Title: Automatic Voltage Regulator and Power System Stabilizer Type Tests for Russian Certification

Paper ID No: 20

Technical Track

Session 3: Power System Stabilisation via Asset Optimisation

Author: Sandro Tuscano

Company: Ansaldo Energia

Country: Italy

Abstract

Ansaldo Energia is completing in Russia the supply of 14 turbogenerator sets equipped with gas turbine AE64.3A. One of the related activities was to obtain the System Operator certification necessary for installation of the AVR (Automatic Voltage Regulator) in the Russian Power System. The AVR and its embedded PSS (Power System Stabilizer) were tested in multiple sessions at the NIIPT research center by connecting them to the Electro-Dynamic Simulator EDS, a physical model including reduced power generators (around 10 kVA), transformers, loads, lines and the related control and recording equipment.

Despite the fact that the regulator under test has already been installed in about 30 countries, during the NIIPT tests several parts of the regulation program had to be modified. In fact new functions had to be added which, although not requested by international standards nor by national grid codes, are specifically required for energy production in the Russian Federation, in order to increase the stability of the Power System and to prevent disconnection of the generating units.

During the NIIPT tests, the AVR underwent dozens of short circuits, fast frequency variations, direct coupling between generators and other tests that cannot be accomplished in real power plants, where the grid cannot be pushed close to its stability limits.

After the above mentioned modifications, the AVR successfully passed the official test program, composed of more than 80 tests specifically devised to guarantee a good behaviour in all critical transients, as damping local and interarea oscillations, field voltage forcing in case of short circuit, or correct action of underexcitation and rotor current limits.

It is hard to obtain such accurate and reliable results with a computer simulation, because of the differences between the software program, the microprocessor and input-output hardware, and the noise that affects the real trends.

Introduction

In recent years Ansaldo Energia cooperated with Russian customers as Power Machines, Stroytransgaz, Enel OGK-5 and Mosenergo, in the building of several power plants located in the Russion Federation, for example at Saint Petersbourg, Tyumen, Adler and Sredneuralskaya. Eleven of these power plants has already been commissioned, and others are under construction. In these projects Ansaldo supplies the turbine-generator set outfitted with the turbine control system, the protection system and the excitation system. Most of these units are equipped with the AE64.3A gas turbine, connected to a 82 MVA generator; one of them is equipped with the AE94.3A gas turbine associated with a 300 MVA generator, in combined cycle with an RT20 steam turbine connected to a 185 MVA generator.

The Russian Federation has a particular Power System that can operate close to the stability limits of the grid, especially in case weak transmission lines have to transfer heavy loads. In these conditions the voltage regulators must be capable of a strong damping action, otherwise the stability could be affected by increasing spontaneous oscillations. Also for this reason the Russian requirements are more severe than other countries, implying that, before a generating unit can be connected to the Russian system, special tests must be carried out to verify the voltage regulator performances and appropriate certification has to be obtained.

Such tests are performed by the power transmission research institute NIIPT of Saint

Petersburg, where the largest existing physical model for electro-dynamic simulations is located. This model makes use of about 70 generators, 150 transformers, 160 loads, 700 transmission lines and a control room equipped with the instrumentation for command, measurement and monitoring, including a 32 channels digital recorder. The generators size ranges between 1,5 and 30 kVA and is designed to endure overcurrents and overvoltages without damage, even when the limiting functions of the regulator under test are not working properly; some of the generators are equipped with special devices to modify the inertia and the time constant.

Test program
To verify the behavior of the voltage regulator, the NIIPT research institute has developed a protocol envisaging 81 tests in different grid configurations and operating conditions, including:
- Single phase and phase-to-phase short circuits
- Set-point reference steps
- Increase of power transmission and low frequency oscillations
- Grid transients with line openings
- Increase and reduction of the grid voltage
- Direct connections between generators terminals, without interposed transformers

These events are used to verify the regulator efficiency, and in particular:
- The PSS capability to damp down oscillations
- The fast field forcing in case of stator voltage drop
- The correct action of the limiting functions
- The correct dynamic response during transients
- The regulators capability to prevent reactive power circulation between their generators

Due to the last group of tests, a couple of twin regulators has to be installed in the laboratory grid.

The voltage regulators installed in the above mentioned power plants are manufactured by EAA in the north of Italy, at Lerma. The regulator has a main loop for stator voltage regulation and an inner loop for excitation current regulation (Figure 1).
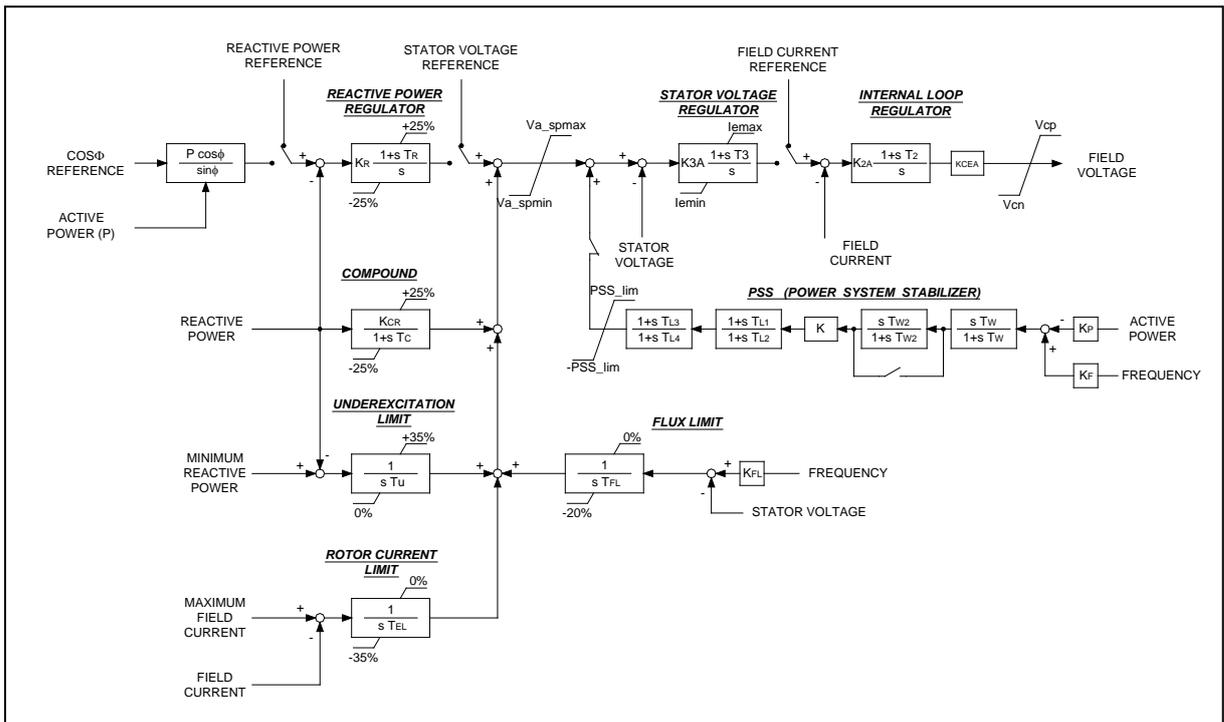
Figure 1 AVR block diagram

This model of regulator was developed in 1998/1999, and has been used with more than 150 turbogenerators installed by Ansaldo Energia in about 30 different countries.

Throughout the last years, the regulator was outfitted with further functions so as to comply with the requirements of different National Grid Codes and customer specifications.

Despite this extensive trial run, the regulator was still not conforming to Russian requirements in some specific conditions, as emerged during the 2011 testing program at the NIIPT laboratory.

During the test sessions in Saint Petersburg, the following main questions have been considered and consequent improvements have been achieved:

1) Effectiveness of PSS damping action
2) Pss inhibition in case of large frequency variations
3) Relè forcing during short circuit
4) Rotor current limiting

1) Power system stabilizer (PSS)

The PSS tests in the NIIPT program have been divided in two different groups to allow verifying the following:

a) Dynamic local machine oscillation tests, which verifies the PSS damping capability of oscillations in the range between 0,8 and 2 Hz.
b) Static aperiodic stability tests, to check the behavior at lower frequencies, ranging between 0,1 and 0,8 Hz.

Initially, the PSS scheme shown in Figure 2 went through the stability tests, with 2 inputs (active power and frequency), 2 wash-out blocks and 2 lead-lag blocks. The frequency is taken from the generator terminal voltage signal, without the need of a speed feedback .
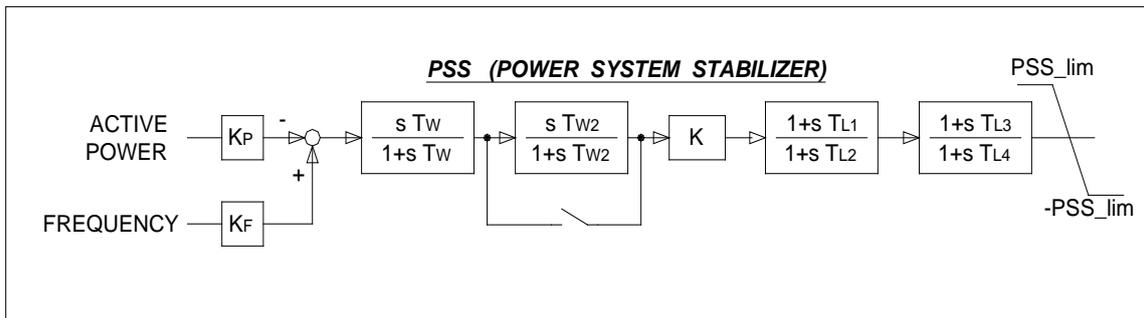
Figure 2 Initial PSS scheme.

In the first tests the PSS parameters were tuned with a simplified method, and thus not optimized for the network of the test circuit. Consequently the results of tests of group b) were not satisfactory, due to the presence of a 0,24 Hz oscillation that was not damped by the PSS, as show in Figure 3.
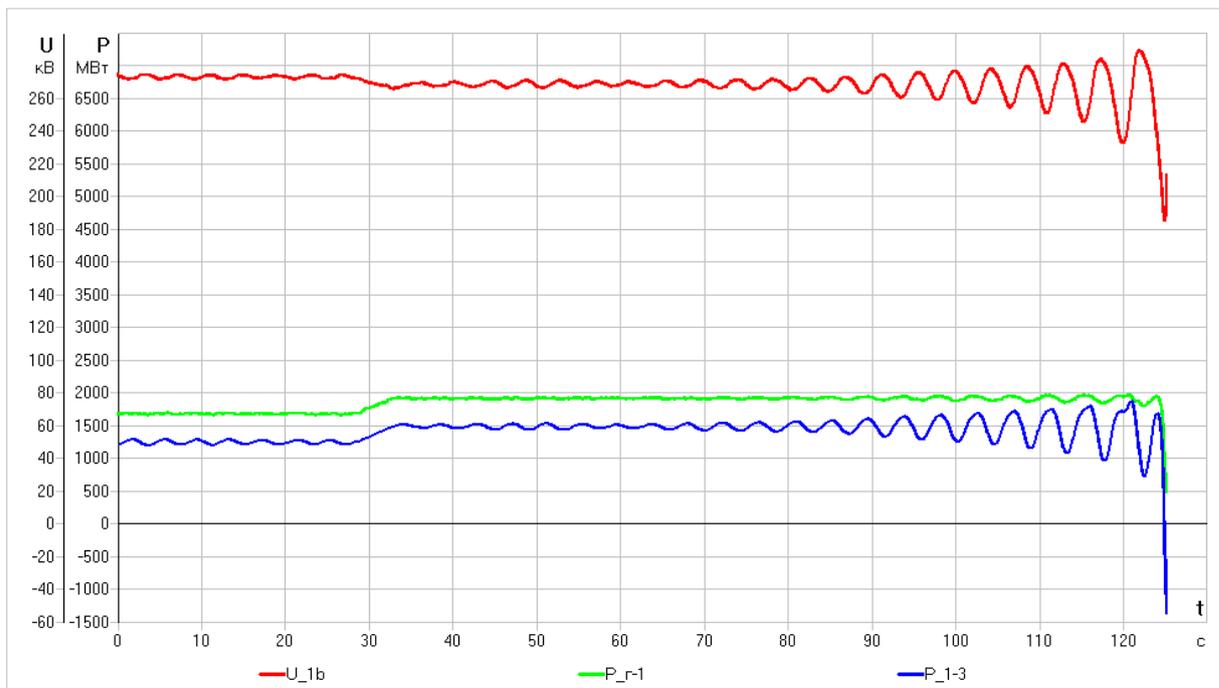

Figure 3 Test 19. Active power Pr1 transmission on line 1-3 increase, for aperiodic stability. Line 4-2 is disconnected. PSS is active. Test failed.
U_1b = voltage at bus bar 1
P_Γ-1 = generator active power
P_1-3 = active power in line 1-3

The PSS tests of group b), relating the aperiodic stability, are particularly tough for the regulator, since the increased active power transmission in the line leads to instability, and the other 3 generators of the test circuit do not contribute to the damping action because their regulators has no PSS. The test circuit is shown in Figure 4.
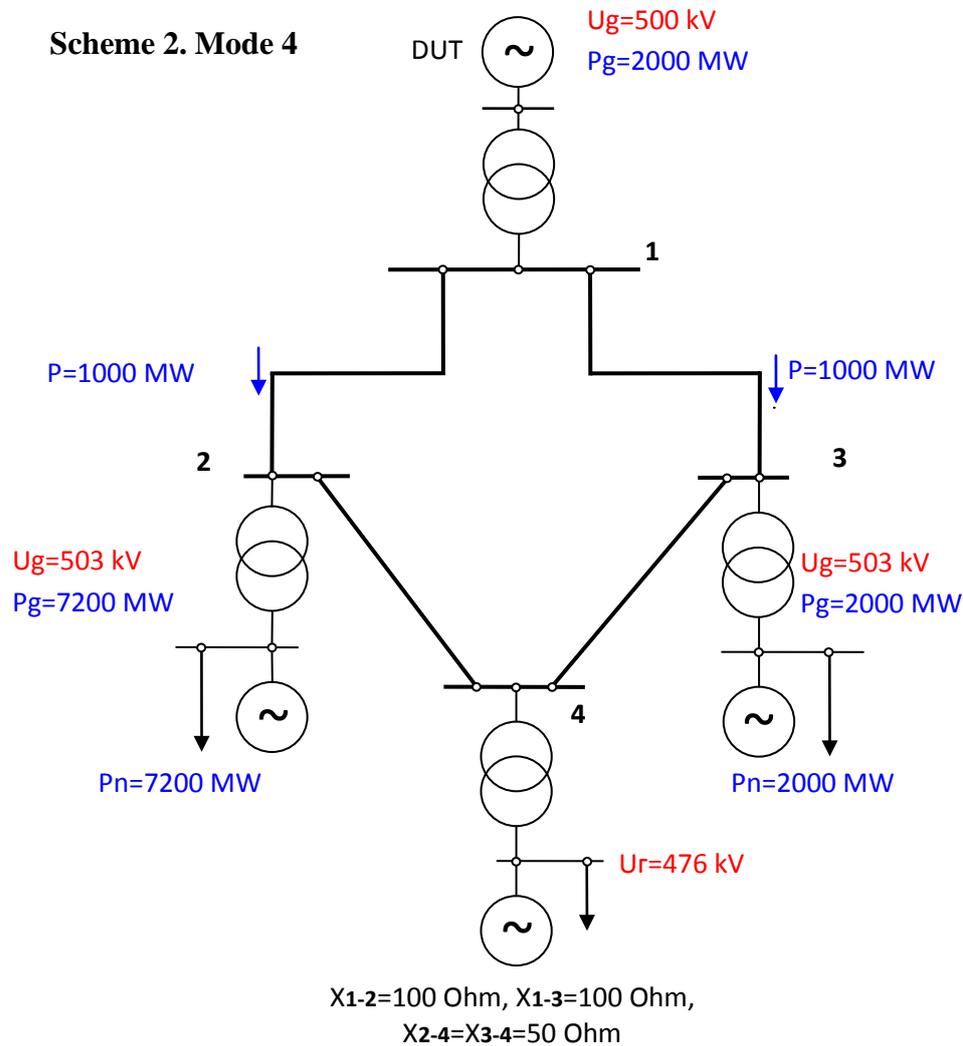
Figure 4. Test circuit for aperiodic stability. In the physical model the voltage and power values are scaled.
The device under test (DUT) is connected to upper generator.

After this first result, a study was done to obtain an optimized tuning of the PSS parameters, in combination with the tuning of the regulator. In fact, the PSS output adds to the generator stator voltage reference, therefore the regulator transfer function in the frequency range of interest must also be considered.

As the goal is to dampen the inter-area oscillations at low frequency, the more efficacious action is obtained by the frequency channel of the PSS, which gain must be tuned at a high value.

With the new set of parameters the stability in the inter-area test was reached, but the new tuning caused a very nervous excitation voltage regulation, with an unacceptable continuous correction of the field voltage that swung more than 40 % of the rated value. Not to mention that an extreme tuning of some parameter specifically aimed to pass one single test, could cause problems in the other tests, because the complete qualification

program must be passed with the same set of regulator and PSS parameters, so the tuning must be balanced for all situations.

In order to reach a radical and fresh solution to this problem the PSS block diagram was completely changed, moving to a more efficient configuration. Two ways were possible:
- Migration to the IEEE PSS2B model
- Adoption of the model shown in Figure 5, already widely and successfully used by Russian manufacturers

Owing to the tight cooperation with Power Machines and Electrosila, the second solution was chosen. For the first time, this scheme was used with a 2 loop regulator, contrary to previous applications on regulators without an internal excitation current loop.
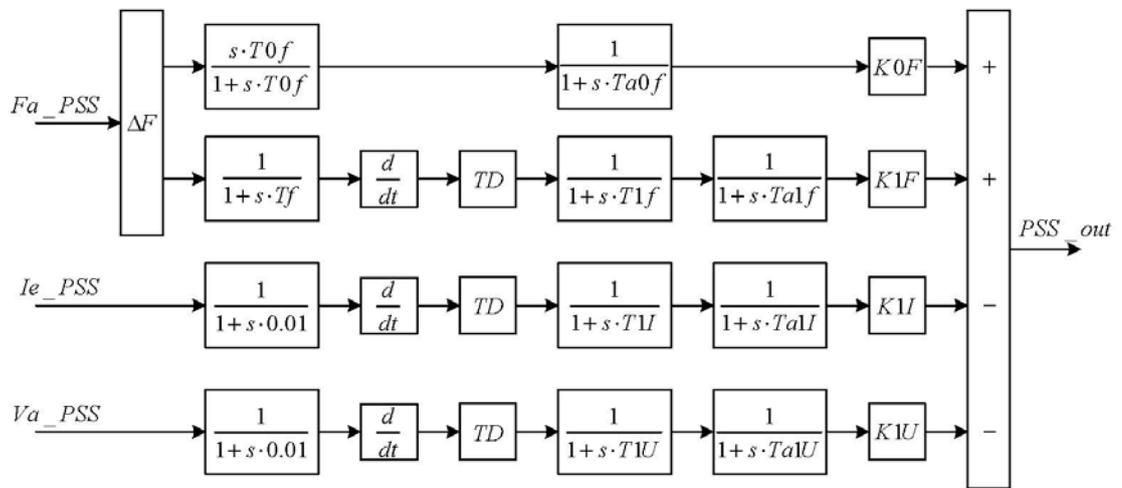

Figure 5 Modified PSS scheme.

The 4 inputs of this type of PSS are:
- frequency deviation
- frequency derivative
- rotor current derivative
- stator voltage derivative

The switch of the PSS scheme to the Russian model allowed to obtain a good result in the aperiodic stability test (Figure 6),as well as in all the other tests of the program.
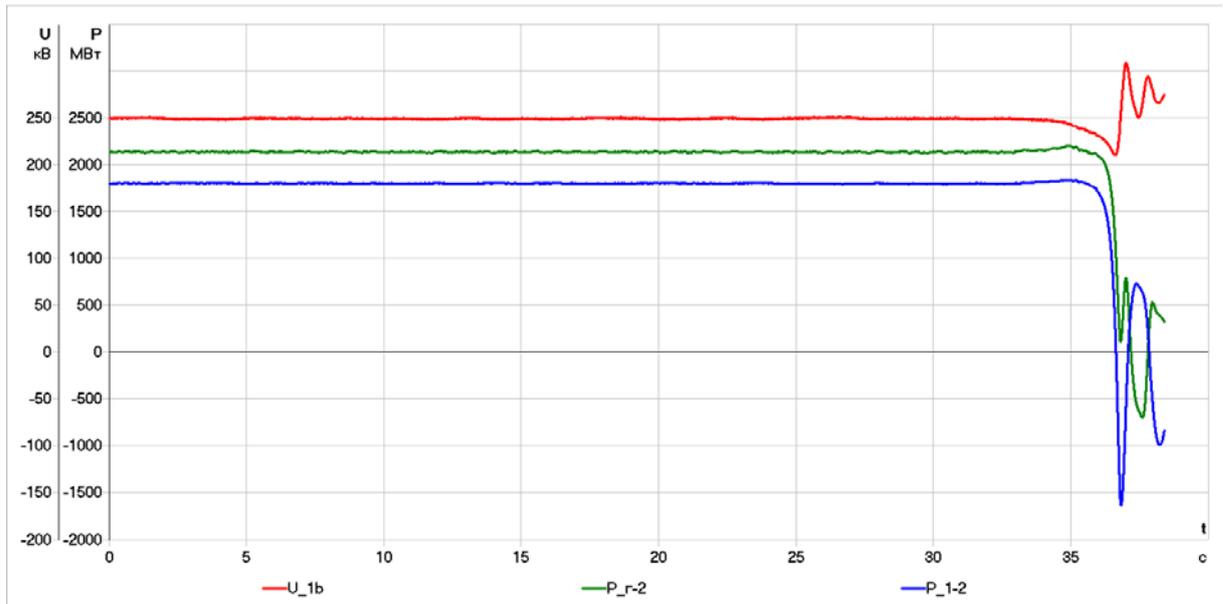
Figure 6 Test 19. Active power transmission on line 1-2 increase, for aperiodic stability.
Line 3-4 is disconnected. PSS is active. Test successful.
U_1b = bus bar 1 voltage
P_Г-2 = active power of the generator controlled by regulator under test
P_1-2 = active power to line 1-2

Figure 7 shows the difference in case the PSS was switched off, resulting in active power oscillations in the transmission line 1-2.
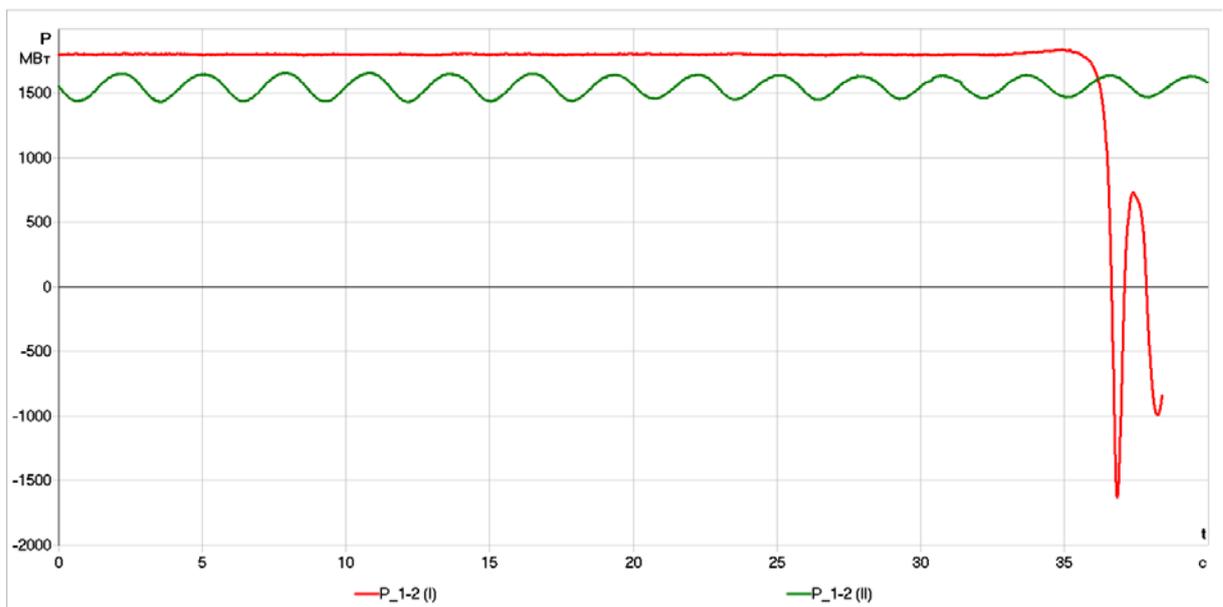

Figure 7 Test 19 and 20. Aperiodic stability test, comparison between PSS on (red trace)
and PSS off (green trace)
P_1-2(I) = active power in line 1-2 in case of PSS active
P_1-2(II) = active power in line 1-2 in case of PSS not active

The main action of this type of PSS is given by the two frequency channels, while the field current and stator voltage channels allow to expand the stability area.
By a selection parameter it is possible to set one of the following configurations:

a) the PSS output is added to the stator voltage reference
b) the PSS output is added to the excitation current reference

The best result has been obtained with scheme b), corresponding to Figure 8 with switch PSS-SW closed and switch PSS1-SW opened.
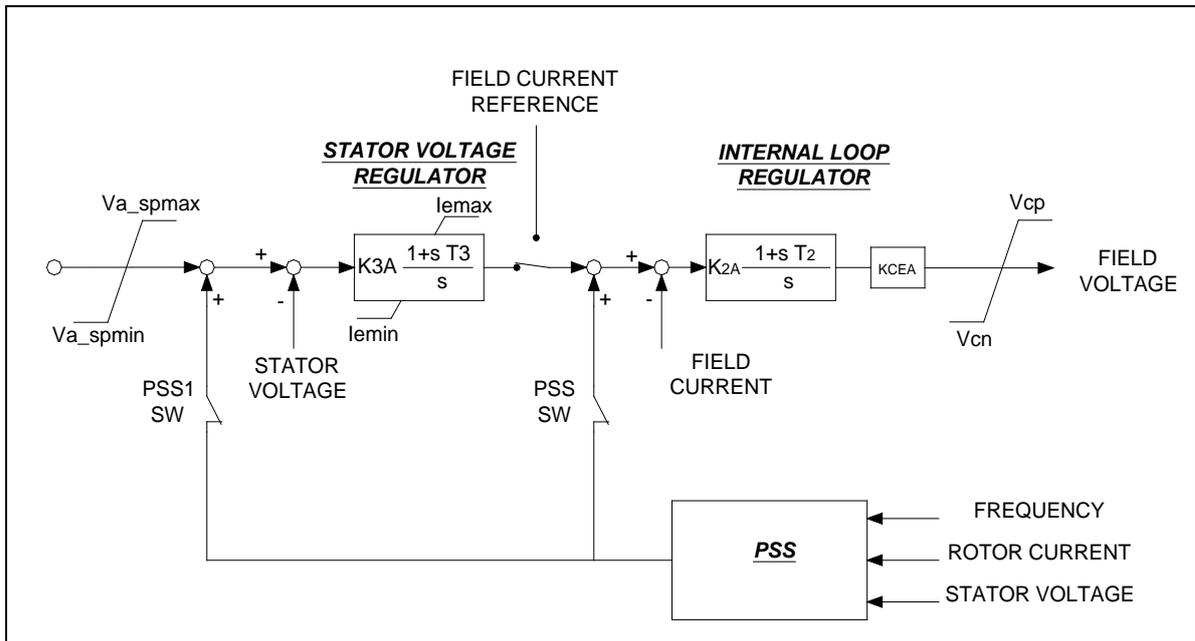

Figure 8 . PSS insertion in the regulation loop.

The critical issue of this PSS scheme is the quality of the frequency signal in terms of resolution and cleanness. Initially the frequency was acquired by an analog signal generated inside the card, but this had a resolution of 16.6 mHz which proved to be insufficient for the proper operation of the PSS.

Therefore the frequency acquisition was improved by using a digital counter at 1 MHz, that allowed to reach the following accuracy in the operating area around 50 Hz:

The frequency acquisition is refreshed each 10 ms and the length of the period is measured between two subsequent rising edges and, alternately, between two subsequent falling edges.

2) PSS inhibition in case of large frequency variations

In case of unidirectional variations of frequency exceeding a certain gradient (> 50 mHz/s), that can be caused for example by disconnection of loads or groups of generation, the PSS contribution may be counterproductive and may affect the stability of the power system. This problem can be avoided by adding a special logic in the AVR, and one of the NIIPT tests is specifically conceived to check this issue.

As the various grid codes and the buyer specifications don't prescribe this corrective tool, the regulator used by Ansaldo wasn't provided with such a function. So it was necessary to add a new logic to disable the PSS in the above described situation and avoid detrimental variations of the stator voltage.
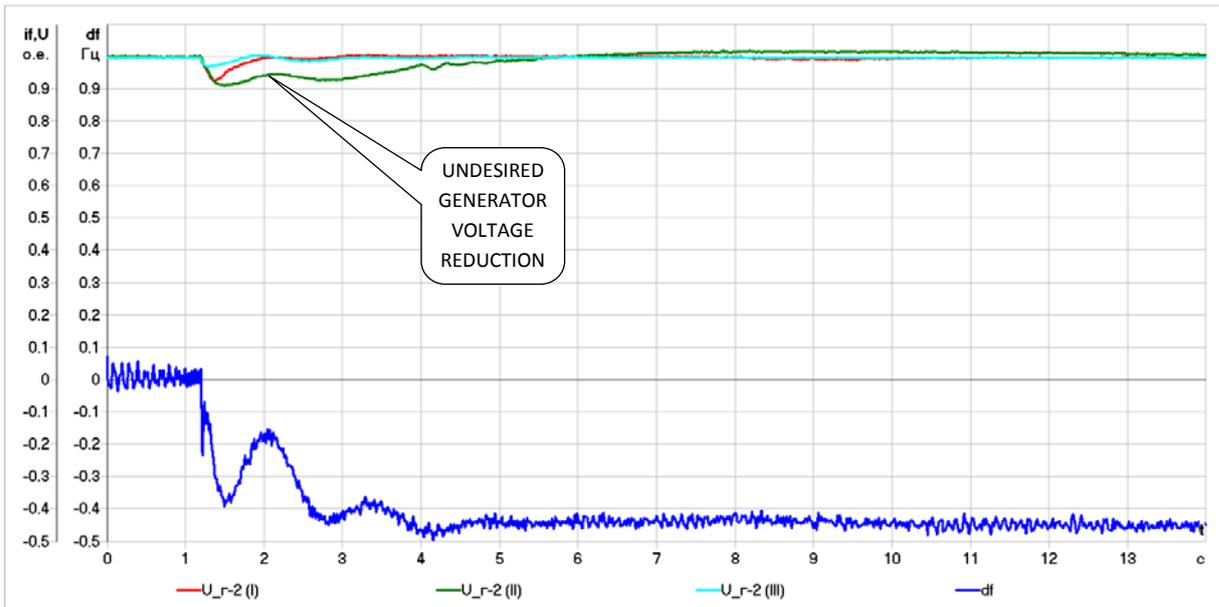
Figure 9 Test 41 and 42. Frequency fall.
U_г-2(I)= generator voltage in case of PSS switched on, with inhibition
U_г-2(II) = generator voltage in case of PSS switched on, without inhibition
U_г-2(III)= generator voltage in case of PSS switched off
df = frequency deviation

Figure 10 Test 37 and 38. Frequency rising.
U_г-2(I)= generator voltage in case of PSS switched on, with inhibition
U_г-2(II) = generator voltage in case of PSS switched on, without inhibition
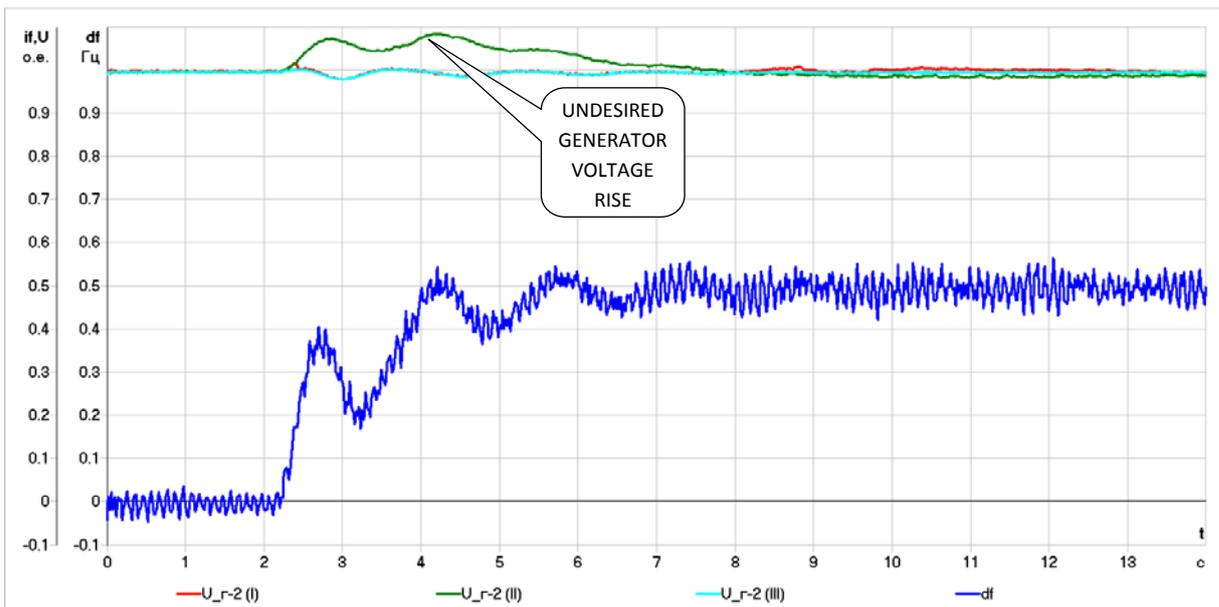*U_г-2(III)= generator voltage in case of PSS switched off*
df = frequency deviation

The execution of this function is delicate, because in order to be effective the intervention must be very fast, within 300 ms, so the logic must elaborate the frequency feedback and command the correct action in a very short time.

This task becomes more complicated because in some cases the PSS must not be de-activated, even if the frequency derivative exceeds 50 mHz/s. This is the typical case of a short circuit, after which the PSS must be working to damp down the oscillations.

As a consequence the regulator has been provided with a logic that discerns the events characterized by unidirectional frequency variations from the events characterized by frequency variations of oscillatory nature, as the transient following a short-circuit. In fact in the first case the PSS must be blocked in order to avoid unjustified alterations of the voltage, while in the second case the PSS must be free to operate.

The algorithm is based on the weighted average of the frequency derivative and the frequency deviation. The resulting signal is then filtered and compared to a threshold with an hysteresis.

The first release of the modified program was tested in Italy at the factory, where it worked correctly, but the behavior in the NIIPT laboratory was unexpectedly different, because of the much higher frequency short term variations and noise in the physical model grid, causing several untimely activations of the function. Based on the NIIPT tests, the function was calibrated in the final arrangement, successfully preventing untimely interventions.

3) Relè forcing

Following a short circuit, the generator terminal voltage falls to a lower value. In case of voltage drops under 80% of the pre-fault condition value, the Russian prescriptions require a very fast field voltage forcing, that must reach the ceiling in less than 60 ms.

In normal operation and small transients the forcing to the ceiling value can be easily accomplished within this time, or even less, but in case of a short circuit the stator current has a sudden increase (typically up to 2-4 p.u.), generating an inducted rise of the excitation current, which causes a transient de-excitation action by the inner field current regulation loop (see Figure 11).
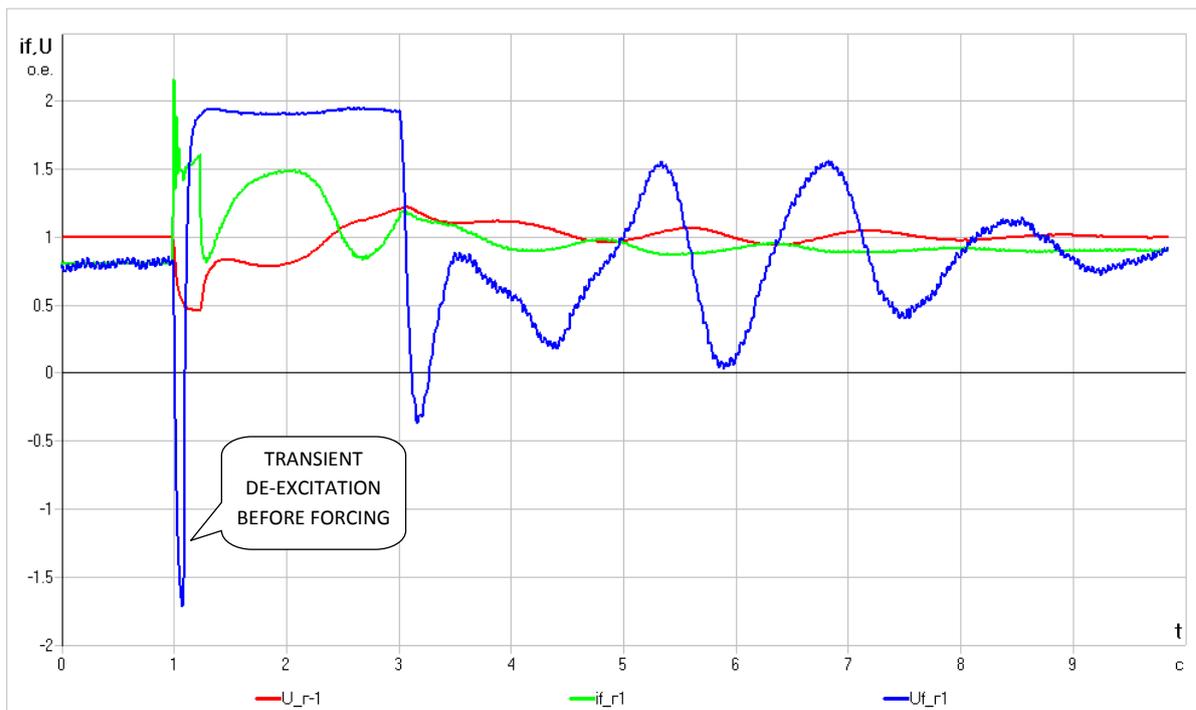

Figure 11 Test 44. Double phase short circuit. Test failed.
U_г-1 = generator voltage
if_г-1 = excitation current

Uf_г-1 = excitation voltage

It was possible to mitigate this undesirable effect by a different tuning of the regulator parameters, but the result was still not enough fast, so it was necessary to add the special 'relé forcing' function, that is already known and used in the Russian applications.

The relé forcing moves back the thyristor firing angle to its minimum value, thus forcing the maximum possible excitation voltage, when the generator voltage is detected to drop under a threshold, typically set at 0,85 pu.

In order to obtain a more effective result, the software that triggers the relé forcing checks not only the stator voltage value, but also the excitation current fast variation which occurs in case of short circuit. The excitation current offers the benefit of a reduced filter in the feedback, providing a fast action. The activation of the relé forcing is given by the formula:

where:

    stator voltage [p.u.], typically 0.85
    Field current [p.u.]
    time
    stator voltage threshold [p.u.]
    adjustable coefficient [p.u.], typical values between 0,1 and 0,6

Only as an indication, the virtual excitation current variation that would had caused the relé forcing activation in case of rated stator voltage, with K=0,6, is given by:

This value is much higher than the maximum gradient that can be reached in the field forcing generated by the regulator.

The exit from the relé forcing was accurately accomplished taking care of the filters and integrators initialization, to avoid inappropriate transients that could reduce the PSS effectiveness.

After the above mentioned improvements, the regulator was able to force a fast excitation ceiling voltage, as shown in Figure 12.
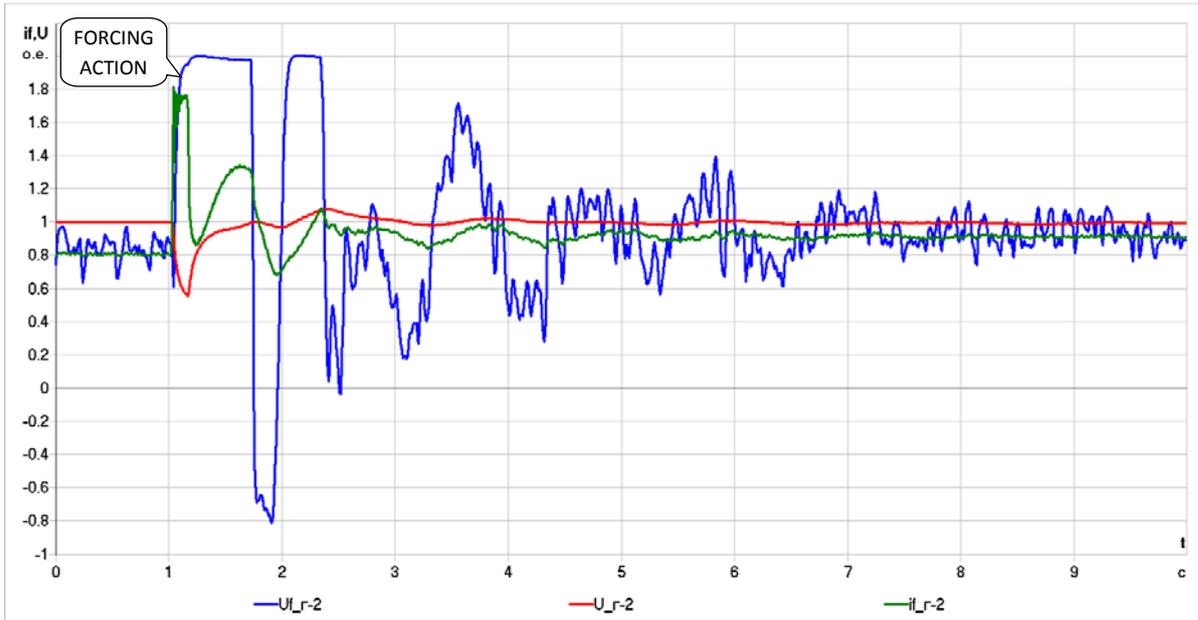
Figure 12 Test 44. Double phase short circuit. Test successful.
Uf_г-2 = excitation voltage
U_г-2 = generator voltage
if_г-2 = excitation current

This test was also useful to verify the correct action of the PSS after the short circuit. The result of the same event carried out with the PSS disabled is illustrated in Figure 13.
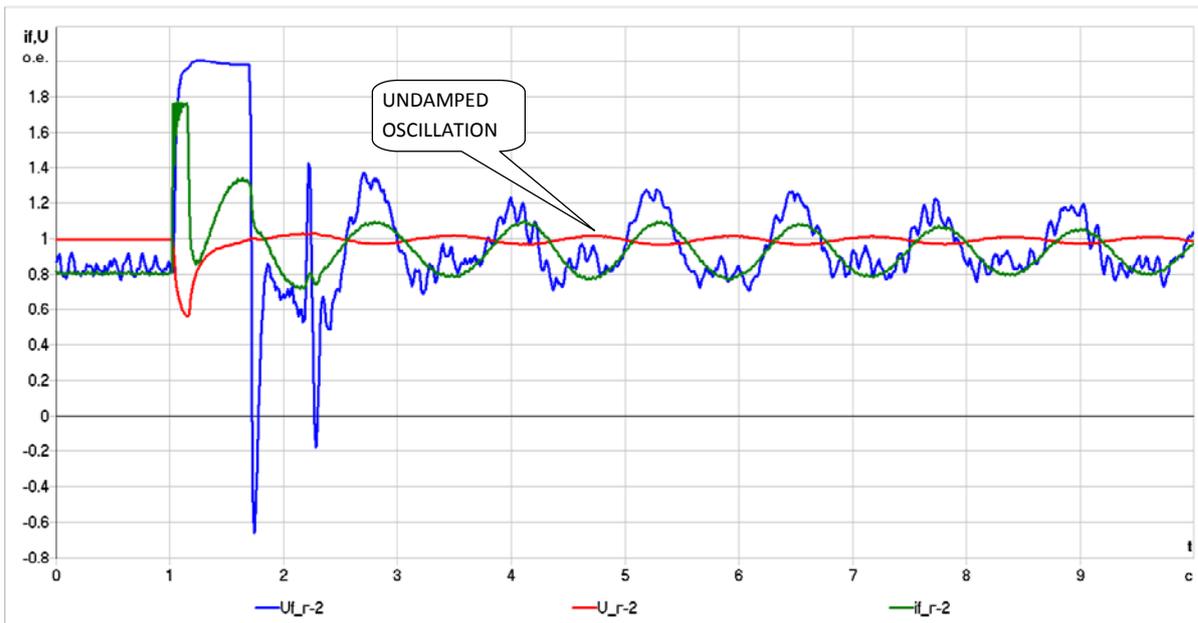

Figure 13   Test 45. Double phase short circuit with PSS switched off.
Uf_г-2 = excitation voltage
U_г-2 = generator voltage
if_г-2 = excitation current

4) Limiters

A minor adjustment in the regulator was done also as concerns the rotor current limit function.

During a short circuit, the rotor current is not controlled only by the regulation, but, due to the induction from the stator current, rises up to values higher than the threshold of the limit. This is emphasized by the oscillations of the rotor current at 50 and 100 Hz.

The logic of the limit intervention was modified: after a short circuit, the relé forcing initially prevails over the rotor limit, and only after a while (about 150 ms) the limiter is allowed to lower the excitation voltage, if necessary to bring back the excitation current under the limit value. The effect of this function can be seen in Figure 13.
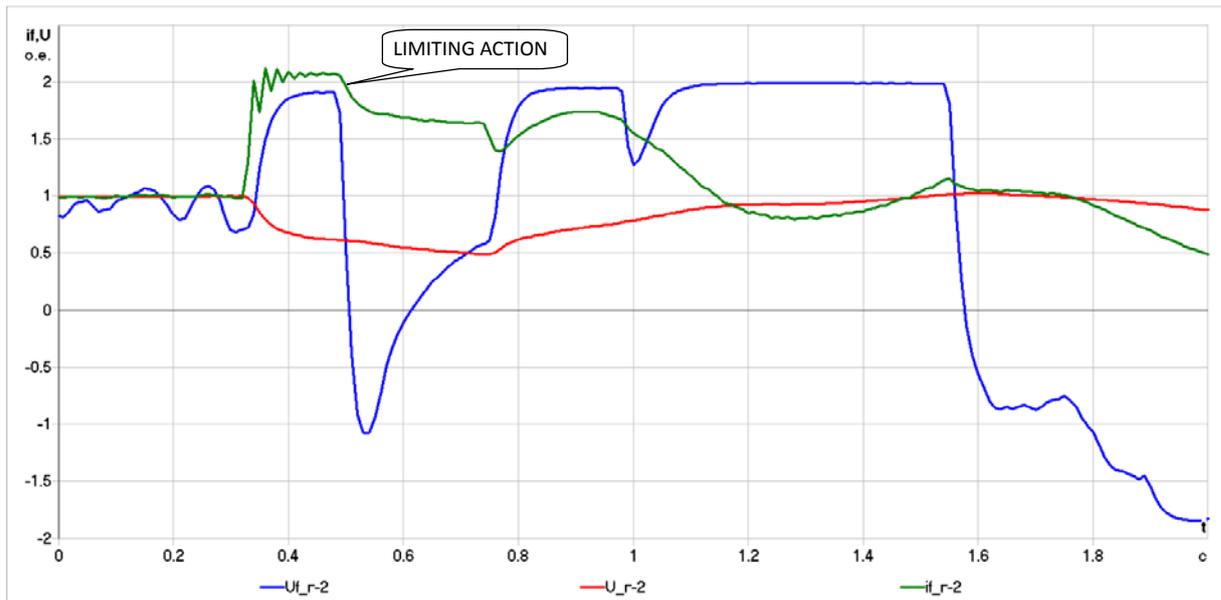

Figure 14 Test 56. Double phase short circuit of 0,4 s duration and rotor limiter intervention.
Uf_г-2 = excitation voltage
U_г-2 = generator voltage
if_г-2 = excitation current

General remarks

The test campaign was useful to reveal some specific issues which cannot be detected by other test methods, as computer simulations and site tests.

It is easy to understand that certain transients, as short circuits and frequency collapses, cannot be carried out during site tests at the power plant. Moreover, the low frequency inter-area oscillations are not often present during the site test, but they only emerge in particular operating conditions.

On the other hand Ansaldo Energia developed a computer model to reproduce the AVR block diagram and functions, the generator (with a fifth order model), the speed regulator and the simplified grid, in Matlab/Simulink simulation platform. This tool is certainly useful to check the theoretical behavior of the regulator, and gives a good result in many situations, but it is not suitable to obtain a realistic result in some particular case. In fact there is an approximation in the mathematical modeling of the physical components, that is also caused by nonlinearities and construction tolerances; moreover the same transfer functions of the block diagram are carried out in a different way in the real AVR and in the computer simulation, because of the differences in the

software program that is written with different computing language and command lines; and other differences are in the input-output hardware, in the sampling time, in the integration method, in the noise that affects the real trends.

For example, to get a good result with issue n. 1 and 2 (PSS and PSS inhibition in case of high frequency variations) the frequency acquisition must have a high resolution, and its derivative must be calculated with a suitable method to obtain a clean signal without an excessive delay. During the NIIPT tests, the method of derivation of the frequency and other quantities, as stator voltage and excitation current, was improved by the use of the following formula calculated in 2i +1 points:

$x' = (i \times (x_i - x_{-i)} + (i - 1) \times (x_{i-1} - x_{-i+1}) + ... + (x_1 - x_{-1})) / (k \times h)$

where

$k = (i \times (i + 1) \times (2i + 1)) / 3$,

x_i – result of the last measurement

i = 2 or 3, depending on the quantity concerned

h = 10 ms, sampling time

The derivative is calculated in the middle of 2i +1 points (e.g. 5 points if i=2), thus introducing a delay $T = i \times h$.

Conclusions

After all the necessary modifications and upgrades, the AVR successfully passed the official test program and was recommended by the NIIPT Research Institute for installation in the Russian Federation.

In the meanwhile, other versions of the regulation program ware developed, with the following alternative regulation schemes:

a) Double loop regulation with inner excitation current loop (same as the tested version) in combination with PSS IEEE 2B model, on the same hardware of the tested AVR.

b) Single stator voltage regulation loop in combination with PSS IEEE 2B model, on a new electronic card compatible with the actual AVR assembly

c) Single stator voltage regulation loop with PSS IEEE 2B model, on a new electronic card and new AVR platform

These configurations are undergoing the factory test phase and will be soon available for installation on Ansaldo turbogenerators. The qualification also include EMC and climatic tests carried out on the operating AVR by a separate certification firm, because configurations b) and c) involve an hardware upgrade, i.e. a new microprocessor and new interface have been installed to increase the AVR performance.

All the improvements devised during the NIIPT test phase have been applied to these new versions. As concerns the power plants in Russian Federation, these new regulators will be available as an alternative to the already certified regulator, but their installation will be possible only after they successfully repeat the NIIPT test program.