Inverter testing and evaluation according to the Brazilian standards; experiences gained in the first two years of operation of the first Brazilian laboratory equipped for this purpose

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Abstract

This work presents the experience gained with the testing of photovoltaic grid-tie inverters to evaluate their compliance with the Brazilian standards. The experience was obtained during the first two years at the Laboratory of Photovoltaic Systems of the Institute of Energy and Environment of the University of São Paulo - LSF/IEE/USP, the first laboratory in Brazil equipped to perform these tests.

Since the LSF is the first laboratory to apply the Brazilian standards procedures, there is still uncertainty if the inverters available international market are able to comply with all the aspects of the standards.

The approach focus on the experiences with inverters that did not comply with the Brazilian standards concerning one or more of its aspects, the difficulties encountered during the tests, and the firmware implementation needed to solve inverter nonconformity with the standards.

By reviewing the data obtained, this work aims to evaluate if the criteria required by the Brazilian standards is obtainable by the inverters that already exist in the market. In case there are non-conformities, the interaction with the inverters technical team will show what are the most critical aspects of the standards, and if they can be implemented in the existing inverters.

To back up the analysis, the laboratory infrastructure is briefly described, mostly to establish the power range and main characteristics of the inverters that can be tested using the LSF infrastructure.

Keywords: Grid tied inverter, equipment evaluation, Brazilian standard.

1. Introduction

Distributed power generation is becoming usual in Brazilian distribution grids, and thus grid-connected systems need compliance with the Brazilian standards, regarding the connection interface and energy quality. The inverters in a photovoltaic system are mainly responsible for establishing the connection and delivering the generated power to the grid. In order to evaluate the string inverters sold in the Brazilian market, the Instituto Nacional de Metrologia, Qualidade e Tecnologia – INMETRO (National Institute of Metrology, Quality and Technology), established a labeling program for inverter evaluation according to the standards NBR 16149, 16150, NBR IEC 62116 of the Associação Brasileira de Normas Técnicas – ABNT (Brazilian Association of Technical Standards) and the INMETRO Normative Regulation Number 357.

To support the inverter labeling program the Laboratory of Photovoltaic Systems of the Institute of Energy and Environment of the University of São Paulo was accredited by INMETRO to test grid-tie inverters and guarantee their compliance to the standards.

This scenario presents a specific challenge for inverters already available in the international market, mostly because for these products to enter the Brazilian market they would need to comply with a new standard specific for that country, where there was still no data available for the inverter performance under the Brazilian criteria.

During the first two years, different inverter brands and models were tested at the laboratory, and although most models showed compliance to the standards, a few cases showed non-compliance with one or more aspects of the standards.

This work presents the data obtained during inverter testing. The main attempt is to inform international inverter manufacturers about the aspects of the Brazilian standards and which aspects will require hardware and software reengineering in order for the inverter to be commercialized in the Brazilian market.

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2. Brazilian standards

The Brazilian standards NBR 16149 and NBR 16150 dictate most of the features of photovoltaic systems´ connection to the power grid, except for the anti-islanding aspect, which is fully described in the NBR IEC 62116, and DC polarity inversion and photovoltaic overload, which are described in the INMETRO Normative Regulation Number 357. All the tests for the conformity criteria are listed in Tab. 1, and are briefly described in the following items.

Tab. 1: Inverter tests according to Brazilian regulation.

Number	Test	Reference standard
1	Flicker	ABNT NBR 16149 and 16150
2	DC-Component injection	
3	Harmonics and wave distortion	
4	Power factor	
5	Reactive power injection/demand	
6	Over/undervoltage	
7	Over/underfrequency	
8	Power control under overfrequency conditions	
9	Reconnection	
10	Automatic out-of-phase reconnection	
11	Active power modulation	
12	Reactive power modulation	
13	Photovoltaic system grid disconnection	
14	Fault ride-through – FRT	
15	Polarity inversion protection	INMETRO nº 357 normative
16	PV overload	
17	Anti-islanding	ABNT NBR IEC 62116

2.1. Test 1: Flicker

The flickering caused to the electric system by the inverter is evaluated during the tests. For the criteria used and test procedures the Brazilian standards make reference to the international standards IEC 61000-3-3, IEC 61000-3-11 and IEC 61000-3-5. This is the only test with direct reference to international standards and all inverters tested in the laboratory complied with this aspect.

2.2. Tests 2, 3, and 4: DC-Component injection, harmonics and wave distortion, power factor

Tests 2, 3, and 4 are grouped together because of the similarity in their procedures. These three tests require de measurement of DC component, harmonics, and power factor of the current injected to the grid for different inverter loading conditions. Tab. 2 presents the conformity criteria for the three tests. It is important to mention that the DC component and harmonics are calculated using the inverter current fundamental component.

Tab. 2: Criteria for tests 2, 3 and 4 for inverter evaluation in Brazil.

Test	Criteria	Limit
2	DC component	< 0.5 %
3	Total harmonic distortion	< 5.0 %
	Odd harmonics – 3rd to 9th	< 4.0 %
	Odd harmonics – 11th to 15th	< 2.0 %
	Odd harmonics – 17th to 21st	< 1.5 %
	Odd harmonics – 23rd to 33rd	< 0.6 %
	Even harmonics – 2nd to 8th	< 1.0 %
	Even harmonics – 10th to 32nd	< 0.8 %
4	Power factor	0.98 lead ~ 0.98 lag

2.3. Test 5: Reactive power injection/demand

The fifth test requires the inverter to operate controlling the reactive power flowing between the inverter and the grid. This control is done regarding the actual active power injected into the grid. The Brazilian standards describe two types of reactive power control. The first type of control is referenced as a power factor curve, and in this mode the inverter is required to change its power factor according to a ramp function related to the active power delivered to the grid. The inverter installer should be able to configure the ramp function in the inverter, with the default values for the test as shown in Fig. 1. The second type of control consists of maintaining a fixed proportion between the reactive power flowing and the active power injected into the grid. This is the same as maintaining a fixed power factor during inverter operation, but the standard requires the installer to input a percentage value for the reactive/active power relation and not a fixed power factor value. Fig. 2 shows the expected operation for the inverter in the second type of control.

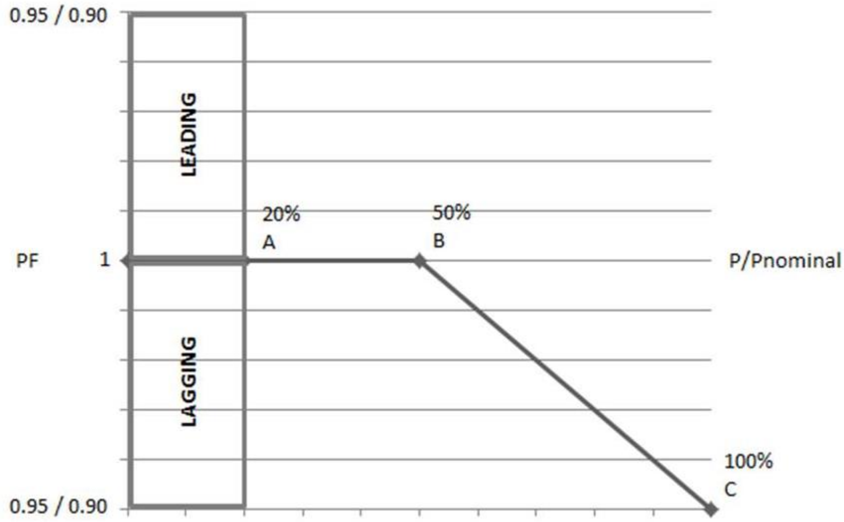

Fig. 1: Reactive power control as a power factor ramp.

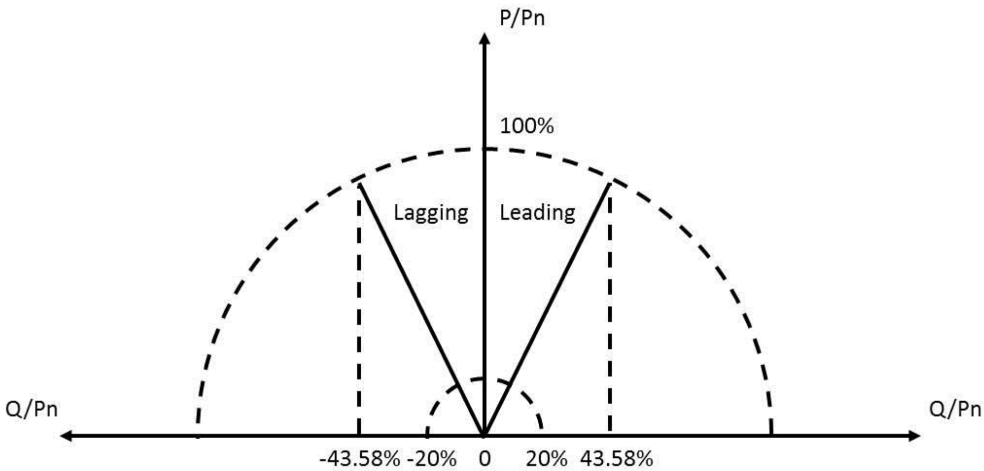

Fig. 2: Reactive power control as a fixed proportion of the active power injected to the grid.

The first type of control is mandatory for inverters with rated power above 3 kW and less or equal to 6 kW; for inverters with rated power equal or above 6 kW, the manufacturer may choose between the two types of control to be implemented in the equipment. Inverters with rated power under 3 kW are not required to have a reactive power control routine.

For the conformity criteria in the first control type, the inverter should be able to attain the power factor values within a ± 0.025 tolerance of the expected values for the injected power above 20 % of the inverter rated power. The second type of control has the same directive but with ± 2.5 % tolerance regarding the expected reactive power.

2.4. Tests 6 and 7: Over/undervoltage, over/underfrequency

The 6º and 7º tests evaluate the inverter regarding the interruption of power injection during abnormal grid conditions. In these tests, the inverter should detect the voltage and frequency values outside the normal operation range and cease to inject power into the grid within the respected time limits. Tab. 3 summarizes the criteria for these tests.

Tab. 3: Grid operation values and power injection interruption time limits for tests 6 and 7.

Voltage range (% V_{rated})	Power injection interruption time limit
V_{grid} < 80 %	0.4 s
80 % ≤ V_{grid} ≤ 110 %	Normal operation
110 % < V_{grid}	0.2 s
Frequency range	Power injection interruption time limit
f_{grid} < 57.5 Hz	0.2 s
57.5 Hz ≤ V_{grid} ≤ 62.0 Hz	Normal operation
62.0 Hz < V_{grid}	0.2 s

2.5. Test 8: Power control under overfrequency conditions

Test eight requires the inverter to control the active power injected into the grid according to the grid frequency. For frequency values between 60.0 Hz and 60.5 Hz the inverter is required to maintain the power injection unaltered, but for frequency values between 60.5 Hz and 62.0 Hz the inverter must reduce the power injected to the grid according to Eq. 1.

$$\Delta P = [F_{grid} - (F_{rated} + 0.5)] * R \qquad \text{(eq. 1)}$$

where:

ΔP is the active power variation, expressed in percentage, based on the active power injected at the moment the frequency exceeds 60.5 Hz (P_M);

F_{grid} is the actual grid frequency;

F_{rated} is the rated grid frequency;

R is the active power reduction factor, expressed in percentage by Hz, adjusted on - 40 %/Hz.

Also, once an overfrequency event is detected and the injected power is reduced, the inverter is required to reestablish the normal power injection only when the grid frequency returns to a value between 60.0 and 60.1 and maintains this value for at least 5 minutes. When the frequency stabilizes, the inverter is allowed to increase the power injection at a maximum rate of 20 % P_M/minute.

The Brazilian standards divide this test procedure in two parts. The first part corresponds to seven frequency points that evaluate the inverter response to overfrequency events. The second part corresponds to the eighth point that evaluates the power injection gradient. Fig. 3 shows the frequency points and the expected injected power; the power injection gradient is evaluated during the transition between points 8 and 1.

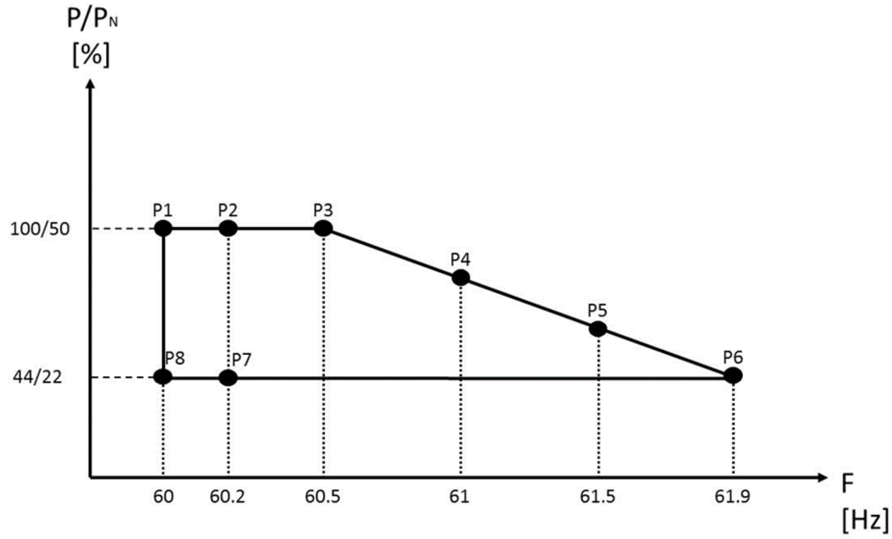

Fig. 3: Frequency points and inverter response for test 8.

The inverter presents conformity with the test requirements if the values measured are as expected in Fig. 3 with a ± 2.5 % tolerance.

2.6. Test 9: Reconnection

This test requires the inverter to reconnect to the grid once the normal operation conditions are detected. The inverter is required to reconnect within 20 to 300 s after the grid returns to normal. After the over and undervoltage tests the reconnection time is measured to verify this test criteria.

2.7. Test 10: Automatic out-of-phase reconnection

This test requires the inverter to withstand two pulses of out-of-phase grid voltage. In the first pulse, the grid voltage waveform skips 90º and, in the second pulse, the waveform skips 180º. The inverter is considered in conformity with this requirement if after each of these events it still injects power into the grid normally.

2.8. Tests 11, 12, and 13: Active power modulation, reactive power modulation, photovoltaic system grid disconnection

Tests 11, 12, and 13 are grouped together because their procedures make use of telecommunication protocols to send commands to the inverter. By using external commands test 11 evaluates if the inverter is capable of limiting the power injected into the grid according to the operator necessity. Test 12 makes use of external commands to evaluate if the inverter is able to operate with reactive power control as described in Fig. 2. These two tests are only required for inverters with rated power above 6 kW. Test 13 is required for all inverters and consists of sending commands for the inverter to start and stop the power injection into the grid.

The Brazilian standards do not establish a communication protocol and require the inverter manufacturer to provide the inverter with a protocol of his choice and all the equipment needed for testing.

2.9. Test 14: Fault ride-through – FRT

Test 14 requires that inverters with rated power equal or over 6 kW withstand voltage sags without disconnecting from the grid. Fig. 4 shows the criteria for the sags duration and inverter expected response regarding the sag event duration.

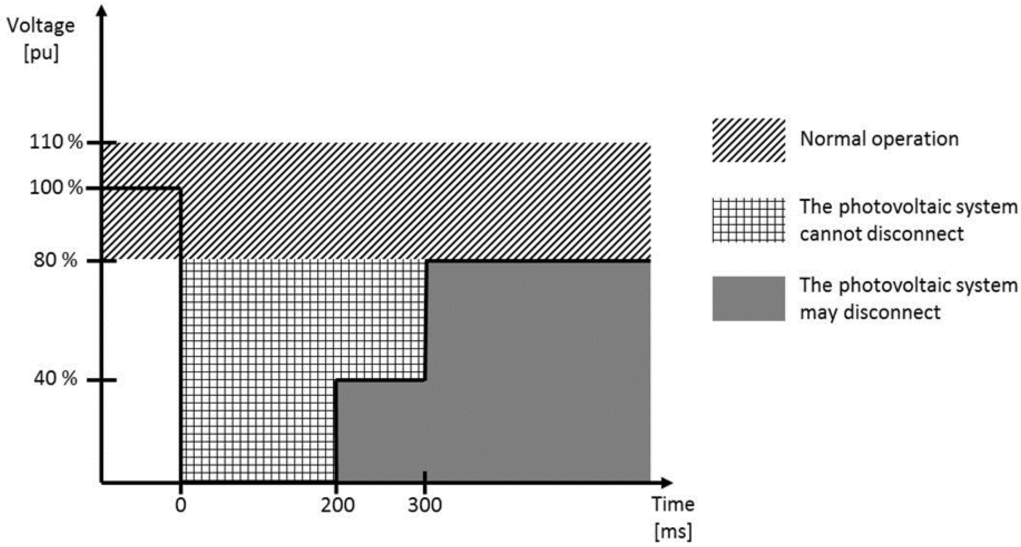

Fig. 4: Inverter response regarding voltage sag duration.

2.10. Tests 15 and 16: Polarity inversion protection, PV overload

Test 15 and 16 are grouped together because their test proceedings are similar and they are both discussed in the INMETRO Normative nº 375. These tests consist of operating the inverter for a period with the DC input polarity inverted, or with an overall DC input capacity 20 % above the inverter rated active power, for each test respectively. After the abnormal operation period, the inverter is operated in normal conditions. The inverter is considered in conformity if after the abnormal conditions it is able to inject power into the grid normally and there is no visible damage to it.

2.11. Test 17: Anti-islanding

The ABNT NBR/IEC 62116, which is a translation of the IEC 62116 standard, describes the anti-islanding test characteristics and procedures. For this test, the inverter is required to detect the absence of grid voltage and stop to provide power to the local load. The procedure takes several test conditions, which vary in power injected by the inverter and the percentage consumed by the local RLC load, but once the grid voltage disconnection occurs the inverter needs to stop the power injection in at least 2 seconds.

3. Laboratory infrastructure

In order to test grid-tie inverters the Laboratory of Photovoltaic Systems of the Institute of Energy and Environment of the University of São Paulo developed a test bench that is composed mainly of: a Solar Array Simulator (SAS) DC power supply, a grid simulator AC power source, a RLC load bank, and a power analyzer. The equipment used in the laboratory and the connection diagram are shown in Fig. 5 and Fig. 6, respectively.

Fig. 5: LSF String Inverter test equipment. From left to right: S.A.S DC power source, grid simulator AC power source, and RLC load bank.

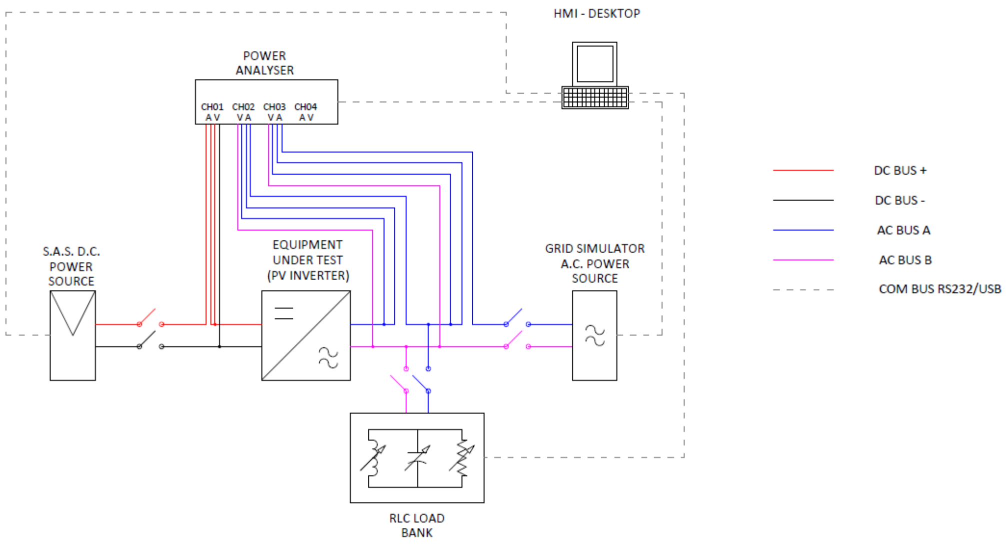

Fig. 6: Laboratory inverter test setup connection diagram.

The test bench equipment allows for testing single-phase inverters with maximum rated power up to 10 kW, as the current INMETRO normative only applies to inverters with rated power equal to or below 10 kW.

4. Inverter test experiences

During the first two years, the laboratory tested 15 inverters with rated power between 250 W and 5,000 W. Among the inverters tested, nine showed conformity with all the tests required by the labeling program, and the others showed nonconformity in one or more tests. Tab. 4 summarizes the inverters tested in the order they were tested, and the conformity criteria.

Tab. 4 shows that the inverters presented nonconformity in tests 2, 3, 4, 5, 6, 7, 8, 13 and 17. Inverters numbers 4, 6, 7 and 8 did not have further development on their firmware, but the manufacturers from inverters 9 and 10 requested to use the laboratory infrastructure to collect data and improve their firmware.

It is important to notice that inverter number 4 is a micro-inverter, designed for use connected directly to a photovoltaic module. This equipment did not have a communication port or telecommunication system that an operator could use to configure its operation or send any type of commands; so it immediately showed nonconformity with test 13.

Tab. 4: Inverters tested and their conformity with the standards.

Inverter	Rated Power (W)	Conformity with the standards?	Nonconformity for tests
1	1,500	Yes	--------
2	3,000	Yes	--------
3	4,600	Yes	--------
4	250	No	6; 7; 13
5	2,000	Yes	--------
6	700	No	3; 4; 8
7	1,500	No	2; 3; 4; 8
8	2,000	No	3; 4; 8
9	4,600	No	3; 5; 8; 17
10	5,000	No	5; 8
11	4,600	Yes	--------
12	1,000	Yes	--------
13	1,500	Yes	--------
14	3,000	Yes	--------
15	5,000	Yes	--------

4.1. Inverter nº 9

Inverter number nine had its firmware updated for harmonic distortion compliance with the Brazilian standards. Fig. 7 shows the results for the 4 evaluations of the harmonic distortion firmware update. The inverter technical team made each update based on the previous results. For the first three evaluations, the inverter presented one or more current harmonics over the limits established by the ABNT NBR 16149. At the fourth evaluation the firmware update lead to an inverter operation in conformity with the Brazilian standard.

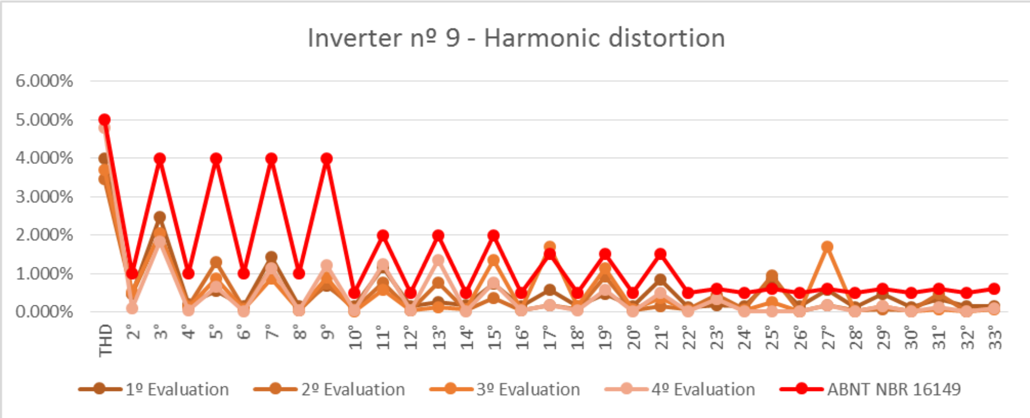

Fig. 7: Harmonic distortion evaluation results for firmware update on inverter nº 9.

After confirming the compliance with the requirements of test 3, the inverter technical team requested to evaluate the power control on overfrequency. At first, the inverter firmware did not present such control. The fourth firmware update implemented the power control required by test 8. One trouble found in this implementation was the misinterpretation of the power injection gradient. During the second evaluation, it was discovered that the value used for the power injection gradient was the inverter rated power and not the P_M value specified by the standard. With this result, the technical team developed a fifth firmware update, which presented conformity for test 8. Fig. 8 and Fig. 9 show the gradient test results for the three evaluations of inverter number nine.

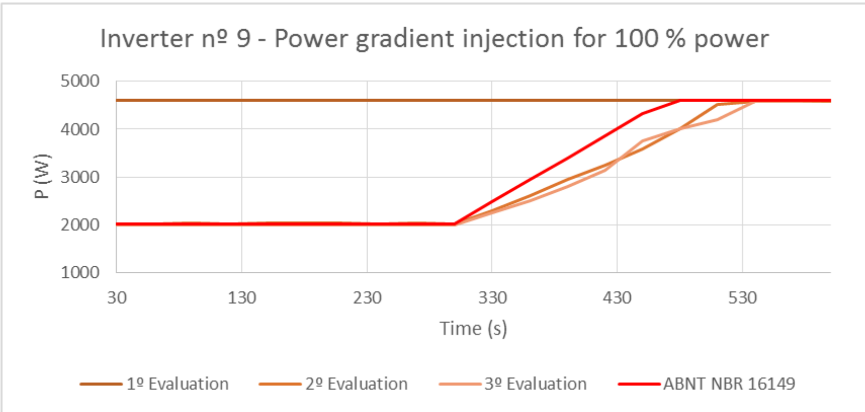

Fig. 8: Power injection gradient evaluation results for inverter nº 9 with 100 % rated power.

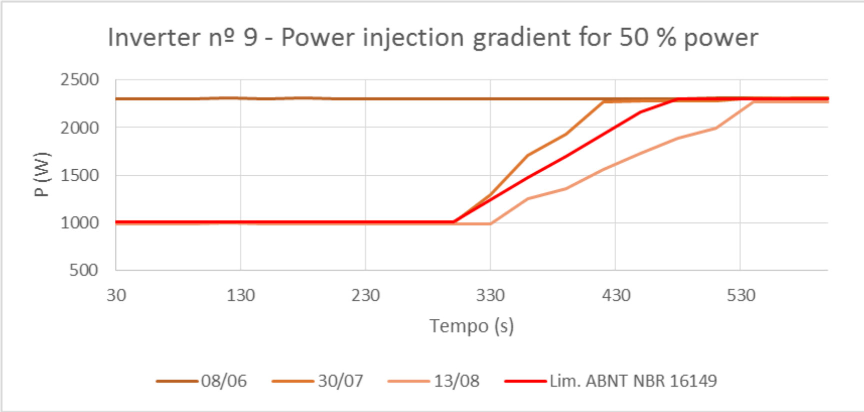

Fig. 9: Power injection gradient evaluation results for inverter nº 9 with 50 % rated power.

With inverter nº 9 in conformity with the requirements of tests 3 and 8, the technical team requested the evaluation for the power factor curve. Fig. 10 shows the results for the first and second evaluations of the power curve. At the first evaluation the inverter presented power factor values very close to the standard upper limit, so the technical team implemented a sixth firmware update to bring the values closer to the standard.

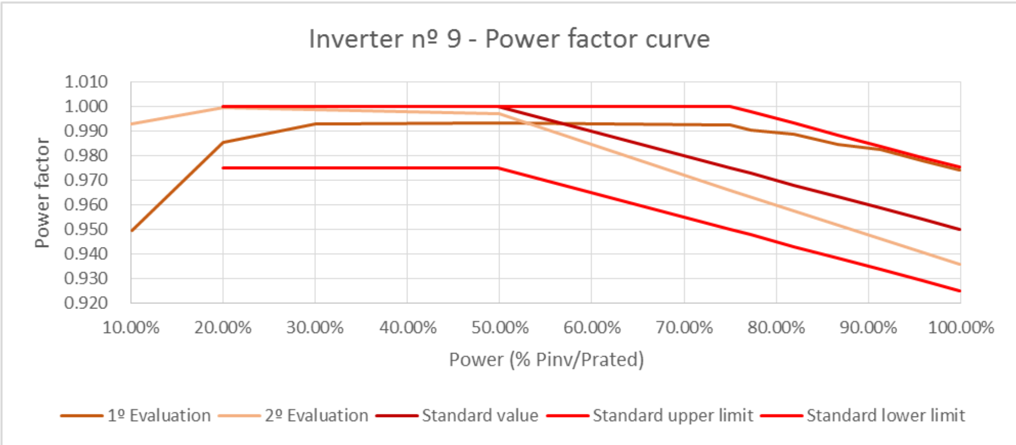

Fig. 10: Power curve evaluation results for inverter nº 9.

Although the inverter did not show conformity with the requirements of test 17, once the inverter showed conformity with tests 3, 5, and 8, the manufacturer did not request additional evaluations and firmware updates.

4.2. Inverter nº 10

Similar to inverter number nine, the inverter number ten also went through firmware updates in order to comply with aspects of the Brazilian standards. The first update was regarding the requirements of test 8. Likewise the values presented by inverter nº 9, inverter nº 10 also used the rated power instead of the P_M value in order to apply the power injection gradient. The inverter technical team then implemented a firmware update in order to comply with test 8. After the first update, the inverter showed compliance with the test requirements but started to present instability problems such as random disconnections from the grid. To correct this problem, the technical team developed a second firmware update to eliminate the inverter operation instability and add the power factor curve operation.

Fig. 13 shows that the firmware update implemented the power factor curve successfully; also, the update solved the disconnection problems. Yet, Fig. 11 shows the power injection gradient did not attain the inverter rated power during the 3rd evaluation, and the equipment was considered in nonconformity with the requirements of test 8. After this firmware implementation, the inverter manufacturer did not request further evaluations for this equipment.

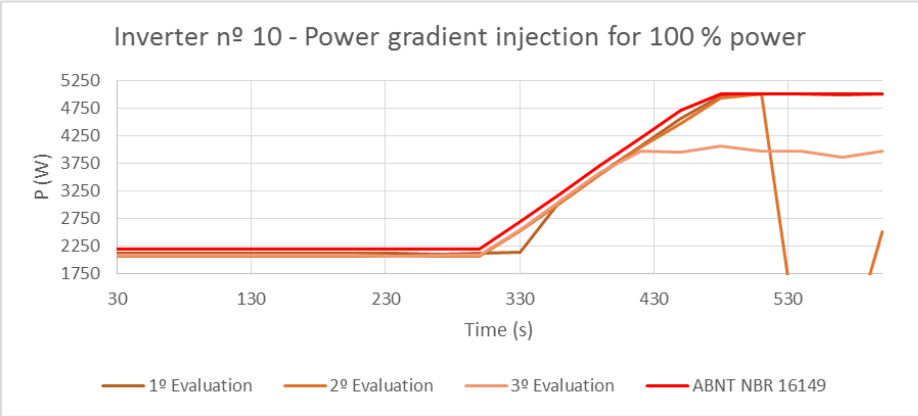

Fig. 11: Power injection gradient evaluation results for inverter nº 10 with 100 % rated power.

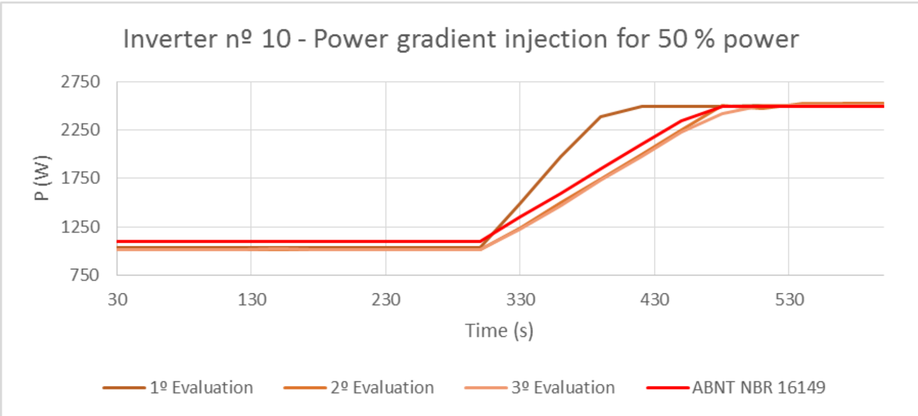

Fig. 12: Power injection gradient evaluation results for inverter nº 10 with 50 % rated power.

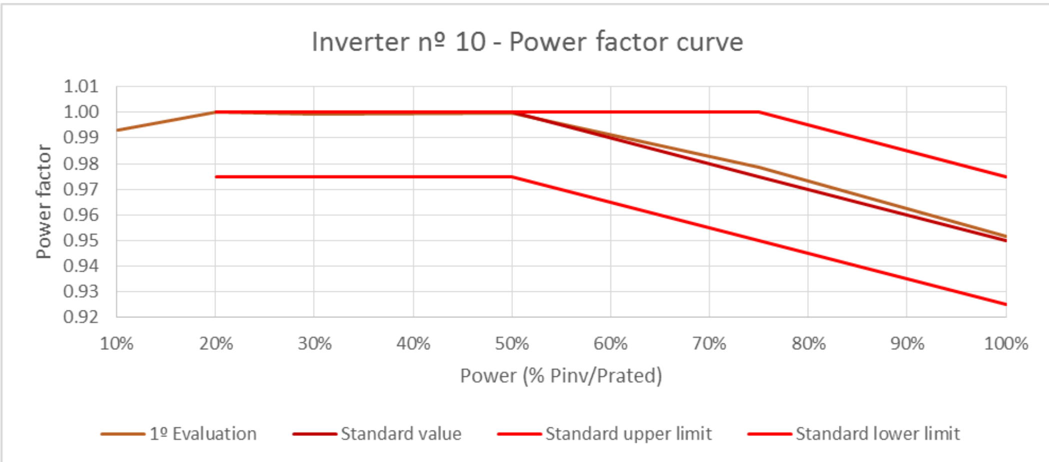

Fig. 13: Power curve evaluation results for inverter nº 10

5. Conclusion

The Brazilian standards evaluate inverters in different aspects: power quality, grid interaction, and safety. Most of the inverters tested in the laboratory were able to present conformity with all the standards requirements. Some of the inverters tested showed nonconformity with different aspects of the standards, but the experience with the manufactures´ technical teams showed that it is possible for equipment already available in the market to attain conformity with the Brazilian standards by firmware update.

The results showed in section 4 back the conclusion where it is possible for equipment already available in the market to receive firmware development in order to comply with the Brazilian criteria. The results also inform manufacturers which aspects should be included in the inverter firmware and how the equipment should perform under test conditions.

It is important to mention that micro-inverters usually do not have a communication port or telecommunication system able to send commands to change the inverter operation, which leads to a nonconformity with the requirements of test 13 and make firmware update unavailable.

As for the most critical aspects of the Brazilian standards, the power control in overfrequency, the power factor curve, and the harmonic distortion requirements showed to be more difficult to attain for the inverters that did not comply with the aspects of the standards.

The Brazilian standards have a rigorous criteria, some types of inverters, like micro-inverters, won't be able to comply with the all the aspects without hardware and software implementations, this could impact in the equipment cost and performance. So for future challenges there is the question that all types of inverters should comply with one general standard or there should be a specify criteria for each type of inverter. Also there is the question about the limit levels of the standards and the discussion of which ones should be revised, for example, inverter n° 9 at the first firmware implementation showed a power factor curve within the limits required by the standard, but the second implementation showed an improvement on the inverter power curve, so a more restrict limit level could help inverter manufacturers to provide equipment with better performance to the market.

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