Investigation and Mitigation of the Amplification of the Harmonic Current to the Filtering System of an Aluminum Smelter

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Abstract: - This paper presents an investigation on the origin of the harmonic amplification verified in the fifth order filter of aluminum reduction plant IV of ALBRAS through from observation of the phase angle difference in the rectifier transformers, as well as current records and measurements in several points. It proposes developing analyses by combining system measurements and studies as based on data obtained. The measurements were conducted inside the control room to the main substation and in the sub-control room to the rectifiers. The results of such investigation were used in mitigation propositions so as to solve the problem. A comparison of the system's harmonic profile before and after solving the problem is also shown.

Key-Words: - Current Harmonic Distortion, Voltage Harmonic Distortion, Harmonic Filters, Banks of Capacitors, Power Quality, Rectifiers.

1 Introduction

Currently, ALBRAS (Alumínio Brasileiro S.A.) Aluminum Smelter Plant, located in Barcarena–PA, has four aluminum reduction plants for aluminum electrolytic reduction. Each aluminum reduction plant is fed by a 208.4MVA – 230kV/ 34.5kV transformer (MT), with two voltage regulator autotransformers (LVR) and six phase-shifting transformers with a "delta/inverted double-wye" configuration. For each secondary that is connected in double-wye, there is one six-pulse rectifier. The rectifiers are parallel-connected on the CC end. The primary of the rectifier transformers has a phase angle difference to minimize the current harmonics into the CA system through the multipulse technique. Such difference must be equal to 10º in such a way that the number of pulses in each rectifying system is 36, and between two groups or two aluminum reduction plants that number is 72. Each aluminum reduction plant also has a bank of capacitors tuned to the 4.08 harmonics, and harmonic filters for components 5 and 7. Such filters, 10MVAr each, are made up of banks of capacitors and air-core reactors. Figure 1 shows the single-line diagram for an aluminum reduction plant.

In 2001, ALBRAS went through renovation of its industrial plant, when the voltage regulator autotransformers and the rectifier transformers of all aluminum reduction plants were replaced by more powerful equipment. In 2003, the banks of capacitors were also replaced in all aluminum reduction plants except for aluminum reduction plant I. 20MVAr banks were replaced by 50MVAr banks so as to maintain the 0.99 power factor in its corresponding bus. Also, improvements were made in cooling the rectifier cubicles. The power of the harmonics filters remained unaltered. After renovation, the rated capacity of the rectifying bus was raised from 1040 V/155 kA to 1104 V/170 kA. Nevertheless, in late 2002, when stoppage of one of the rectifiers of aluminum reduction plant IV was required, an absurd increase in the current of the fifth order filter to that plant – also, an overheating-related physical problem, was reported. After this incident, it was observed that, even with all rectifiers running normally, the current of the fifth order filter to aluminum reduction plant IV remained a little higher, thus causing the maintenance crew to alter the reactor's tap to this filter in order to minimize the problem.

This paper presents an investigation on the origin of the harmonic amplification observed in the fifth order filter of aluminum reduction plant IV at ALBRAS starting from checking the phase angle difference of the rectifier transformers and through the current records and measurements in several points as shown in Figure 1. The red marks show the measurements made inside ALBRAS main substation. The blue marks indicate the measurements conducted inside the sub-control rooms of the rectifiers. As for data collection, a Real Time, Three-Phase Magnitude Gauge/Recorder was used. Investigations show that the overload of the mentioned filter provokes a substantial increase in the current's harmonic distortion, which may reach much higher values when compared to those values from other aluminum reduction plants. This paper proposes developing analyses by combining measurements and studies on the system as based upon the information collected. Field measurements were conducted inside the control room to the main substation and in the sub-control room to the rectifiers so as to verify strategic points associated with aluminum reduction plant IV of the electric system of ALBRAS. A comparison of the system's harmonic profile before and after solving the problem is also shown.

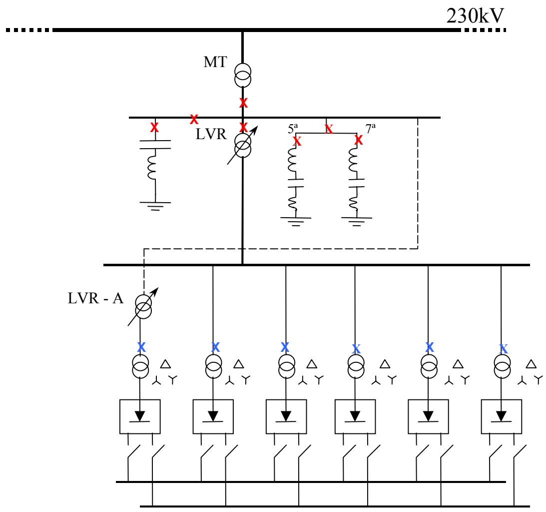

Fig.1: Single-line diagram of a reduction plant and measuring points

2 Comparative Harmonic Assessment Among Aluminum Reduction Plants Before the Mitigating Measure

In order to survey the system's harmonic profile and determine the actual extent to the harmonic penetration problem identified by ALBRAS engineers, measurements were conducted at the red-marked points shown in Figure 1 in all aluminum reduction plants. Tables 1, 2 and 3 carry a summary of the Total Harmonic Distortion to the current (THD_i%) found, and having all rectifiers running. Such tables show an existing harmonic overload in the filters of the 5th and 7th harmonics of aluminum reduction plant IV, since the THDi% of this equipment reaches 60% or more of the fundamental current. Such overload becomes even more evident upon comparing the THDi% values for each aluminum reduction plant. In phase A, for instance, the THDi% of the 5th harmonic filter of reduction plant IV reaches a point where it is 5.2 times greater than THDi% in the filter of the 5th harmonic of reduction plant I and 4.5 times as great as the THDi% in the 5th harmonic filter of reduction plant II. The 7th harmonic filter THDi% in reduction plant IV is 8.5 times greater than the THDi% in the 7th harmonic filter of reduction plant I, 11.8 times as great as the THDi% in the 7th harmonic filter of reduction plant II, and 10.8 times greater than the THDi% in the 7th harmonic filter of reduction plant III.

Table 1: Total Harmonic Distortion of Current in Phase "A"

Measuring Point	Reduction Plant I	Reduction Plant II	Reduction Plant III	Reduction Plant IV
Transformer secondary (MT)	0.9	1.00	*	1.77
Primary side of the LVR	4.88	4.73	*	4.40
Shunt Capacitors	1.85	1.78	2.23	5.79
Common point to filters	7.63	8.40	15.59	45.62
5th harmonic filter	13.33	15.42	29.30	68.91
7th harmonic filter	7.23	5.20	5.67	61.48

Table 2: Total Harmonic Distortion of Current in Phase "B"

Measuring Point	Reduction Plant I	Reduction Plant II	Reduction Plant III	Reduction Plant IV
Transformer secondary (MT)	0.94	0.92	*	1.52
Primary side of the LVR	4.92	4.72	*	4.24
Shunt Capacitors	2.13	1.26	1.86	5.15
Common point to filters	9.53	9.15	19.35	45.68
5th harmonic filter	14.15	18.48	35.52	68.87
7th harmonic filter	13.13	6.14	6.38	60.68

Table 3: Total Harmonic Distortion of Current in Phase "C"

Measuring Point	Reduction Plant I	Reduction Plant II	Reduction Plant III	Reduction Plant IV
Transformer secondary (MT)	0.93	1.00	*	1.88
Primary side of the LVR	5.08	4.58	*	4.38
Shunt Capacitors	1.39	2.41	2.76	6.40
Common point to filters	9.65	8.53	19.37	45.33
5th harmonic filter	16.96	16.73	32.97	59.42
7th harmonic filter	9.12	5.85	6.62	60.38

* No measurement in Reduction Plant III.

In addition to the high distortions in the 5th and 7th harmonic filters to aluminum reduction plant IV, overload in the bank of capacitors of this plant was also observed. In that case, the THDi% of phase C reaches a point where it is 4.6 times greater than the THDi% in the bank of capacitors of reduction plant I, 2.65 times greater than the THDi% in the bank of capacitors of reduction plant II, and 2.3 times greater than the THDi% in the bank of capacitors of reduction plant III. Tables 1, 2 and 3 also show an imbalance in the THDi% of the equipment among phases A, B, and C in all aluminum reduction plants, highlighting the 7^{th} harmonic filter of reduction plant I, which shows a 45% difference between the THDi% of phases A and B. Therefore, it can be inferred that there is overload in 5^{th} and 7^{th} harmonic filters of aluminum reduction plant IV caused by a considerable increase in current distortion. Such distortion spreads throughout the system and reaches such sensitive equipment as the bank of capacitors, thus reaching much higher values when compared to those obtained in the other aluminum reduction plants.

It should be stressed out, however, that those distortions found in the current of the regulator transformers (LVRs) primary and in the current of the input transformers (MTs) secondary of those aluminum reduction plants where measurement was performed, showed reduced values, which indicates that the problem in aluminum reduction plant IV does not spread on to supplying system. Also, a THDv% (Total Harmonic Distortion of Voltage) measurement was conducted on the 230kV bus. The results, shown in Table 4, show that the distortion levels of input voltage are found to be below 1.5%, which is the maximum THDv% allowed according to USA's *Standard IEEE-519*, of IEEE – Institute of Electrical and Electronics Engineers, and also according to the Brazilian proposition by the GCOI/ GPS – Grupo Coordenador para Operação Interligada/ Grupo Coordenador do Planejamento do Sistema (Interconnected Operation Coordinating Group / .System Planning Coordinating Group).

Table 4: THDv% on the 230kVAR Bus

Phase	A	B	C
THDv%	1,09	1,03	1,33

3 Investigation on the Addition of the Fifth Harmonic Current to Aluminum Reduction Plant IV's Filtering System

In order to detect the origin to the harmonic amplification problem of aluminum reduction plant IV, a detailed analysis of this system was carried out starting from verification of the phase angle difference of the transformers that feed the rectifiers. After that, a comparison was made of results to aluminum reduction plant II, the operation of which being similar to aluminum reduction plant IV, with the same phase angle difference as applied to the transformers. These results pointed out to alteration associated with the first rectifier of aluminum reduction plant IV, rectifier 19. For that reason, although the analyses have been conducted for all rectifiers of aluminum reduction plants II and IV, this paper shows only those results associated with the first rectifiers of these aluminum reduction plants, rectifiers 7 and 19, respectively, due to room limitations.

Initially, the analysis of the current produced in the transformers primary will be presented. For an ideal operating status, the resulting waveform is as shown in Figure 2 [1]:

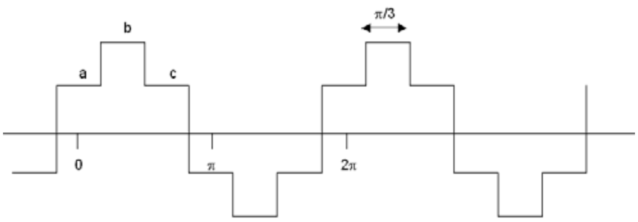

Fig. 2: AC Current for ideal rectifier operation

By taking the waveform shown in Figure 2 as the baseline, one can theoretically determine the equations that define amplitudes *a*, *b* and *c* by using equations 1 to 3 (angle-of-lead connection mode transformers) [2]:

$$a = \frac{I_d}{\sqrt{3}}\left(\sqrt{3} \cdot \cos\theta - \text{sen}\,\theta\right) \quad (1)$$

$$b = \frac{I_d}{\sqrt{3}}\left(\sqrt{3} \cdot \cos\theta + \text{sen}\,\theta\right) \quad (2)$$

$$c = \frac{2I_d\,\text{sen}\,\theta}{\sqrt{3}} \quad (3)$$

These equations were applied to the transformers of rectifiers 7 and 19 so as to determine the theoretical values of *a*, *b* and *c*. The I_d amplitudes were obtained from the manufacturer's instructions manual and vary according to the current of the DC end of each rectifier (approximately 29.33kA). The θ values, for calculation purposes, are fixed at 12.5 degrees.

Next, the comparisons made between current waveforms which were collected from sub-control II and sub-control IV for rectifiers 7 and 19, which theoretically should have the same calculated values of *a*, *b* and *c*, are presented. It is taken into account that aluminum reduction plant II is the reference at the time of comparisons, since it does not have any major problems in its equipment. Measurements were conducted with all rectifiers of the operating aluminum reduction plants at the sub-control room of the plants (the blue markings in Figure 1). The waveforms colleted at the sub-controls, despite being of a qualitative character basically, meet the requirements for the analyses. Collections were made in phase "A" of the rectifiers.

3.1 Comparison of the current waveforms obtained in the primary side of the phase-shifting transformers of rectifiers 7 and 19

Figure 3 brings a comparison between the waveforms of the primary of the transformers feeding rectifiers 7 of aluminum reduction plant II (red line) and 19 of aluminum reduction plant IV (blue line).

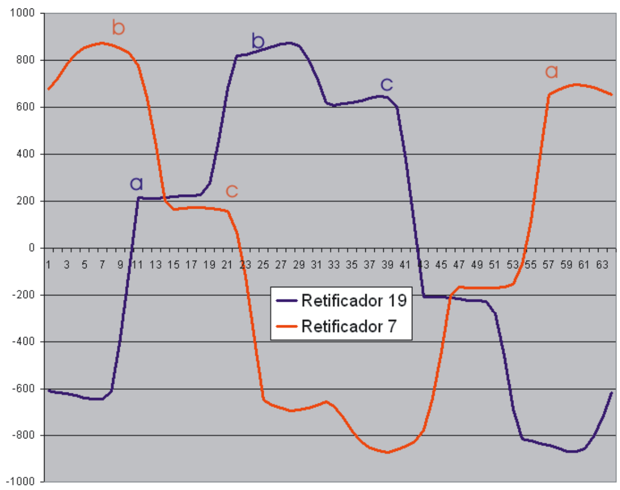

Fig. 3: Current waveforms collected at the primary of the phase-shifting transformers.

Table 5 shows a comparison between the expected values, which were calculated through equations 1, 2 and 3, and the values obtained through the measurements in aluminum reduction plants II and IV.

As mentioned before, these two rectifiers should have similar characteristics like, for example, phase angle difference, harmonic distortion levels etc.; and, therefore, should have similar waveforms. Yet, the results obtained show that there is a problem with the phase-shifting transformer feeding rectifier 19 of aluminum reduction plant IV. In order to verify existing suspicions, further investigations were conducted considering the operation of aluminum reduction plant IV with and without the presence of rectifier 19 and by comparing these results with those obtained for aluminum reduction plant II, as shown below.

Table 5: Comparison between the calculated values and those collected for rectifiers 7 and 19

	Calculated values	Current measured in the primary of TC – Rectifier 7	Current measured in the primary of TC – Rectifier 19
a	3,41	3,76	1,19
b	4,41	4,75	4,80
c	1	0,94	3,55

3.2 Determining the behavior of aluminum reduction plant IV with and without rectifier 19

In order to prove the existence of problems associated with rectifier 19, a procedure was conducted to investigate the harmonic profile of aluminum reduction plants II and IV. The goal was to analyze the consequences brought about by removing certain strategically chosen rectifiers, since both aluminum reduction plants should have similar performances, given the same difference values of the transformers feeding the rectifiers. The points used for data collection are those marked with a red "x" in Figure 1. In order to render the analysis easier, the measurement results were summarized into three cases by comparing the results obtained for aluminum reduction plant II against those collected for aluminum reduction plant IV, as can be seen in Tables 6, 7 and 8.

3.2.1 All rectifiers running at normal operation

According to Table 6, one can see that at the moment when both aluminum reduction plants being analyzed have all their rectifiers operating normally, the distortion levels of aluminum reduction plant IV reach extremely high values in comparison with aluminum reduction plant II. The current harmonic distortion in the filter of the 5^{th} harmonic of aluminum reduction plant IV, for instance, is on average four times as great as the THDi% of the 5^{th} harmonic filter in aluminum reduction plant II. In the 7^{th} harmonic filter of aluminum reduction plant IV, the THDi% reaches just over 11 times the value found in aluminum reduction plant II. Moreover, the distortion in the bank of capacitors in aluminum reduction plant IV is three times greater than that found in aluminum reduction plant II.

Table 6: Current Harmonic Distortion in Phases A, B and C

Measuring Point	Reduction Plant II			Reduction Plant IV		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
Power transformer secondary (MT)	1.00	0.92	1.00	1.77	1.52	1.98
Primary side of the LVR	4.73	4.72	4.58	4.40	4.24	4.38
Shunt Capacitors	1.78	1.26	2.41	5.79	5.15	6.40
Common point to filters	8.40	9.15	8.53	45.62	45.68	45.33
5th harmonic filter	15.42	18.48	16.73	68.91	68.87	69.42
7th harmonic filter	5.20	6.14	5.85	61.48	60.68	60.38

3.2.2 Operation without rectifiers 7 and 19 of aluminum reduction plants II and IV, respectively

As Table 7 shows, when rectifier 7 of reduction plant II was taken out of operation, the distortion levels increased significantly, since the composition of the 36 pulses made up by all rectifiers of that reduction plant jeopardized. In reduction plant IV, however, instead of increasing with withdrawal of rectifier 19, as was expected, the levels of THDi% were significantly reduced in relation with the values found when all rectifiers were under normal operation.

Table 7: Current Harmonic Distortion in Phases A, B and C

Measuring Point	Reduction Plant II			Reduction Plant IV		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
Power transformer secondary (MT)	1.27	1.20	1.31	1.61	1.31	1.78
Primary side of the LVR	4.30	4.41	4.37	4.39	4.31	4.38
Shunt Capacitors	3.22	3.12	3.83	4.21	3.30	4.58
Common point to filters	33.05	34.61	32.81	25.10	25.40	25.14
5th harmonic filter	49.81	51.68	50.85	39.10	39.52	39.99
7th harmonic filter	44.52	43.87	44.99	36.65	36.35	34.85

In order to conclude the analyses, a comparison was made of the removal of rectifiers 12 and 24 – the last rectifiers of reduction plants II and IV, respectively, as shown below.

3.2.3 Operation without rectifiers 12 and 24 of aluminum reduction plants II and IV, respectively

As shown in Table 8, when rectifier 12 of aluminum reduction plant II was taken out of operation, the distortion levels increased significantly, since the composition of the 36 pulses made up by all rectifiers in normal operation was again jeopardized. In aluminum reduction plant IV, on the other hand, an excessive increase in the levels of THDi% occurred due to the presence of rectifier 19. Therefore, based upon the dada shown previously, it can be asserted that the phase-shifting transformer feeding rectifier 19 is the especially responsible for the high distortion levels in aluminum reduction plant IV.

Table 8: Current Harmonic Distortion in Phases A, B and C

Measuring Point	Reduction Plant II			Reduction Plant IV		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
Power transformer secondary (MT)	1.34	1.21	1.36	2.21	2.03	2.31
Primary side of the LVR	9.85	8.72	8.73	9.04	12.10	8.94
Shunt Capacitors	2.43	2.21	3.11	8.95	8.24	9.35
Common point to filters	26.53	28.61	26.19	76.98	77.67	76.51
5th harmonic filter	32.65	31.98	31.75	116.83	117.66	117.02
7th harmonic filter	42.94	42.37	42.67	105.03	105.52	103.37

4 Mitigating Methods Adopted

After looking into the phase-shifting transformer's manufacturer's catalogs and manuals and field investigations to inspect the connecting cables, an inversion was indeed found in phases “A” and “C” at the input to the transformer feeding rectifier 19. This occurred by accident, since identification of colors at the input to the transformer follows the Japanese Standard (Red - Phase “A”; White – Phase “B”, and Blue – Phase “C”), exactly the contrary to the ABNT (the Brazilian Standards Association) adopted in Brazil (Blue - Phase “A”, White – Phase “B” and Red – Phase “C”). In order to have this problem solved, an inversion was made between phases “A” and “C” of the transformer, and also a new adjustment of the reactor taps of the harmonic filters to the aluminum reduction plant was performed so as to optimize their tuning.

Tables 9, 10 and 11 show the existing levels of harmonics in the aluminum reduction plants after inversion of the phases in the phase-shifting transformer feeding rectifier 19. It can be seen that now the distortion levels of aluminum reduction plants II and IV are much closer to each other than before mitigation.

Table 9: THDi% in Phase A with all rectifiers under normal operation, after the problem mitigating

Measuring Point	Reduction Plant II	Reduction Plant III	Reduction Plant IV
Transformer secondary (MT)	0.88	1.14	1.39
Primary side of the LVR	4.62	4.39	4.89
Shunt Capacitors	2.03	2.16	3.08
Common point to filters	7.69	14.17	5.41
5th harmonic filter	14.77	23.29	10.10
7th harmonic filter	5.11	6.84	4.44

Table 10: THDi% in Phase B with all rectifiers under normal operation, after the problem mitigating

Measuring Point	Reduction Plant II	Reduction Plant III	Reduction Plant IV
Transformer secondary (MT)	0.67	1.17	1.06
Primary side of the LVR	4.56	4.48	4.88
Shunt Capacitors	1.23	1.37	2.20
Common point to filters	9.79	14.20	5.48
5th harmonics filter	16.26	23.84	9.98
7th harmonics filter	5.81	6.42	3.70

Table 11: THDi% in Phase C with all rectifiers under normal operation, after the problem mitigating

Measuring Point	Reduction Plant II	Reduction Plant III	Reduction Plant IV
Power transformer secondary (MT)	0.91	1.07	1.59
Primary side of the LVR	4.60	4.51	5.09
Shunt Capacitors	1.94	2.43	3.87
Common point to filters	7.71	13.52	5.75
5th harmonics filter	13.94	20.84	9.32
7th harmonics filter	6.14	8.22	4.89

By comparing Tables 1 and 9 one can notice a 46.8% reduction in the distortion of the bank of capacitors; an 84.34% reduction in 5th harmonic filter; 92.78% reduction in 7th harmonic filter and 21.47% down for the secondary of the transformer feeding aluminum reduction plant IV (MT-4). Table 12 shows that the distortion levels caused by withdrawal of one of the rectification modules did not vary significantly, either after removal of rectifier 19 or of any other, as was the case of rectifier 24, differently from what was shown in Table 8.

Table 12: THDi% in Phases A, B and C upon removal of rectifiers 19 or 24

Measuring Point	Reduction Plant II – “19”Rectifier out of operation			Reduction Plant IV - “24”Rectifier out of operation		
	Phase A	Phase B	Phase C	Phase A	Phase B	Phase C
Power transformer secondary (MT)	1.79	1.62	2.00	1.70	1.53	2.00
Primary side of the LVR	4.28	4.28	4.31	9.31	9.27	9.38
Shunt Capacitors	4.42	3.61	4.91	4.49	3.66	5.62
Common point to filters	26.81	26.88	26.59	27.75	26.67	27.29
5th harmonics filter	38.05	38.72	38.78	36.33	35.66	37.19
7th harmonics filter	37.48	36.39	35.27	43.01	41.75	42.10

5 Conclusion

The non-controlled three-phase rectifiers are broadly used in industrial applications where direct current is needed in any process in the plant. In such cases, association of rectifiers in parallel is common. Nevertheless, proportionally to its importance, the rectifiers are also some of the largest polluting sources regarding the power quality of the system. Due to the broad use of such equipment, constant verification of the generated harmonic currents and the level of distortion resulting from its introduction to electric systems is required.

This paper aimed at the investigation of current amplification to the filtering system of the ALBRAS plant, more specifically at the main substation to one of the Aluminum Reduction Plants. Through comparison of theoretically calculated values as well as successive analyses of the waveforms collected, the suspicion that resonance of some sort provoked by replacement of equipment at the substation, started in 2001, was gradually being eliminated. Through analyses of the transformers diagrams, the inversion of phases of the phase-shifting transformer of rectifier 19 was found.

The problem was solved with the inversion between phases “A” and “C” of the transformer. However, the useful life of the substation’s equipment was in jeopardy as some tie-beams of the reactor of the harmonic filter had broken due to overheating; also, a great amount of energy was wasted.

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