ABB Varspeed generator boosts efficiency and operating flexibility of hydropower plant

Fixed-speed turbines in hydro-electric power plants operate most efficiently at a so-called best efficiency point (bep) that represents the best combination of speed, head and discharge. Away from the bep, the hydraulic efficiency drops sharply. By operating the turbines at variable speed, overall efficiency can be optimized despite a varying head and discharge. Spain's Compuerto hydropower plant was chosen for a pilot project with an ABB Varspeed generator – a variable-speed machine based on the sub/supersynchronous cascade. It is demonstrating that Varspeed offers better plant efficiency and grid frequency control, plus more flexible power control in the pumping mode.

Variation of the speed of large electric machines driven by hydropower turbines or used to drive pumped storage units allows better overall plant efficiency, more flexible power control in the pumping mode, and improved power system frequency control. There are several ways in which the speed of a large machine can be varied: pole changing, use of a variable-frequency stator supply (via a load-commutated inverter), or use of a sub/supersynchronous cascade, in which an asynchronous machine is doubly fed (ie, via the stator and the rotor). ABB has been at the forefront of development in all three areas, and each of the methods is now proven.

Francis turbines and pump-turbines used in hydropower and pumped storage plants have a runner with fixed geometry. Advanced computer software and scale-model laboratory tests are used to optimize the runner design for a given head, discharge and speed. Although very high efficiency figures have been achieved in this way, they are only valid at the so-called best efficiency point, or bep. Away from the bep, the efficiency drops sharply. Since the hydropower turbine's operational regime is dependent on the discharge and head, and therefore highly variable, the turbine design engineers make compromises – both technical and economical – based on the prevailing operating conditions. Consideration also has to be given to possible instabilities and cavitation zones. Operation of the machine outside of the bep region not only lowers the efficiency but also increases the risk of cavitation or instability.

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Further, a unit operating at fixed speed in the pumping mode does not allow control of the discharge, and therefore of the power taken from the grid.

Synchronous machines are inherently fixed-speed units, and in hydropower applications are either driven by turbines or drive pumps. ABB offers a range of machine designs that allow variable speed [1 – 3]:

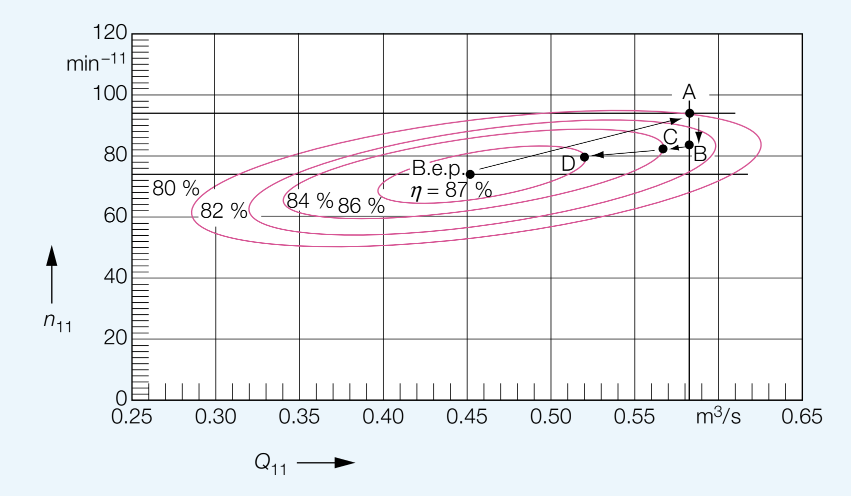
- Pole-changing synchronous machines
- Synchronous machines which are stator-fed at variable frequency via a load-commutated inverter (LCI)
- Asynchronous machines with a wound rotor fed at variable frequency (sub/supersynchronous cascade)

Compuerto pilot project

ABB has accumulated a wealth of experience with sub/supersynchronous cascades in connection with frequency converters that the company has supplied to various European railways [4]. Based on this experience, it was decided to go ahead with a pilot project to demonstrate the benefits of the sub/supersynchronous cascade for hydropower applications.

The site that was chosen for the pilot project is the Compuerto hydropower plant in Spain. This is owned by Iberdrola, S.A., who also partially financed the project through the Spanish Association of Electrical Utilities (PIE).

The Compuerto hydropower plant is located on the upper reaches of the river Carrión, in Velilla de Rio Carrión, a community in the province of Palencia. Key plant data include:



Hill diagram showing the topographic curves of efficiency for a pump turbine operating in the turbine mode. A shift in the operating point to A (discharge and speed maintained, head 60% of initial value) causes efficiency to drop from 87 to 80%. Recovery to 83% efficiency (B) is possible by reducing the speed to 88%, with further improvement possible (C, D) by reducing the discharge. **1**

n_{11} *Rotational speed (see eqn 1)*
Q_{11} *Discharge (see eqn 2)*
Bep *Best efficiency point*
η *Efficiency*

- A head of between 102 and 63 m
- Two units, each with a 600 rev/min Francis horizontal-shaft turbine
- A rated discharge of 12 m³/s per unit
- Generators rated at 12.5 MVA

Compuerto has been in operation since 1967 and is connected by a 3 km long 46-kV power line to the switchyard of a nearby fossil-fuelled generating station. The power plant receives water from the largest reservoir, with a volume of 95 million m³, on the Carrión river. The hydro scheme was built initially to provide water for irrigation, electric power generation having only a second priority. The water discharge programme is therefore determined by the river authority and is based primarily on agricultural needs. As a rule, the irrigation period is from April 1 until October 1, the reservoir being allowed to fill up during the rest of the year. This yearly programme had to be given due consideration during the development of the pilot project.

Improved performance of hydromachinery operated at variable speed

A hydraulic machine is characterized in [5] by the following unit values:

- Unit speed $n_{11} = n \cdot D / \sqrt{H}$ (1)
- Unit discharge $Q_{11} = Q / (D^2 \sqrt{H})$ (2)

In these equations, H is the nominal head, Q the rated discharge, n the nominal speed and D the runner diameter.

Based on these values, the topographic curves of efficiency for a given turbine or pump-turbine working in turbine mode can be presented as in **1**, also known as a hill diagram. Inserting the figures for H, Q, n and D in equations (1) and (2) , values are calculated for n_{11} and Q_{11} which lie close to the bep that gives the best energetic conversion. The diagram shows that if the values for Q and n are maintained and H lies at only 60 percent of its initial value, the operating point will shift to A, with a drop in efficiency from 87 to 80 percent.

By reducing the speed to 88 percent of its initial value, operating point A shifts to B, resulting in an efficiency recovery to 83 percent. Further improvements in efficiency could be obtained with lower discharges, whereby the operating point is moved to C and D. Thus, when the speed can be varied in the turbine mode the machine operator is given a new degree of freedom in seeking better efficiency.

In the pumping mode the efficiency behaves similarly but there is now also an additional option: control of the discharge through speed variation. Pumps with a fixed-geometry runner have a limited capability for controlling the discharge (ie, through the guide vane mechanism), but by varying the speed it is easy to control the head, the discharge and the shaft power. The following relationships exist as rules of thumb:

- Head variation

  $H = k_h \cdot n^2$ (3)
- Discharge variation

  $Q = k_q \cdot n$ (4)
- Power variation

  $P = k_p \cdot n^3$ (5)

where k_h, k_q, and k_p are proportionality coefficients.

2 gives the pump head versus discharge characteristics for four different speeds between 1.015 and 0.925 pu. This diagram demonstrates the possibility of controlling a pump operating against a constant static head and shows the dynamic head losses due to the penstock. In **3**, the discharge results and power control range are given as a function of the speed. Also, it is easily understood from **2** that a fixed-speed pump has only one operating point, with no possibility of control. The operating point is given by the intersection of the system characteristic with the pump head versus discharge curve.

Besides contributing significantly to wider operating ranges for the pump head and discharge, variable-speed operation avoids the cavitation and instabilities that can affect plant maintenance, service life and vibration levels as well as aquatic life in the river [3].

Main technical data of the Compuerto pilot project

One of Compuerto's two hydropower generators was selected for the pilot project. To this end, its salient pole rotor was replaced by a three-phase wound rotor of new design using a procedure which will also be suitable for future retrofit projects.

For obvious reasons, the active power rating of the generator could not be changed. However, the limitations of the doubly fed machine in terms of the magnetizing current have led to the conclusion that the rated power factor in normal operation should be unity, which does not represent a limit for pumping mode applications.

The rotor is fed by a thyristor-based cycloconverter, powered via three transformers as shown in the single-line diagram in **4**.

The nominal data for the pilot project are:

- Rated power 10 MW
- Rated power factor (at 'return point') 1.0
- Synchronous speed 600 rev/min
- Operating speed range ±10 %

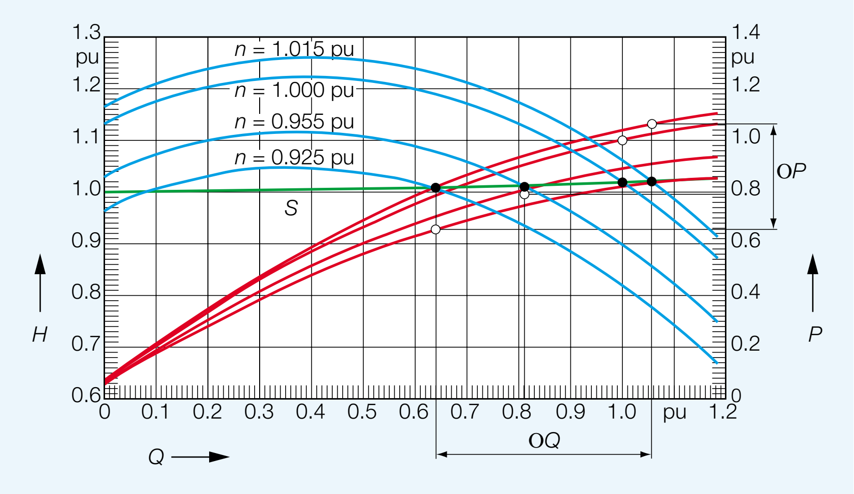
Several changes had to be made to the main equipment. As already mentioned, these included the replacement of the existing salient-pole rotor by a new, cylindrical type **5** with its three-phase winding connected to sliprings, the new rotor cascade with frequency converter (in this case a cycloconverter), and installation of three three-phase transformers to match the 50-Hz voltage side of the converter to the generating voltage of 13.8 kV.

A new plant control system also had to be installed.

Control

The Varspeed control concept used in the Compuerto hydropower plant is based on:

- Speed control via the turbine
- Power control via the asynchronous machine



Pumping operation at variable speed. The total head and shaft power characteristics are shown for an optimum guide vane opening. **2**

H *Generated head (pu)*
Q *Discharge (pu)*
n *Pump speed (pu)*
P *Shaft power (pu)*
S *System characteristic*
OQ *Range of discharge control*
OP *Range of shaft power control*

In normal operation, the main control functions are divided between two separate controllers, each of which has dedicated tasks.

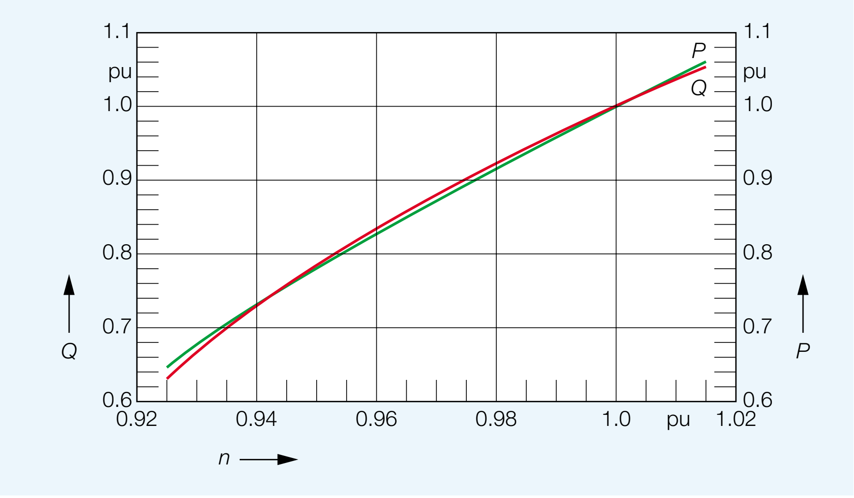
The functions required to control the cycloconverter and the asynchronous machine are implemented in one of the controllers, while the second executes those functions relating to general control and the operation of the turbine governor.

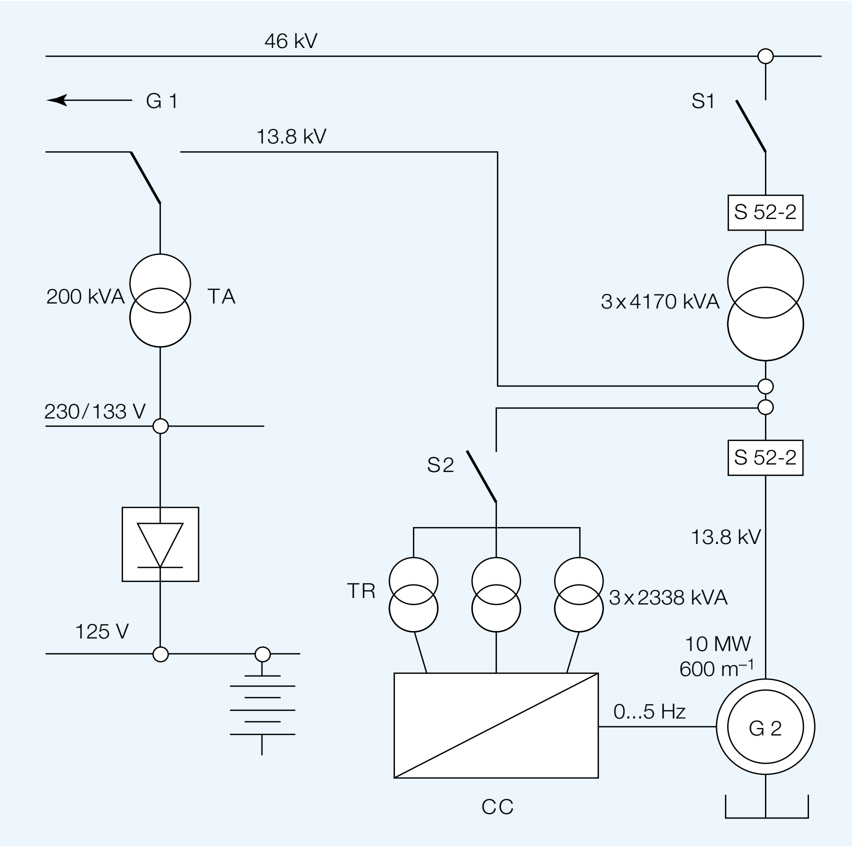
Analogue and digital input/outputs are provided for the exchange of data between the controllers.

To keep modifications to a minimum the turbine is controlled through the original hydromechanical governor, which has

Shaft power control with speed variation. The results are for a hydraulic system with fixed static head. **3**

Q *Discharge (pu)* *n* *Pump speed (pu)* *P* *Shaft power (pu)*

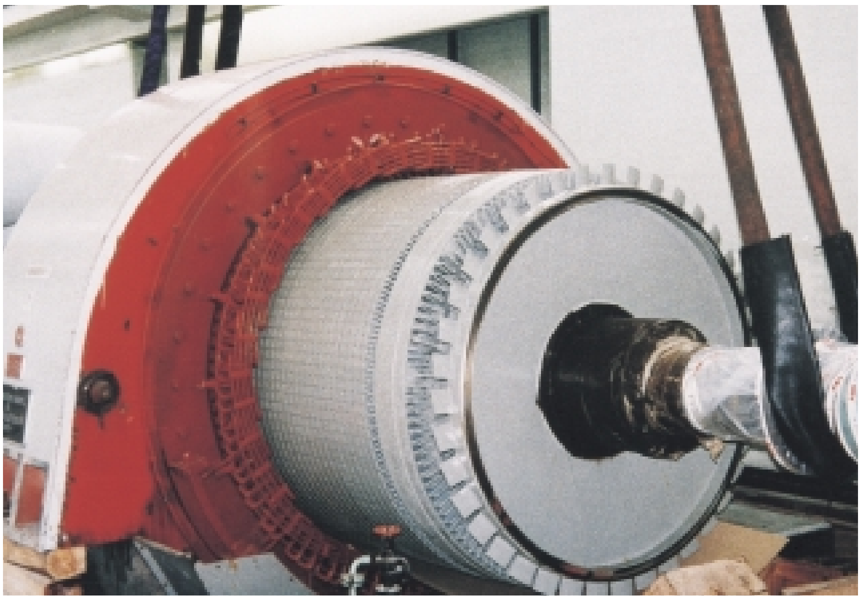




Single-line diagram of the Varspeed unit installed in the Compuerto hydropower plant **4**

G 1	*No 1 unit, conventional synchronous machine*	TA	*Auxiliary services transformer*
G 2	*No 2 unit, Varspeed*	TR	*Transformers for cycloconverter*
CC	*Cycloconverter*	S1, S2	*Disconnecting switches*
		S 52–2	*Circuit-breakers*

The rotor of the Varspeed generator being installed in the Compuerto plant **5**



been specially adapted for the purpose. In the Compuerto plant, the speed setpoint can be changed manually at the control panel to allow checking of the unit's behaviour at different speeds within the operating range.

The operational capabilities of the overall system are given by the *P–Q* diagram in **6**.

The control hardware is based on ABB's programmable high-speed controller (PHSC), a bus-oriented, programmable microprocessor system with interface and supervision module [6].

The application software for the PHSC has been written in user-friendly FUPLA. This function block programming language is object-oriented and provides a powerful graphic environment that runs on standard personal computers.

Vibration

As already mentioned, operation of the hydropower plant is subject to certain constraints due to the priority that is given to the irrigation scheme. Also, because of delays in the production of some of the plant equipment, there was less time than was originally planned for the installation work and necessary adjustments prior to commissioning. The project partners therefore decided to carry out partial commissioning with the unit in asynchronous mode during the period that was available in 1993.

During commissioning, it was observed that vibration in the stator frame and core was unacceptably high. Two facts combined to produce this strong vibration:

- The stator winding of the Compuerto unit has a fractional number of slots per pole and phase, with the result that subharmonics occur in the armature reaction. In the case of the original synchronous units this phenomenon was the cause of relatively low exciting forces. Due to the synchronous rotor being replaced by an asynchronous design, it became necessary to reduce the airgap in order to minimize the magnetization current. The reduced airgap causes an increase in the magnetic field of the armature reaction, leading to the exciting forces and vibration amplitudes also increasing.

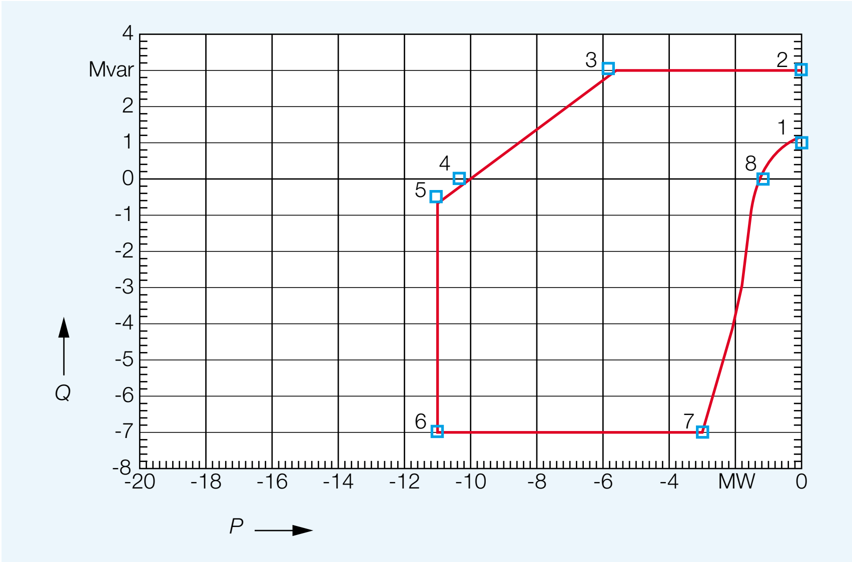
- The frame and stator core of the original Compuerto machines exhibited a mechanical resonant frequency very close to 100 Hz, which coincides with the frequency of the exciting forces.

Since the unit had to be operated within the framework of the 1993 irrigation season, it was decided to modify the connections of the stator winding coils in order to lower the winding factor of the responsible subharmonic of the armature reaction and so reduce the exciting forces. This was successful in achieving a reduction in vibration levels, but they were still twice as high as the maximum figure permitted by the standards. Accordingly, the unit was operated during the summer of 1993 at 60 percent of its rated power to reduce the vibration amplitude.

Investigations and tests were started as soon as the excessive vibration was observed **7**. Tests showed that a rigid connection exists between the frame and core, which meant that the vibration level could only be lowered by reinforcing the existing ribs of the frame. The necessary strengthening was obtained by welding a radial reinforcement to each of the frame's ribs. All of the modifications to the frame were carried out on the site.

Final vibration tests have shown that the modification has caused the resonant frequency to shift to 110 Hz, and that there has been a significant improvement in the vibrational behaviour at 100 Hz. The maximum vibration measured on the stator frame cover of the Varspeed machine is 10 mm/s, a figure comparable with the 7.5 mm/s measured on the synchronous machine. All of these values lie within the limits given in the standards for this type of machine.

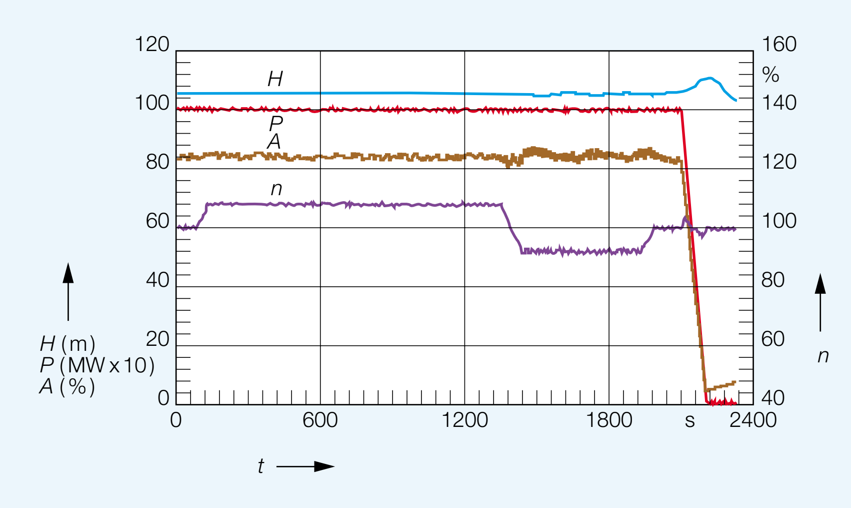
Vibration could be a problem for Varspeed retrofits in which the rotor is changed and the stator configuration is left intact. ABB has gained considerable experience in this area, and also has the measuring and analytical tools that are needed to evaluate the prospects for retrofit projects, ie, whether or not it would pay to equip existing units with Varspeed.



Performance chart for the Compuerto pilot project. The active power range is negative during conventional generator operation. **6**

P — *Active power (MW)*
Q — *Reactive power (MVAr)*
Points 1–8 — *Test points at 100% speed*

Vibration tests being carried out on the Varspeed generator in the Compuerto hydropower plant **7**



Speed changes at constant power **8**

H Hydraulic head
P Active power
A Turbine guide vane opening
n Speed

Commissioning

The total lead time for the Compuerto project (until commissioning of Varspeed ended in March 1994) was 24 months. Because of the operating restrictions that resulted from the irrigation programme, commissioning had to be carried out in two phases, ie, during

- asynchronous operation of the unit in the summer of 1993, and
- Varspeed operation after the 1993 irrigation period.

The complete Varspeed system was commissioned in the last week of March, 1994. This involved the following tests:

- Speed governor tests
- Synchronization and coupling tests
- Active and reactive power measurement
- Load rejection tests
- Speed setpoint tests at different power levels
- Start/stop chain tests
- Testing of the remote control

In general, the results of the tests confirmed the good performance of the overall system, extending from the hydraulic circuit to the power grid.

An oscillogram showing the changing speed at constant power is reproduced in **8**.

Operating experience

The Compuerto pilot project has been running for three years. The results obtained from asynchronous operation in 1993 were obviously of less value than those obtained during 1994, when the generator was run in Varspeed mode. The project installation was handed over to the utility in 1995, in which year it ran for some 2,500 hours.

Asynchronous operation lasted 2,500 hours. Valuable experience was gained with the 10-MW asynchronous generator during this time, as the machine ran constantly with a vibration level equal to twice the maximum figure given in the standards.

A more detailed investigation was carried out during the 1994 season, when the machine was run in true Varspeed mode. 2,855 hours of operation were recorded during this time, the average power being 7,602 kW. Since the beginning of 1995, the Compuerto unit has run in Varspeed mode without any operating restrictions. The original vibration problem has been solved.

Operating incidents that did occur were insignificant and could be resolved by making minor adjustments to the equipment and software. Today, the Varspeed unit in the Compuerto hydropower plant exhibits the same degree of availability as the original synchronous unit operating in parallel with it. Due to its flexibility, preference is given to the Varspeed unit whenever the power plant has to be operated under part-load conditions.

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