha + \frac{\pi}{3}\right)\right] \quad (9)$$

If $V_{d0} = \frac{3}{\pi}\hat{V}_{Linea} = 514.16V$ and $V_d = 130V$ it results $\alpha = 78.364°$. The line current produced by the rectifier without filters and with RL load type, has the shape indicated in Fig. 9 b), the fundamental component and the harmonics fulfill the relations $\left|\frac{\hat{I}_5}{\hat{I}_1}\right| = 0.1409$ and $\left|\frac{\hat{I}_7}{\hat{I}_1}\right| = 0.0628$.

When there is not a free wheel diode, the line current has the shape of Fig. 9a) and the harmonic spectrum satisfies $\left|\frac{\hat{I}_h}{\hat{I}_1}\right| = \frac{1}{h}$, where $h$ is the harmonic indices, $\left|\frac{\hat{I}_5}{\hat{I}_1}\right| = 0.2$ and $\left|\frac{\hat{I}_7}{\hat{I}_1}\right| = 0.14286$. Therefore, using a free wheel diode is advisable because it improves the line current harmonic spectrum.

*1) Filter design*

  *a)      Aperiodic filter*

The capacity is calculated to compensate the reactive power consumed by the rectifier when $\alpha = 78.36364°$. The reactive power consumed is calculated using equation (10)

$$\frac{Q}{P} = tg\left[\frac{1}{2}\left(\alpha + \frac{\pi}{3}\right)\right] \quad (10)$$

If the active power is $P = P_{dc} = 13000W$, one obtains $Q = 34190.057VAR$. Next, the required capacity is calculated by equation (3), where $U_L = 381.051V$, yielding $C_{f\Delta} = 249.8\mu F$.

The inductance of the filter is calculated with equation (4) where $\omega_C = 4\omega$, $C_{f\lambda} = 3C_{f\Delta} = 750\mu F$, obtaining $L_f = 0.844mH$.
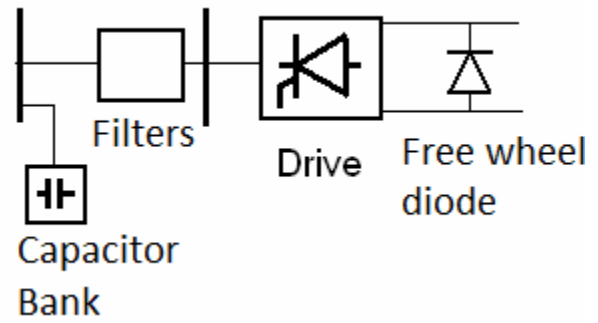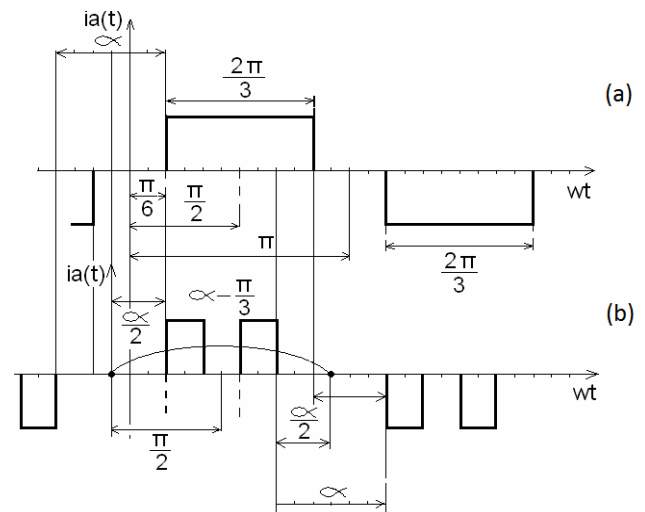


Fig. 8.Diagram of proposal III.



Fig. 9.Line Current in a rectifier with R-L load.
  (a)    Within free wheel diode
  (b)    With free Wheel Diode

  *b)      5th and 7th filters*

For $5^{th}$ harmonic filter the inductance is calculated using equation (4). If $\omega_C = 5\omega$ and with a capacity of $C_5 = 33\mu F$ it results $L_{f5} = 12.28mH$.

For the $7^{th}$ harmonic filter the inductance is calculated with eq. (4). If $\omega_C = 7\omega$ and $C_7 = 33\mu F$ it results: $L_{f5} = 6.2659mH$.

*2) Capacitors for compensation of reactive power*

From the simulations it results that $\cos\varphi$ is more than 0.9, so compensation is not necessary.

*3) Power loss and efficiency*

For the aperiodic filter the rms current is calculated using equation (6). If $r_s = 0.1\Omega$ and $X_C = 12.73\Omega$, one obtains $I_{fA} = 29.926A$. The power loss is calculated with equation

(7) and results $P_{fA} = 268.67W$ .

For the 5$^{th}$ harmonic filter the power loss is calculated by equation (7). If $r_{S5} = 0.1\Omega$ and the rms current obtained by simulation is $I_{f5} = 44.156A$ , it results $P_{f5} = 584.93W$ .

For the 7$^{th}$ harmonic filter the power loss is calculated by equation (7). If $r_{S7} = 0.1\Omega$ and the rms current obtained by simulation is $I_{f7} = 19.72A$ , it results $P_{f7} = 116.71W$ .

The efficiency is calculated with equation (8). If the active power consumed is $P_d = 13000W$ and the total power loss is $P_{Loss} = 970.31W$ it results $\eta = 0.93$ .

*4) Performance with change in frequency*

From the simulations in ATPDraw having frequency changes of $\pm 1Hz$ , the results are presented in tables V, VI, y VII. It may be appreciated that the dc voltage harmonic spectrum maintains the form but there is some rise in the harmonics components.

The line current keeps with little change the harmonic spectrum shape, even if the values of the harmonic components raise in general. However, the harmonic components 5$^{th}$ and 7$^{th}$ grow more than the others. The current in the 5$^{th}$ and 7$^{th}$ filters reduce their values when the frequency changes.

*5) Performance with asymmetrical voltages*

Simulations in ATPDraw with voltage asymmetry were done including two types of asymmetry, one of them named (15%, 0%, 0%) has the phase R above 15% the nominal value, the phases S and T with 0% of change, while the other one named (+10%, -5%, 0%) has a phase R rise of 10% , a phase S decrease of 5% from the nominal value and phase T unchanged.

The simulations results show that the dc voltage has all the even harmonic components, but the harmonic components multiple of six become significant.

In the harmonic spectrum of the line current, a 3$^{rd}$ harmonic component appears, while the rest of the harmonics components do not vary. The harmonic spectrum of the filters currents keeps the same values for its components.

*B. Proposal II*

In this proposal there is a transformer to have $\alpha = 0$ and then the reactive power consumed by the rectifier is null.

The rms line voltage necessary to meet with a dc voltage of 130V and $\alpha = 0$ can be calculated using equation (1). It results a required peak voltage $\hat{V}_L = 136.135V$ .

*1) Transformer design*

TABLE V
LINE CURRENT -CHANGE OF FREQUENCY

| I (phase) RMS-A | 50 | 49 | 51 |
|---|---|---|---|
| RMS total | 23.69 | 28.86 | 30.51 |
| 1 | 23.46 | 25.39 | 29.72 |
| 5 | 2.34 | 13.68 | 7.38 |
| 7 | 0.74 | 3.69 | 0.87 |
| 11 | 1.63 | 0.63 | 0.51 |
| 13 | 1.33 | 1.06 | 0.28 |

TABLE VI
FILTERS CURRENTS-CHANGE OF FREQUENCY

| I RMS-A | 50 | 49 | 51 |
|---|---|---|---|
| I 5 | 31.13 | 22.59 | 25.19 |
| I 7 | 13.73 | 1.87 | 4.61 |

TABLE VI
DC VOLTAGE-CHANGE OF FREQUENCY

| Vd-V | 50 | 49 | 51 |
|---|---|---|---|
| 0 | 133.4 | 130.1 | 141.2 |
| 6 | 146.2 | 175.5 | 173.8 |
| 12 | 52.73 | 57.29 | 78.96 |
| 18 | 41.62 | 53.06 | 51.78 |
| 24 | 34.42 | 32.35 | 41.3 |
| 30 | 23.18 | 29.93 | 31.41 |

A primary voltage of $U_1 = 198V$ , which is 10% below the nominal value , is adopted. With the $\hat{V}_L$ calculated, the rms secondary voltage is $U_2 = \dfrac{\hat{V}_L}{\sqrt{2}\sqrt{3}} = 55.58V$ . Then the transformation relation is calculated from (9) resulting 3.5629.

In nominal conditions there is a phase voltage of 220V and from the transformation relation calculated it can be deduced that the rms secondary voltage is 61.79V, then the angle $\alpha$ may be calculated by equation (1) obtaining $\alpha = 25.926°$ .

*2) Filters design*

*a)        Aperiodic filter*

The reactive power consumed by the rectifier is calculated by eq. (2), if $P = P_d = 13000W$ and $\alpha = 25.926°$ giving $Q = 6319.75Var$ . The capacity is obtained using (3). Since $U_L = U_2\sqrt{3} = 96.26V$ it results $C_{f\Delta} = 723.63\mu F$ . The inductance is calculated using (4). If $\omega_C = 4\omega$ and $C_{f\lambda} = 3C_{f\Delta}$ it obtains $L_f = 0.2916mH$ .

*b)        5th and 7th harmonics filter*

These filters are designed in the same form that it was pointed in the proposal I of this study case II.

### 3)  Capacitors for reactive power compensation

From simulations in ATPDraw it can be seen that $\cos\varphi$ is above 0.9 and there is no need of compensation.

### 4)  Power loss and efficiency

For the aperiodic filter the current is calculated by (6). If $R_S = 0.1\Omega$, $U_L = 96{,}26V$, $X_{f\Delta} = 4.398\Omega$ it results $I_f = 21.87A$. The power loss is calculated using equation (7). One obtains $P_{fA} = 143.48W$.

The power loss in the 5th harmonic filter is calculated by equation (7). If $R_{S5} = 0.1\Omega$ and the rms current obtained by simulation is $I_{f5} = 21.52A$ it results $P_{f5} = 138.93W$.

The power loss in the 7th filter is calculated using equation (7). If $R_{S7} = 0.1\Omega$ and the rms current obtained by simulation is $I_{f7} = 14.4A$ it results $P_{f7} = 62.21W$.

The efficiency is calculated with the equation (8). If $P_d = 13000W$ and the total power loss is $P_{Loss} = 344.62W$ it results $\eta = 0.97$.

### 5)  Performance with frequency changes

From simulations in ATPDraw one may obtain similar results that those ones pointed for the proposal I of the study case II.

### 6)  Performance with asymmetrical voltages

Similarly, from simulations in ATPDraw one can obtain similar results that those ones pointed for the proposal I of the study case II.

## CONCLUSIONS

From the analysis of the proposals one may conclude that for the Case I, working with variable voltages from 200V to 400V the better choice is the option I, because it needs a lower value of capacity of the automatic compensator and it is not necessary a transformer.

For the Case II, with constant voltage equal to 130V, there are similar efficiency and performance, so the option I, with free wheel diode and without transformer, was adopted.

## REFERENCES

[1]  R. Chauprade, "Control electrónico de los motores DC" ,*2da* ed. Gustavo Gilli, México DF.

[2]  G. Seguier, "Los convertidores estáticos de energía. Conversión alterna-continua", *1ra* ed. Gustavo Gilli, México DF.

[3]  G. Seguier, "Electrónica de potencia", *3ra* ed. Gustavo Gilli, Barcelona, España.

[4]  W. M. Flanagan, "Handbook of transformer design of applications" , *2da* ed., Mc Graw Hill, USA.

[5]  E. A. Cano Plata, H. E. Tacca, "Modelado y simulación en electrónica de potencia con ATP", *1ra* ed. Universidad Nacional de Colombia. Colombia.

[6]  S. R. Castaño, E. A. Cano Plata, "Calidad de servicio de energía eléctrica", *1ra* ed. Universidad Nacional de Colombia. Colombia.