Brüel & Kjær application notes

Detecting Loose Windings in Hydroelectric Generators

This Application Note describes a method for detecting loose copper windings in large hydroelectric power generators. Vibration analysis is used to detect characteristic signatures in the spectrum caused by the vibrating bars. The origin of vibration in AC generators is briefly explained, and the instrumentation required for measurement and analysis is discussed.

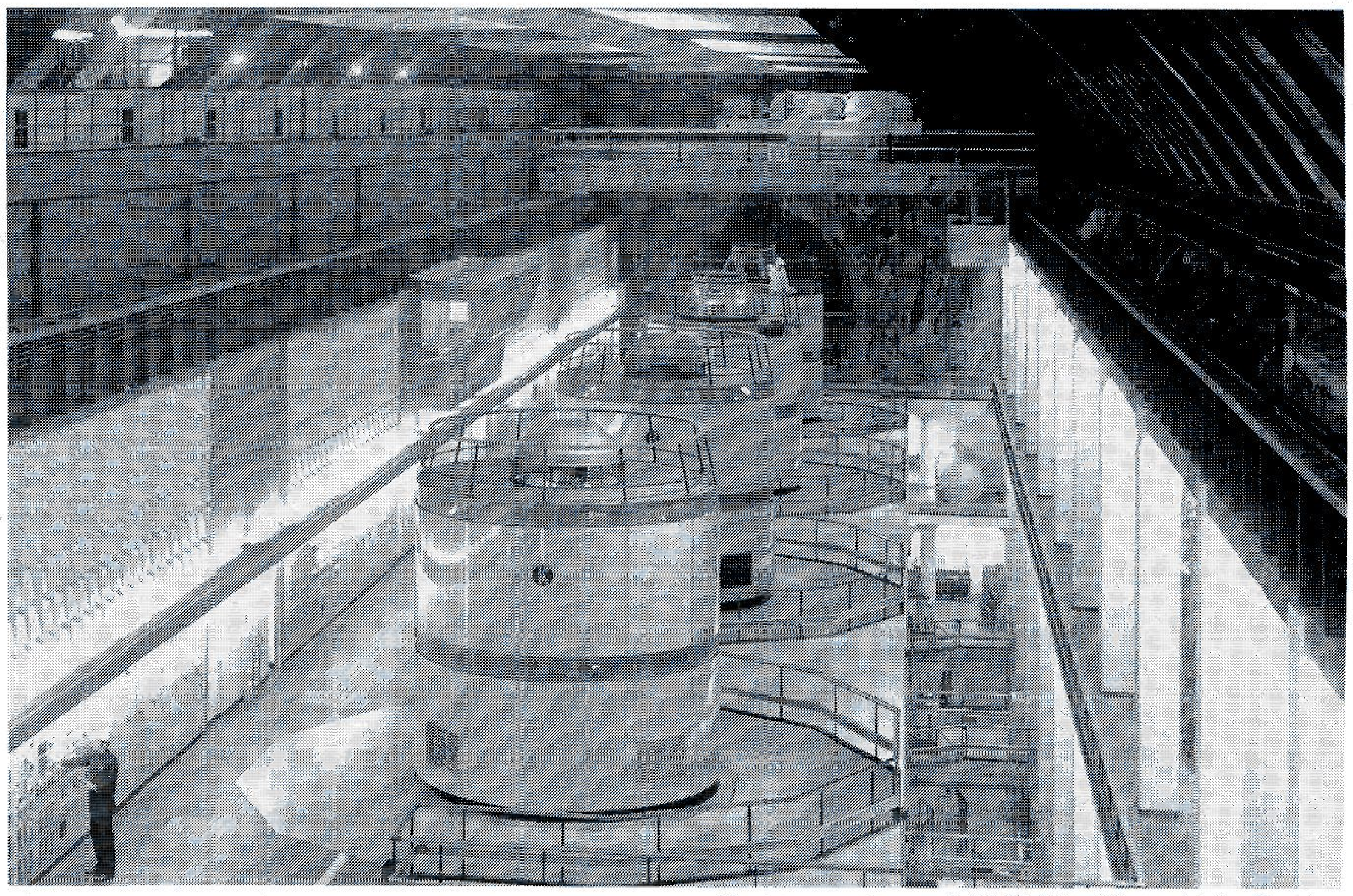

Photo courtesy of GEC Machines Ltd., Rugby

A typical hydroelectric power station, showing four 100 MW generator units

Theory

Vibration of the stator in a multipole generator is the result of several forces acting within the unit. The windings, which are copper bars mounted in slots on the stator, experience an outward-directed force at the pole-passing frequency of 120 Hz. This force is caused by interactions between the induced current in the bars and the magnetic field of the passing pole. In addition to the electrically and magnetically induced vibration, it is reasonable to find mechanically-induced vibration at turbine blade-passing frequencies and random components due to turbulence and cavitation in the turbine. Note that there is no force on the stator at the line frequency of 60 Hz; the forces are in the same direction regardless of the polarity of the passing pole.

The vibration spectrum due to these forces would therefore be expected to consist of lines at 120 Hz and its harmonics, with no line at 60 Hz. There would also be lines at blade-passing frequencies from the turbine as well as random noise from turbulence and cavitation.

Because the individual strengths of the magnetic poles in the rotor vary, and also because of rotor eccentricity and out-of-roundness, the 120 Hz harmonics are amplitude modulated at 2,9 Hz, which is the frequency corresponding to the shaft speed of the turbine. This amplitude modulation creates sidebands in the vibration spectrum at intervals of 2,9 Hz around each harmonic. These sidebands are generally low in amplitude and are usually masked by random noise in the spectrum, but they can be seen in some high-resolution spectra.

If the copper bars are not perfectly rigid in their slots in the stator, the forces on them will cause them to move. This motion can act as a nonlinearity of the overall stiffness of the structure. Ref. 1 has shown that a structure with non-linear stiffness can generate vibrations at subharmonic frequencies (1/2, 1/3, etc.) of the periodic forcing frequencies. The most likely subharmonics will occur at 60 Hz and at harmonics of 60 Hz; they will appear in the spectrum between the 120 Hz harmonic series.

Because the relative levels of the subharmonics are much lower than the levels of the 120 Hz series, they are usually masked by the random part of the vibration spectrum. A time synchronous averaging process can reduce the random signal enough to expose the subharmonics if they exist. Synchronous averaging is signal averaging in the time domain with the start of each average initiated at a particular point on the waveform by a trigger pulse. The trigger is normally derived from a tachometer which generates a pulse at the same instant in the cycle of a rotating part. In this case, however, the 60 Hz line frequency was used as the trigger for the synchronous averaging because it is precisely aligned with the motion of the rotor. It was also easily available, eliminating the need for special equipment to generate a trigger.

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Measurements

To test the above theory, a number of measurements were made on several large hydroelectric generators in Washington State, U.S.A.

The Brüel & Kjær Dual Channel Signal Analyzer Type 2032 was used to perform the synchronous averaging and to calculate the spectra. The 60 Hz trigger signal was obtained from a stepdown transformer powered from the 110 volt mains. Synchronous averaging in the time domain is a built-in function of the 2032; spectra calculated from such averages are called Enhanced Spectra.

In the initial experiment, the vibration signal and the trigger signal were fed directly into the Analyzer. An Accelerometer Type 4384 was mounted on the outside surface of the stator in a radial direction midway between the upper and lower edges of the stator. Spectra were displayed on the Analyzer screen.

As the number of averages increased, the random noise level decreased to a maximum of 50 to 60 dB below the peak levels of the 120 Hz harmonics, and the subharmonics based on 60 Hz became visible. Several similar trials were made at different locations around the stator. In each case the 60 Hz subharmonics were visible, but with differing amplitudes at each location.

In the next experiment, the vibration signal and the trigger signal were recorded on the Portable Tape Recorder Type 7007. It was found that the subharmonics were just as visible on the tape-recorded data as they were from the direct signals, proving that recording data on tape is a valid method of collecting vibration data. Figs. 1 and 2 are reproduced from taped data.

The subharmonics may possibly be caused by mechanical looseness in the structure of the generator other than the copper bars themselves. The third experiment proved otherwise. The accelerometer was placed on the steel housing about 12 in (30 cm) away from its previous location. After several hundred averages, the spectra showed no evidence of subharmonics even though the 120 Hz harmonics were present as in the previous measurements.

Conclusions

Fig. 1 is an Enhanced Spectrum from the stator of Unit 32 at Diablo Dam in Washington State. This generator had just been rebuilt, and the stator bars were expected to be in good condition. The 60 Hz subharmonics can be seen at relatively low amplitudes at frequencies below 1 kHz. These subharmonics are a result of unavoidable looseness in the bars.

Fig. 2 is also an Enhanced Spectrum, but from Unit 31 at Diablo Dam. Unit 31 had not been rebuilt recently. Note the strong 60 Hz subharmonics between 1 kHz and 2 kHz. Although the levels varied at different positions around the unit, the levels in Fig. 2 are representative. The variations indicate varying degrees of looseness in the different bars.

Because different generators will always exhibit varying degrees of assembled stiffness, it is not possible to correlate a precise level of subharmonics with a given degree of looseness. For this reason, a machine must be monitored on a continuing or periodic basis and any increases in the subharmonic levels noted over time. Software programs are available that do this in a straightforward manner. However, it can be said that lower-frequency subharmonics may indicate small amounts of motion in the bars, while increased subharmonic levels above 1 kHz probably indicate that the bars are impacting the stator slots.

Reference

1. Broch, Jens Trampe. Mechanical Vibration and Shock Measurements. Nærum, Denmark: Brüel & Kjær 1980.

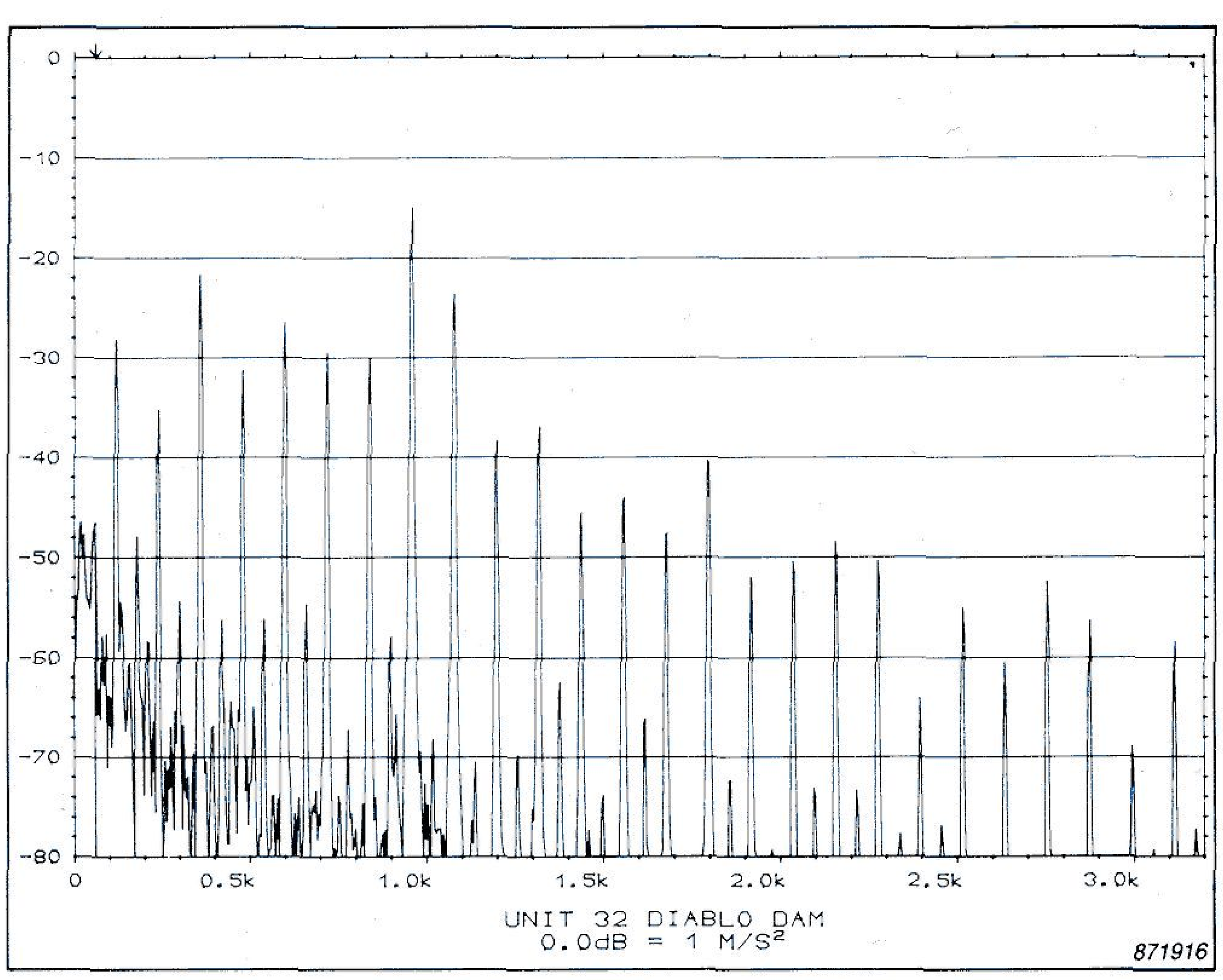

Fig. 1. Enhanced Spectrum of a newly-rebuilt generator

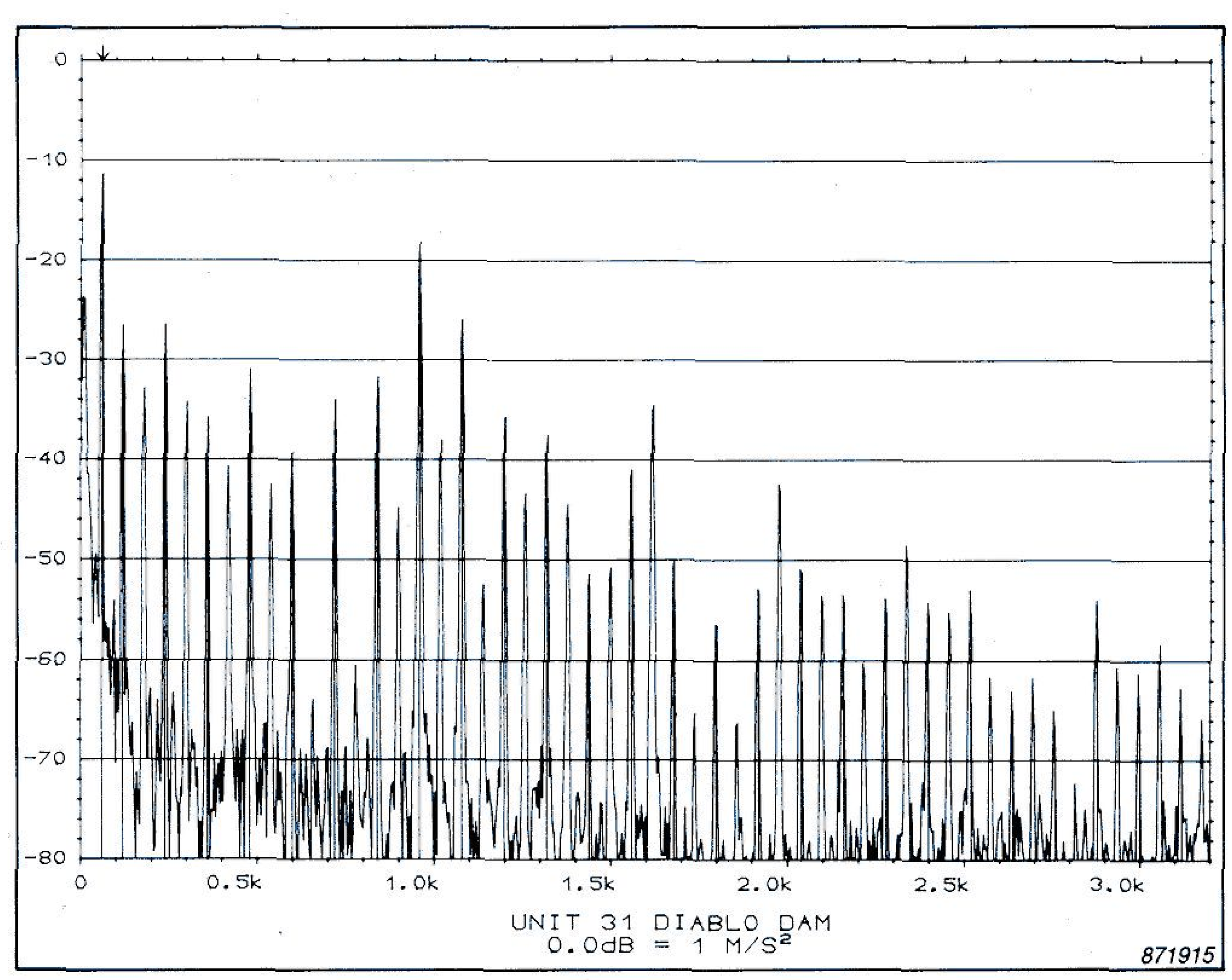

Fig. 2. Enhanced Spectrum of an old generator

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