ANALISIS DE LAS VARIACIONES DE VOLTAJE OCASIONADAS POR CONVERTIDORES DE POTENCIA.

Analysis of Voltage Notches Caused by Power Converters

ANDRÉS ESCOBAR MEJÍA
M.Sc. en Ingeniería Eléctrica
Profesor Asistente
Universidad Tecnológica de Pereira
andreses1@utp.edu.co

MAURICIO HOLGUÍN LONDOÑO
M.Sc. en Ingeniería Eléctrica
Profesor Asistente
Universidad Tecnológica de Pereira
mau.hol@utp.edu.co

RESUMEN
Los elementos de estado sólido han sido de gran importancia en la conversión de potencia ac-dc y dc-ac a nivel de transmisión. A nivel de transmisión y/o distribución los conversores son usados para acoplar dispositivos FACTS, acoplar generadores de diferentes tipos a la red e integrar fuentes renovables de energía. Sin embargo, en ocasiones ellos generan la degradación de la calidad de la energía eléctrica dada su naturaleza no lineal. El presente artículo presenta los diferentes problemas causados a nivel de distribución por la implementación de un rectificador trifásico y las posibles soluciones en el punto de acople con la red para mitigar su efecto.

PALABRAS CLAVES: Calidad de energía, convertidores de potencia, variaciones de voltaje.

ABSTRACT
Solid state elements have been used in many applications that use power converters in transmission and distribution systems. At both the transmission and distribution level power converters play and important role integrating not only conventional generators and FACTS devices but renewable sources. Power quality degradation is the price that must be paid it however. This paper analyzes different voltage problems that ac/dc converters may create. Special attention will be given to voltage notches and the possible alternatives to reduce its effect.

KEYWORDS: *Power quality, power converters, voltage variations, voltage notches.*

1. INTRODUCTION

Three-phase controlled rectifiers have a wide range of applications including motor drives, power supplies, and large high voltage direct current (HVDC) transmission systems [1], [2]. The principal purpose of a rectifier bridge is to produce a dc voltage and current from an ac source through a rectifying process that can be controlled or uncontrolled.

Uncontrolled rectification is performed by diodes where the conduction time occurs naturally with the fluctuation of supply voltage and load [3]. In this process the magnitude of the output dc voltage is constant and only varies with the ac source voltage (a diode rectifier bridge cannot control the dc magnitude).

Controlled rectification is accomplished using either naturally commutated (or line-commutated) power electronic devices (thyristors) or forced-commutated devices (GTO, IGBT, MOSFET) [2], [3]. In the case of line-commutated devices, a gate terminal is used to control the conduction time of the device which can be used to determine the polarity of the source voltage. Most thyristors have the characteristic that the gate signal can be removed and the device will remain in its forward-conduction mode. This is an important distinction between thyristors and other power electronic devices [2]. Thyristor-based controlled three-phase bridge rectifiers control the dc output load voltage by varying the thyristor firing angle $(0^0 < \alpha < 180^0)$. Forced-commutated rectifiers are made with semiconductor devices (IGBTs) with gate-turn-off capability which allows full control of the converter due to the switch on and off actions [4].

Due to the commutation process in a rectifier bridge, the input line currents are far from being sinusoidal, which means that harmonic components are introduced into the system. There are many topologies which use thyristor converters; however, in this work the characteristics of a three-phase full-wave rectifier are analyzed along with the different harmonics characteristics inherent to the rectification process. The voltage and current waveforms resulting from the rectification process will be compared with those that may exist throughout the power system and which are defined in the Standard IEEE 519-1992 [5].

Fecha de Recepción: 13 de Mayo de 2011
Fecha de Aceptación: 14 de Julio de 2011

2. THREE-PHASE RECTIFIER CIRCUIT

The three-phase thyristor rectifier is perhaps one of the most widely used converter units in power electronics [6]−[8]. A conventional three-phase rectifier is shown in Fig. 1. The circuit includes a three-phase voltage source, an inductance L_S, a rectifier bridge, an inductance L_D and a resistive load connected at the dc-side. The inductance L_S represents the equivalent impedance of the system in which the rectifier is connected. The rectifier bridge uses thyristors as switched devices which conduction time can be controlled. The inductance L_D is used to filter the dc output.

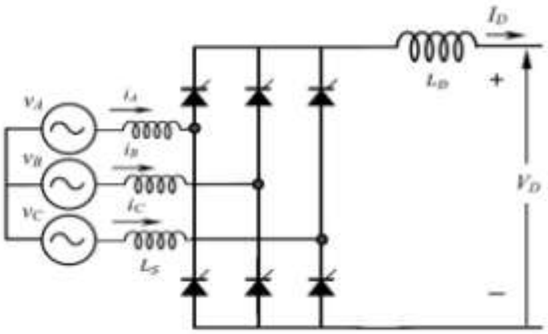


Figure 1. Three-phase thyristor converter

3. THYRISTOR-BRIDGE RECTIFIER OPERATION

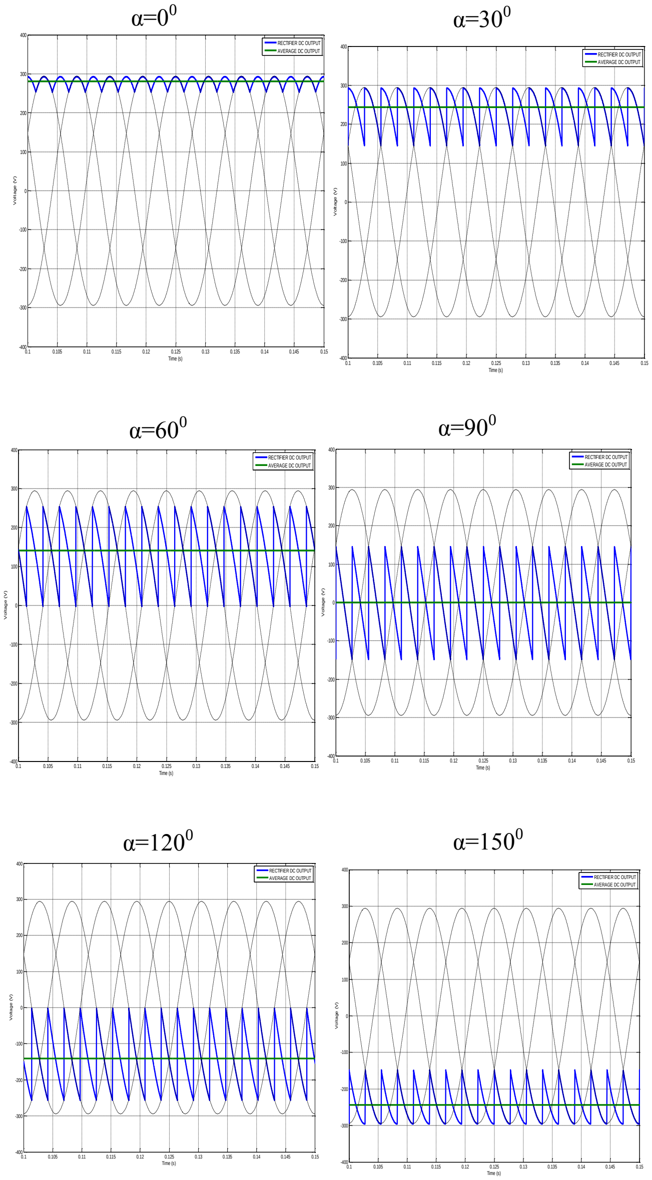
In some power applications is desired to control the dc voltage that is applied to the load. For thyristors the conduction time can be controlled and it depends on the line-frequency ac voltage waveform and the control inputs; the average dc output voltage can be controlled by delaying the instants at which the thyristors are followed to start conduction [4] as is defined in equation (1).

$$V_D = \frac{3\sqrt{2}}{\pi} V_{LL} \cos\alpha \tag{1}$$

Where V_{LL} is the line-to-line rms voltage at the rectifier input and α is the delay or firing angle which is the phase angle of the voltage at which the thyristor on. In order to understand the rectifier operation two cases are contemplated. First, the rectifier without inductors at the dc-side and second, considering the inductors.

3.1 Ideal Circuit

To analyze the rectifier operation, first it is assumed that L_S is equal to cero and the current I_D is purely dc. By adjusting the firing angle is possible to adjust the average value of the load voltage. Fig 2 shows the voltage at the dc-side when the firing angle varies from 0^0 to 150^0. Since there is not an impedance between the source and the rectifier, the rectifier input voltage is sinusoidal; however the line current looks like a square waveform. Phase a input current is shown in Fig. 3 when the delay angle is 60^0 and 90^0. For this particular case the line-to-line input voltage is 208-Vrms and I_D is 10A.


$\alpha=0^0$ $\alpha=30^0$

$\alpha=60^0$ $\alpha=90^0$

$\alpha=120^0$ $\alpha=150^0$

Figure 2. Rectifier dc-side when α varies from 0^0 to 150^0

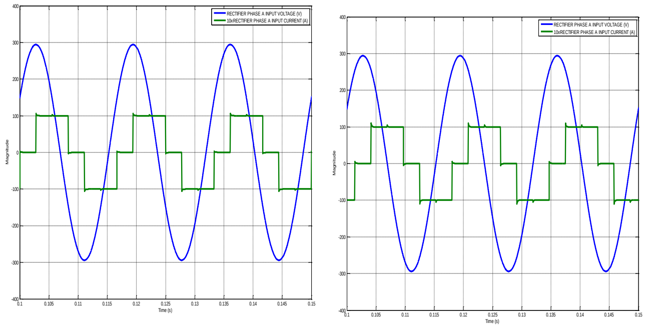


Figure 3. Rectifier input current for α equal to 60^0 and 90^0

The total rms value of the input current can be calculated as [4],

$$I_S = \sqrt{\frac{2}{3}} I_D. \qquad (2)$$

3.2 Real circuit inclusion of L_S

In most cases, the three-phase rectifier is connected to a power grid through a transformer. Both, conductor and transformer have impedances that must be considered for the analysis. To evaluate the impact of the L_S in the system and example is presented in next the section.

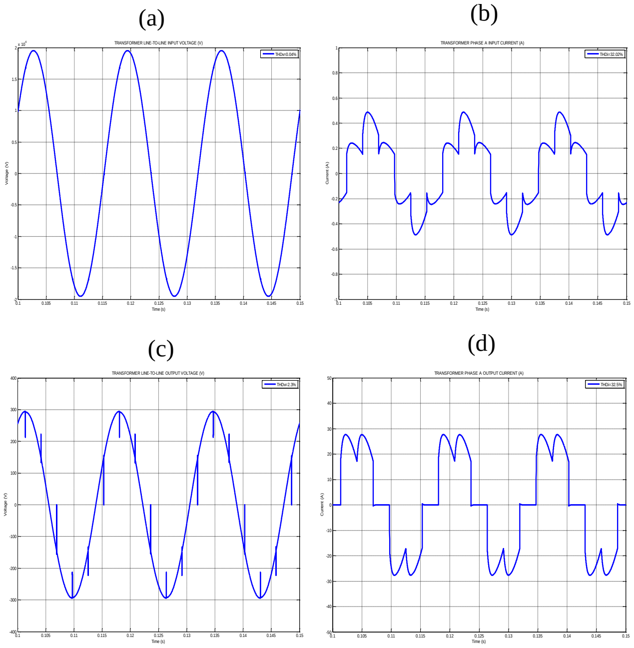
4. SYSTEM UNDER ANALYSIS

A three-phase fully-controlled rectifier based-on thyristors shown in Fig. 1 is connected to a power system through a 75-kVA 13.8kV-208V delta-wye distribution transformer whose series impedance is (1.3+j1.6) % on the transformer base. The short-circuit power on the 13.8-kV side is 250MVA. A 10-Ω resistor is connected through a 3mH inductor at the dc-side. The thyristors firing angle is 30^0.

The system characteristic impedance is determined as 0.76Ω at the transformer primary side.

By Fourier analysis, the rectifier input rms current at fundamental frequency is determined as 18.87A. Using this value as the maximum demand load current the short-circuit ratio I_{SC}/I_L at the PCC (in this case at transformer secondary side) is 36,743.

Figure 4 shows both voltage and current waveforms at transformer primary and secondary side.



(a) (b) (c) (d)

Figure 4. Transformer input voltaje and current (a), (b), and output voltage and current (c), (d), when the delay angle is set at 30^0

5. POWER QUALITY ANALYSIS

As is presented in Fig 4, at the primary side the THDv is 0.04% and the THDi is 32.02%. At the secondary side the THDv is 2.4% and the THDi is 32.5%. Table 10.3 in [5] set up the limits for the current distortion at the PCC. As is listed in Table 1, at the transformer secondary side the fifth and the eleventh harmonic components exceed the recommended values. Thus, a tuned filter may be implemented to reduce the magnitude of these particular harmonics.

Figure 4(c) shows voltage notches that are produced when the ac-side is shorted momentary during the commutation interval by the thyristors through the inductance L_S. Figure 5 shows more in detail notch characteristics for voltages at transformer primary and secondary side. At the PCC the notch depth is 147V. The width of the notch is 10μs, thus the notch area is 1,470 volt-microseconds. Table 10.2 in reference [5] establishes that the notch area must not exceed 7,107[1]. For this particular case the notch limit is not exceeded. For the notch analysis the methodology presented in [9] is contemplated.

Table 1. Current distortion in percent of fundamental at PCC

Harmonic	I(%)	θ_i(Deg)	Exceeds Limit?
1	100	1.30	-
5	26.94	193.30	**YES**
7	8.90	149.00	**NO**
11	10.05	4.10	**YES**
13	4.39	-22.30	NO

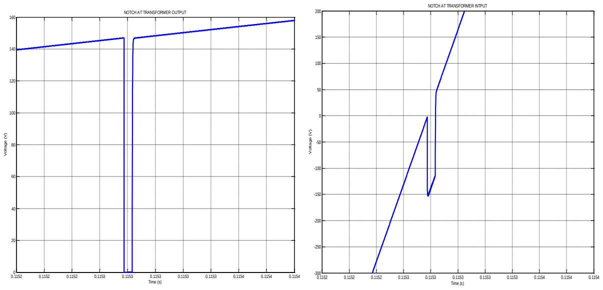


Figure 5. Transformer input and output voltage

In order to eliminate the fifth and the eleventh harmonic components at the PCC, filters must be used to absorb harmonic currents. This allows keeping current distortion within limits listed in Table 10.3 [5]. Two single-tuned filters are designed following the same methodology presented in [10]. In this case is required to reduce the

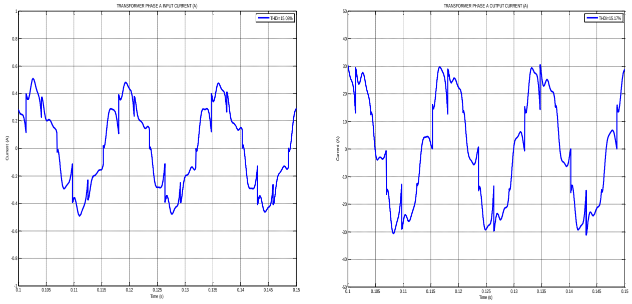
---

[1] According to [5] the value A_N for other than 480 V systems should be multiplied by V/480.

magnitude of the 5th and the 11th harmonics. For each filter the fixed capacitors, placed at PCC, are rated at 50% of the rectifier rated power (6.8KVA). In Fig 6, the transformer input and output current are presented. Table 2 lists the current distortion after the filtering process.

Table 2. Current distortion in percent of fundamental at PCC

Harmonic	**I(%)**	**θ_i(Deg)**	**Exceeds Limit?**
1	100	60.60	-
5	6.88	-8.00	**NO**
7	8.69	147.20	**NO**
11	0.23	-64.40	**NO**
13	3.24	-23.70	**NO**



(a) (b)

Figure 6. Transformer input (a) and output (b) currents.

Notice in Fig. 6 that the THDi for the high-voltage side is now 15.08% while for the low-voltage side or PCC is 15.17%. Placing the two-single tuned filters reduces the THDi by approximately 50%. Now, increasing the bank capacitor rated allows reducing more the fifth and the eleventh harmonics, however more current is drawn from the source. For this case the input rms current of the rectifier is 19.26A.

6. CONCLUSIONS

Results show that static converters cause significant problems with power quality. However, strategies like placing filters and line reactors alleviate the power quality degradation at the PCC by reducing harmonic magnitudes to an acceptable level.

At the PCC current harmonic distortion is mainly cause by the rectifier, however, voltage harmonic distortion is caused when large line impedances are connected between the rectifier and the source. This means that the utility is responsible for voltage distortion.

7. REFERENCES

[1]. R. Shaffer, “Fundamentals of power electronics with Matlab,” first edition, 2007, Da vinci engineering series, Thomson Learnin Inc, USA.

[2]. M. H. Rashid, “Power electronics handbook,” Academic press, 2001, Canada.

[3]. B. K. Bose, “Modern power electronics and AC drives,” 2002, Prentice hall, USA.

[4]. N. Mohan, T. M. Undeland, and W. P. Robbins, Power Electronics: Converters, Applications and Design, 3rd ed. New York: Wiley, Oct. 2002.

[5]. IEEE Std 519-1992, “IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems.”

[6]. T. Wildi, “Electrical Machines Drives, and Power Systems,” 4th ed, Prentice Hall, 2000.

[7]. P. Pejovic, and J. W. Kolar, “Exact analysis of three-phase rectifiers with constant-voltage loads,” IEEE Trans. Circuits Syst. II, Express briefs., vol. 55, no. 8, pp. 743–747, Aug. 2008.

[8]. M. Norhisam, A. Saadon, R. N. Firdaus, I. Aris, S. M. Bashi, “The three phase rectifier with harmonic injection current,” in conf. 2010 IEEE Student Research and Development (SCOReD), Kuala Lumpur, Malaysia, Dec. 2010, pp. 397-400.

[9]. R. Ghandehari, A. Shoulaie and D.Habibinia “The Problems of Voltage Notch Phenomena in Power AC/DC Converters,” in Universities Power Engineering Conference, 2007. UPEC 2007, 4-6 Sept. 2007

[10]. W. P. Gibbons, “Current and voltage waveform distortion analysis on three-phase “wye” power systems with rectifier loads,” IEEE Trans. Ind. Appl., vol. IA-19, no. 2, pp. 181–190, Mar./Apr. 1983.