CURRENT DISTRIBUTION IN PARALEL SEMICONDUCTOR HIGH CURRENT RECTIFIERS – REAL CASE STUDIES

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***Abstract* – Power ratings of rectifying equipment can greatly exceed the capability of single rectifying devices. Parallel combinations of devices or equipments are common to increase current rating. It is essential to ensure that current is shared fairly evenly between semiconductors under normal and overload conditions. This paper presents an analysis of current distribution among parallel semiconductors based on real case measurements in high power rectifiers with simultaneous current acquisition in all legs and devices. RMS current values and its deviation among parallel devices are presented.**

***Keywords* – Paralleling semiconductors; High Power Rectifier; Power Semiconductor Devices.**

I. INTRODUCTION

Electrolytic processes consume more than 6% of the total electrical generating capacity of the United States and require high current rectifiers [1]. These converters are implemented using parallel association of diodes or thyristors that feature high efficiency and reliability. It is essential to ensure that current is shared fairly evenly between semiconductors under normal and overload conditions.

The main objective of this paper is to verify the influence of the busbar design and influences of the mutual inductance on the adjacent semiconductors in the current balance of parallel semiconductors. Measurements obtained from several high current rectifiers (10 kA to 80 kA) of electro-intensive plants installed in Brazil and Peru that produce aluminum, zinc, nickel, and chlorine are presented in this paper. The rectifiers were chosen in accordance to operational availability. Measurements were performed on new and old plants of several manufactures (ABB, BBC and Siemens) using diodes and thyristors as semiconductors

This paper is organized as follows: First, an overview of the rectifiers' busbar structures and description of the current measurement equipment are presented in section II. Section III gives a brief description of the main installations characteristics. Sections IV to VII show the measured values of rectifiers with vertical, horizontal and quadriform bus bar structures respectively. Final remarks and comments are presented in section VIII.

II. CURRENT MEASUREMENT EQUIPMENT

There are numerous rectifier circuits in use with different busbar designs. The most common busbar arrangements are horizontal, vertical (newest), and quadriform or square frame (oldest) as illustrated in Fig. 1.

The main factors that influence the current distribution balance, [2,3,4,5,6] in parallel semiconductors are:

- Semiconductors direct voltage drop (V_F);
- Fuse ohmic resistance;
- Electromagnetic coupling and induced EMFs;
- Busbar design;
- Contact face conditions;
- Semiconductor tightening;
- Semiconductor and fuse cooling efficiency.

All current measurements were performed with a RCEM (Rectifier Condition and Evaluation Monitoring) system manufactured by Dynamp [7], designed for non-contact current measurements in rectifiers with multiple elements in parallel. The data acquisition unit is connected to a laptop and each of the 120-channels are fed to current sensors. The current sensors are flexible Rogowski coils [8] that produce output voltage signals proportional to the measured currents. Fig. 2 illustrates the measurement arrangement.

Data are available in an Excel spreadsheet showing the RMS values of: i) the individual semiconductor current, ii) the total rectifier current; iii) the leg current and iv) the average leg current.

Horizontal bars

Vertical bars

Quadriform bars

Fig. 1. Common Bar design structures

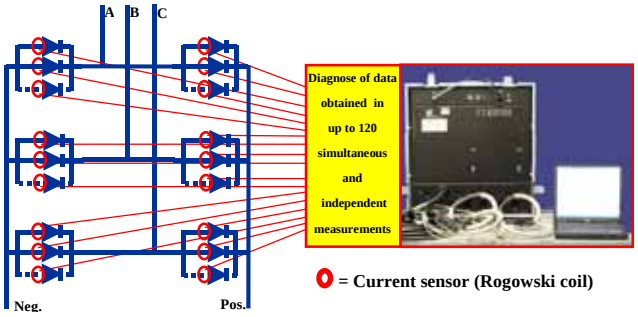


Fig. 2. Measurement arrangement

III. REAL CASES OVERVIEW

Table I lists the principal data of the rectifiers evaluated. The rectifier power circuit is identified by its code according to ANSI Standard C57.18. The twenty cases enclosed in this study were grouped conveniently in Table II to facilitate comparison between rectifiers with similar topology.

TABLE I
Summary of rectifiers main data

Case	Manu-facturer	Busbar design	ANSI Circuit	Diode or Thyritor	Qty in parallel	I_{TOTAL} (kA)
01	BBC	Vertical	26	Thyristor	20	48
02	BBC	Vertical	26	Thyristor	20	48
03	BBC	Quadriform	52	Diode	6	50
04	BBC	Quadriform	52	Diode	6	50
05	ABB	Horizontal	52	Diode	3	60
06	Siemens	Vertical	45	Diode	4	20
07	BBC	Vertical	45	Diode	14	40
08	BBC	Quadriform	52	Diode	4	18
09	Siemens	Vertical	52	Diode	4	22
10	ABB	Horizontal	32	Thyristor	6	80
11	BBC	Vertical	26	Thyristor	6	36
12	ABB	Horizontal	26	Thyristor	4	12
13	BBC	Horizontal	46	Diode	6	30
14	BBC	Horizontal	46	Diode	6	30
15	BBC	Vertical	25 / 26	Diode	18	26
16	BBC	Vertical	25 / 26	Diode	18	26
17	BBC	Vertical	25 / 26	Diode	18	28
18	BBC	Vertical	25 / 26	Diode	18	28
19	ABB	Vertical	25	Thyristor	6	24
20	ABB	Vertical	25	Thyristor	6	24

TABLE 2
Rectifiers groups

Group	Rectifier Cases	Busbar design	Qty in parallel
A	01 / 02 / 07 / 15 / 16 / 17 / 18	Vertical	14 / 18 / 20
B	06 / 09 / 11 / 19 / 20	Vertical	04 / 06
C	05 / 10 / 12 / 13 / 14	Horizontal	03 / 04 / 06
D	03 / 04 / 08	Quadriform	04 / 06

IV. VERTICAL BUSBAR DESIGN (Group A)

Rectifiers with a vertical bus bar design and 14, 18 and 20 semiconductors in parallel were selected for analysis.

Figure 3 shows schematic diagram of the case Nº. 17. This rectifier has 216 diodes, divided in two bridges (108 diode per bridge) with 18 diodes (9+9) in parallel per leg (or branch). The transformer windings connection of bridge 1 is Dd_0, (ANSI C57.18 no. 25) and that of bridge 2 is Yd_{11}, (ANSI C57.18 no. 26). The busbar design of this rectifier is similar to the quadriform arrangement, but it was classified, as a vertical busbar because of its higher vertical dimension that minimizes the horizontal bar electromagnetic influence.

Limitation of sensors forced separate measurements in each bridge. Based on practical experience and historical values, a current unbalance up to ±20 % and 100% overload factor are acceptable in high power rectifiers.

Table 3 shows the spreadsheet with the measurement results of case no. 17. The current deviation of each device is calculated based on the current average of its own leg. The data acquisition system automatically signalizes current unbalances over ±20 % (red cells for positive unbalance and blue cells negative unbalance). The percentage current deviation for complete rectifier is calculated from the average values of the percentage current deviation of the four branch groups shown in the right column.

The same procedure was adopted for all rectifiers (cases 1, 2, 7, 15, 16, 17 and 18) of Group A and the percentages of current unbalance are presented in Table 4. Data were grouped conveniently in order to enable comparison of unbalances in devices of similar location in rectifiers with different devices in parallel.

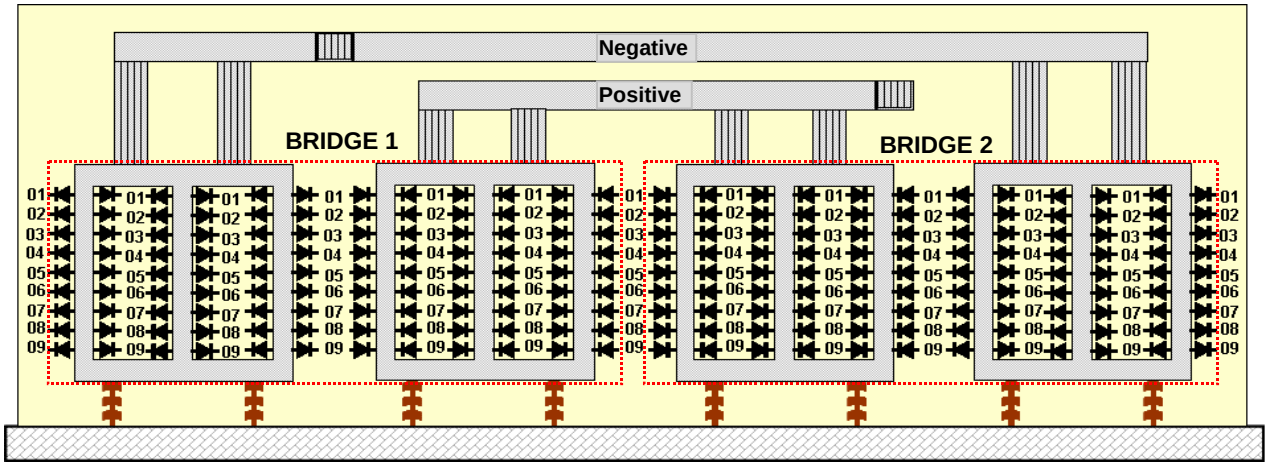
Figure 4 shows graphically the average current unbalance in vertical busbar rectifiers of Group A. The color scheme in Fig. 4 is the same of the columns in Table 4.

TABLE 4
Group A - Rectifier's current unbalance percentages

Group A - Rectifier with vertical bars design								
Id.	Rect. 01	Rect. 02	Rect. 07	Rect. 15	Rect. 16	Rect. 17	Rect. 18	Total Avg.
Upper	-2.31	8.58	12.42	-16.50	-16.48	-11.00	-5.28	-4.37
	-0.51	-5.46	-6.84	3.90	4.96	-3.42	5.96	-0.20
	-3.79	1.71	-14.99	1.14	3.75	4.18	3.11	-0.70
	-3.56	-10.01	-7.05					-6.87
	-6.42	-8.33						-7.37
Center	-1.18	5.59						2.21
	2.38	1.18						1.78
	1.56	6.77	-4.32					1.33
	2.75	5.92	-4.24	3.94	1.53			1.98
	4.98	11.22	3.40	4.13	3.60	5.12	0.75	4.74
	5.21	-0.84	6.47	3.37	1.09	2.33	1.22	2.69
	-0.82	-0.38	6.61			-0.52	3.20	1.62
	-6.42	-10.61	2.66					-4.79
	-3.24	-14.40						-8.82
	-8.35	-2.89						-5.62
Lower	1.57	-0.51						0.53
	-2.74	-1.57	-12.69					-5.67
	1.43	4.67	10.39	-0.61	5.97	3.14	-1.81	3.31
	8.28	0.56	-7.38	8.97	8.91	3.14	2.80	3.61
	11.17	8.78	15.58	-8.33	-13.34	-8.45	-9.95	-0.65

TABLE 3
Vertical busbar rectifier - case n. 17

Unit Number:		No. 17 - Left side		Date:	10/19/06			HI:	20	% Above Avg			
Rectifier Current:		8870	A	Time:	7:25:02 PM			LO:	-20	% Below Avg			
	Leg 1A – U'1		Leg 2A – W1		Leg 3A – W'1		Leg 4A – V1		Leg 5A – V'1		Leg 6A – U1		Average
Diode	Current	% Dev	Current	% Dev	Current	% Dev	Current	% Dev	Current	% Dev	Current	% Dev	(% Dev)
Upper 1	199.6	-33.44	289.2	-5.49	261.4	-10.26	289.6	-2.15	256.2	-8.11	263.3	-6.05	-10.92
2	240.9	-19.66	325.6	6.41	282.2	-3.11	268.8	-9.18	268.4	-3.72	300.9	7.36	-3.65
3	345.8	15.32	310.7	1.56	334.8	14.94	298.3	0.79	251.3	-9.87	316.1	12.81	5.92
4	348.9	16.33	287.0	-6.20	299.3	2.75	301.8	1.95	318.0	14.08	297.2	6.03	5.82
5	323.3	7.81	263.0	-14.04	263.6	-9.51	291.6	-1.48	293.4	5.24	294.3	5.03	-1.16
6	343.0	14.36	326.2	6.63	289.3	-0.69	298.4	0.82	268.9	-3.57	281.8	0.56	3.02
7	373.5	24.54	354.6	15.89	267.0	-8.33	276.1	-6.73	242.9	-12.88	177.8	-36.55	-4.01
8	226.7	-24.40	334.2	9.22	377.8	29.69	392.0	32.45	325.7	16.83	319.7	14.07	12.98
Lower 9	297.3	-0.86	263.2	-13.98	246.2	-15.47	247.3	-16.46	284.4	2.01	271.1	-3.26	-8.00
Total	2699.0		2753.7		2621.5		2663.9		2509.2		2522.3		
Average	299.9		306.0		291.3		296.0		278.8		280.3		
	Leg 1B – U'1		Leg 2B – W1		Leg 3B – W'1		Leg 4B – V1		Leg 5B – V'1		Leg 6B – U1		Average
Diode	Current	% Dev	Current	% Dev	Current	% Dev	Current	% Dev	Current	% Dev	Current	% Dev	(% Dev)
Upper 1	220.5	-18.08	187.8	-31.45	243.2	-12.68	253.1	-9.98	218.5	-22.19	213.0	-23.37	-19.63
2	316.3	17.48	185.3	-32.39	254.2	-8.77	311.4	10.76	288.6	2.81	267.2	-3.88	-2.33
3	224.0	-16.81	309.2	12.82	303.2	8.86	304.3	8.24	249.6	-11.11	317.1	14.08	2.68
4	257.2	-4.46	317.5	15.88	297.0	6.60	272.7	-3.00	321.5	14.52	312.1	12.26	6.97
5	208.2	-22.66	318.1	16.10	236.1	-15.25	304.1	8.14	260.5	-7.21	305.9	10.03	-1.81
6	300.6	11.65	255.2	-6.87	279.9	0.48	304.2	8.18	340.0	21.11	269.7	-2.98	5.26
7	308.2	14.46	333.0	21.53	350.8	25.93	250.1	-11.05	311.0	10.78	321.6	15.69	12.89
8	275.8	2.45	312.6	14.07	280.5	0.68	288.1	2.47	197.7	-29.59	257.0	-7.53	-2.91
Lower 9	312.2	15.96	247.5	-9.67	262.3	-5.85	242.5	-13.76	339.4	20.88	238.2	-14.30	-1.12
Total	2423.1		2466.3		2507.2		2530.6		2526.7		2501.8		
Average	269.2		274.0		278.6		281.2		280.7		278.0		
Unit Number:		No. 17 - Right side		Date:	10/19/06			HI:	20	% Above Avg			
Rectifier Current:		8785	A	Time:	8:22:09 PM			LO:	-20	% Below Avg			
	Leg 1A – U'2		Leg 2A – W2		Leg 3A – W'2		Leg 4A – V2		Leg 5A – V'2		Leg 6A – U2		Average
Diode	Current	% Dev	Current	% Dev	Current	% Dev	Current	% Dev	Current	% Dev	Current	% Dev	(% Dev)
Upper 1	303.5	6.18	248.7	-14.58	298.7	-0.33	164.8	-40.04	245.4	-11.08	385.7	39.46	-3.40
2	179.8	-40.03	306.7	0.23	327.5	12.43	238.9	-19.28	324.3	16.32	352.4	25.76	-0.76
3	313.8	4.64	308.5	0.82	367.8	26.28	334.2	12.91	284.8	2.14	245.2	-12.51	5.71
4	305.2	1.76	304.0	-0.65	337.0	15.70	317.4	7.24	285.5	2.41	254.7	-9.13	2.89
5	299.0	-0.29	320.0	4.58	275.8	-5.30	236.8	-19.99	283.7	1.74	309.3	10.38	-1.48
6	288.9	-3.67	310.0	1.32	286.9	-1.52	310.1	4.77	335.1	20.19	157.9	-43.67	-3.76
7	321.3	7.14	336.8	10.06	275.1	-5.55	323.4	9.25	273.1	-2.05	339.6	21.16	6.67
8	285.5	-4.79	327.4	7.02	251.2	-13.76	340.6	15.08	197.8	-29.07	215.9	-22.95	-8.08
Lower 9	275.2	-8.23	158.7	-48.13	277.5	-4.75	208.1	-29.69	254.0	-8.88	228.3	-18.53	-19.70
Total	2572.2		2620.7		2697.5		2474.4		2483.6		2489.0		
Average	285.8		291.2		299.7		274.9		276.0		276.6		
	Leg 1B – U'2		Leg 2B – W2		Leg 3B – W'2		Leg 4B – V2		Leg 5B – V'2		Leg 6B – U2		Average
Diode	Current	% Dev	Current	% Dev	Current	% Dev	Current	% Dev	Current	% Dev	Current	% Dev	(% Dev)
Upper 1	244.5	-9.89	241.2	-10.40	262.5	-3.80	259.6	-8.99	235.0	-17.32	361.1	22.65	-10.08
2	155.8	-42.61	272.3	1.17	213.5	-21.72	365.0	27.92	286.0	0.64	214.5	-27.12	-6.92
3	330.8	21.88	265.5	-1.35	271.0	-0.67	161.8	-43.27	384.7	35.36	294.3	-0.02	2.39
4	314.7	15.96	289.8	7.67	250.0	-8.38	332.0	16.36	262.8	-7.51	425.3	44.48	4.82
5	398.8	46.94	262.9	-2.30	286.3	4.93	336.7	18.02	287.9	1.31	202.9	-31.08	13.78
6	167.6	-38.25	263.2	-2.22	311.6	14.23	265.3	-6.99	284.7	0.19	411.1	39.63	-6.61
7	255.2	-5.96	311.2	15.64	271.5	-0.49	297.9	4.44	203.0	-28.56	336.0	14.14	-2.99
8	262.8	-3.16	275.6	2.41	294.5	7.94	345.5	21.12	353.8	24.48	16.7	-94.32	10.56
Lower 9	312.3	15.08	240.6	-10.62	294.5	7.96	203.7	-28.61	259.8	-8.59	387.5	31.64	-4.96
Total	2442.4		2422.3		2455.4		2567.6		2557.6		2649.4		
Average	271.4		269.1		272.8		285.3		284.2		294.4		



L6A	L6B	L4A	L4B	L2A	L2B		L1A	L1B	L5A	L5B	L3A	L3B		L6A	L6B	L4A	L4B	L2A	L2B		L1A	L1B	L5A	L5B	L3A	L3B
U1		V1		W1			U'1		V'1		W'1			U2		V2		W2			U'2		V'2		W'2	
Negative Branch							Positive Branch							Positive Branch							Negative Branch					
Bridge 1 – Left Side – ANSI 25 – (Dd_0)														Bridge 2 – Right Side – ANSI 2 6 – (Yd_{11})												

Fig. 3. Vertical busbar rectifier -illustrative diagram and connection tags

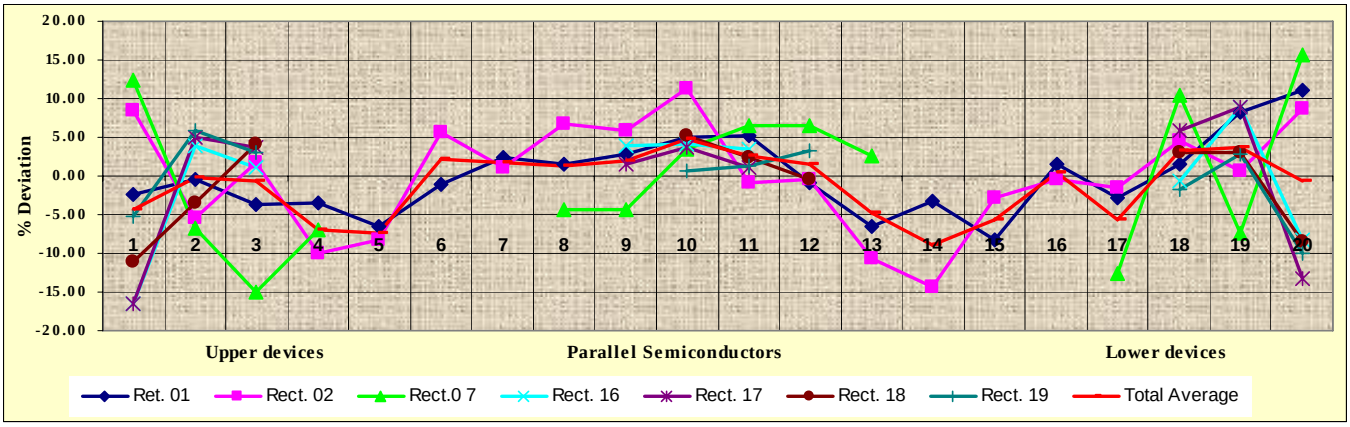


Fig. 4. Percentage of current unbalance in vertical busbar rectifiers — GROUP A

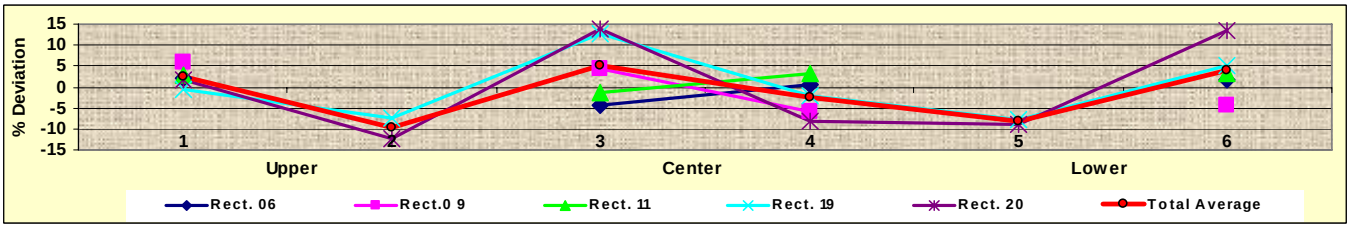


Fig. 5. Percentage of current unbalance in vertical busbar rectifiers — GROUP B

V. VERTICAL BUSBARS DESIGN (Group B)

Rectifiers with a vertical bus bar design and 4 and 6 semiconductors in parallel were selected for analysis. This rectifier group is similar to group A, but with less number of devices connected in parallel and percentages of current unbalance are shown in Table 5.

Figure 5 shows graphically the average current unbalance in vertical busbar rectifiers of Group B. In can be notice that the behavior of the current distribution among parallel devices in Group B is quite different from those of Group A, even both having vertical busbar design. About 50% of the data in Table 5 is lower than 5%, which is a typical value current unbalance in rectifier with small quantity of parallel devices.

TABLE 5
Group B - Rectifier's current unbalance percentages

Group B - Rectifier with vertical bars design						
Id	Rect. 06	Rect. 09	Rect. 11	Rect. 19	Rect. 20	Total Average
Upper	2.06	5.91	2.77	-0.51	1.61	**2.37**
				-7.39	-12.25	**-9.82**
Center	-4.44	4.52	-1.27	12.73	13.93	**5.09**
	0.51	-6.07	3.31	-2.05	-8.01	**-2.46**
Lower				-7.74	-8.89	**-8.31**
	1.88	-4.36	3.08	4.96	13.60	**3.83**

VI. HORIZONTAL BARS DESIGN (Group C)

Rectifiers with a horizontal busbar design and 4 and 6 semiconductors in parallel were selected for analysis.

At first glance, the difference between vertical and horizontal busbars seems to be its position (standing or lying) but in fact, it is the electrical connection to the AC system. In vertical busbars, each bar is connected to one AC phase, whereas in the horizontal design each bar is connected to the three AC phases. Figure 6 illustrates this fact showing the busbar connections to AC system in cases 13 and 14.

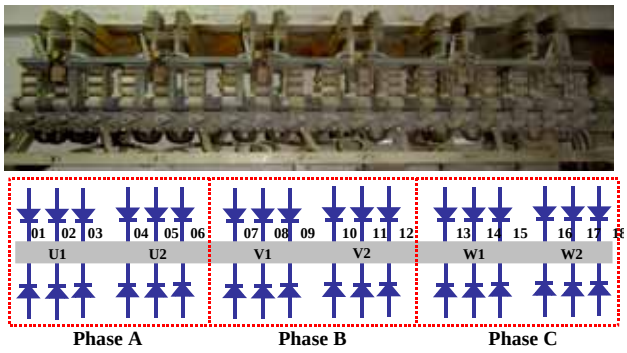


Fig. 6. Illustration of a horizontal busbar design

Table 6 shows the percentages of current unbalances of the rectifiers with horizontal busbar design. Note that the number of lines indicates the number of devices in parallel, but the Group C rectifiers have a maximum of 6 devices in parallel. The explanation of this apparent incoherence is that all devices are connected to the horizontal bar as shown in Fig. 6. Therefore, in order to evaluate current unbalance it makes sense consider devices connected to same busbar. Fig. 7 shows graphically the average current unbalance in horizontal busbar rectifiers of Group C.

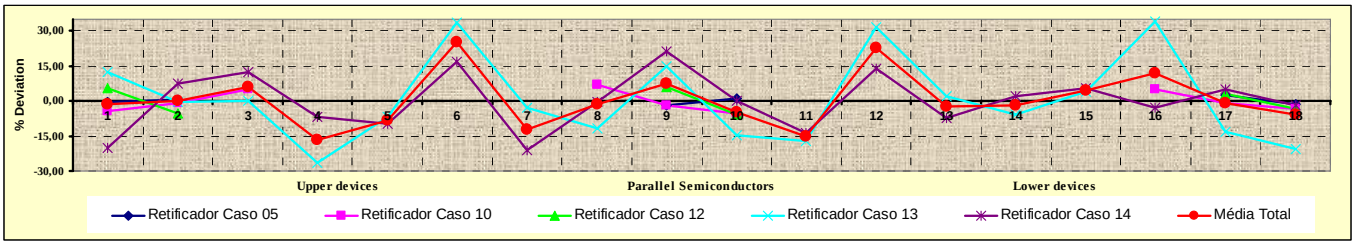


Fig. 7. Percentage of current unbalance in horizontal busbar rectifiers — GROUP C

FIGURE 6: Percent current unbalance of each rectifier (Group C)

TABLE 6
Group C - Rectifier's current unbalance percentages

Group C - Rectifier with vertical bars design						
Id.	Rect. 05	Rect. 10	Rect. 12	Rect. 13	Rect. 14	Total Average
Left	-0.62	-4.29	5,55	12.32	-19.92	**-1,39**
	0.31	-0.89	-5,55	-0.39	7.47	**0,19**
		5.04		0.00	12.45	**5,83**
				-26.62	-6.96	**-16,79**
				-6.82	-9.77	**-8,29**
				33.43	16.73	**25,08**
Center				-3.11	-20.95	**-12,03**
		6.99		-11.62	-0.34	**-1,66**
	-1.94	-1.85	5,80	14.74	21.29	**7,61**
	0.97	-5.14	-5,80	-14.69	-0.06	**-4,94**
				-16.97	-13.80	**-15,39**
				31.66	13.86	**22,76**
Right				1.93	-7.25	**-2,66**
				-5.69	1.92	**-1,89**
				3.75	5.33	**4,54**
		4.76		33.77	-3.15	**11,79**
	2.43	-1.11	3,23	-13.07	4.88	**-0,73**
	-1.22	-3.65	-3,23	-20.70	-1.73	**-6,11**

VII. QUADRIFORM BARS DESIGN (Group D)

Rectifiers with a quadriform busbar design and 4 and 6 semiconductors in parallel were selected for analysis.

In order to evaluate current unbalance it makes sense to consider devices connected to same phase and that are physically connected in parallel.

The Table 7 present the percentage current deviation values of Group D rectifiers and Fig 8 the graphics.

TABLE 7
Group D - Rectifier's current unbalance percentages

Group D - Rectifier with vertical bars design				
ID	Rect. 03	Rect. 04	Rect. 08	Total Average
Left	3.17	0.22	-3,48	**-0,03**
	1.95	3.52		**2,73**
Center	-5.12	-3.74	-6,61	**-5,15**
	7.11	5.15	14,08	**8,78**
Right	-3.88	3.03		**-0,42**
	-3.93	-8.85	-3,99	**-5,59**

VIII. FINAL REMARKS

A. Rectifiers with vertical busbar design (Groups A and B)

The vertical busbar design is common even in old as well as in new rectifiers. It is adequate for lower current applications (up to 15 kA) because it nowadays require a less number of devices in parallel and the transformer design is more compact. As shown in Figs. 4 and 5, the current distribution among parallel devices is uniform over the busbar length. It was noticed that the current at the busbar extremities is lower than at the center .

B. Rectifiers with horizontal busbar design (Group C)

The horizontal busbar design is adequate for higher current ratings (over 15 kA). Generally 12 pulse rectifiers are employed which requires a high number of AC transformer connections. The current unbalance is similar to the vertical busbar design. Again the current at the busbar extremities is lower than at the center.

C. Rectifiers with quadriform busbar design (Group D)

The quadriform busbar design was found in older rectifiers manufactured by BBC with DC current ratings between 20 kA and 50 kA. These rectifiers are composed of parallel association of "one way converters" (midpoint connection rectifiers) with a small number of devices in parallel. The current unbalance is low and the current at the busbar extremities is lower than at the center.

D. General comments

In this paper, current measurements were preformed on 20 high current rectifier plants. The difference from other similar studies [10, 11] is the simultaneous current measurement in all devices.

It was notice that devices located at the busbar extremities conducts less current than devices at the bar center. This may be result of the impedance compensations at the busbar connections, which mitigates electromagnetic coupling effects and induced EMFs. This compensation involves an impedance increase of the AC connections at busbar extremities. This can be achieved by increasing the busbar length or adding special toroidal iron cores interlacing the connections of devices located at the busbar extremities.

Figure 9 presents the busbar current unbalance of all groups. It can be noticed that the current distribution among parallel device is fairly uniform and independent of busbar

design. Group C (horizontal busbar design) rectifiers show a more pronounced current unbalance.

The higher current ratings of modern semiconductor devices [9] results in rectifier with less number of devices connected in parallel and consequently the current unbalance is lower.

Even so it is important to know the current distribution in older rectifiers, since from the Brazilian installed base shown in Fig. 10 many plants operate with rectifiers older than 20 years.

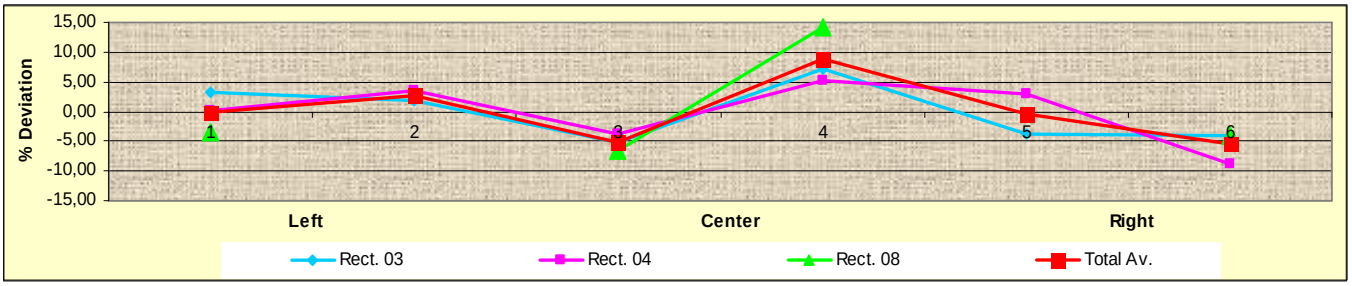


Fig. 8. Percentage of current unbalance in quadriform busbar rectifiers — GROUP D

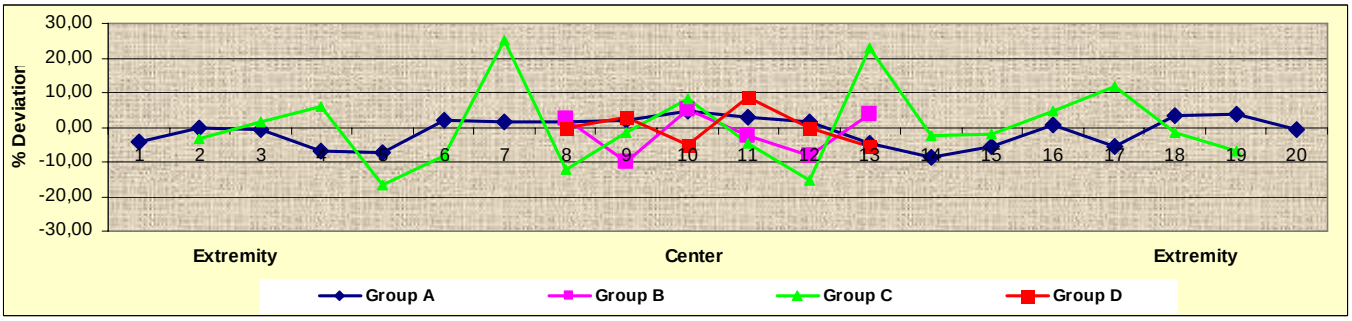


Fig. 9. Percentage of current unbalance in rectifiers Groups A, B, C and D

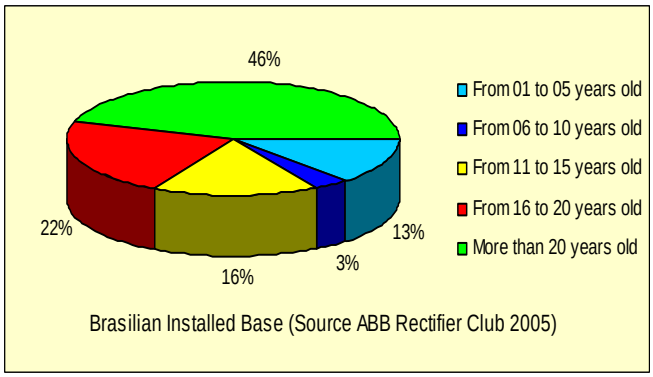


Fig. 10. Brazilian rectifier installed base (241) rectifiers

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