**Vibration Measurement Techniques for Wind Turbines Generator**

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**Abstract:** The paper is focused on the measurement equipments used in monitoring and diagnosis of wind turbine generators. The vibration analysis components, i.e. piezoelectric transducers and charge amplifiers are discussed. Section II presents the two models of vibration transducers, namely the charge source and voltage source models are presented. The performances of piezoelectric transducers are highlighted based on the analytic equations that determine the operation of their elements. Sections III and IV refers to the charge and voltage amplifiers and highlights the influence of the component elements on the frequency response. At the same time it is presented the influence of the connectors linking of the transducer and of the amplifier on the amplifier’s gain. In section V, experimental results, a three channel transducer-amplifier circuit, developed by the authors, is presented. The point is, that by using the similitude with electrical systems, it is highlighted the dissymmetry occurring between three measurement points placed on the stator of the wind turbine generator and shifted in space by 120°. This dissymmetry represents an indication of mechanical faults in the motor. The oscillograms of the vibrations on the three channels of the wind turbine along with the quantities provided by the piezoelectric transducer-charge amplifier system are presented. These oscillograms are processed by an acquisition board.

**Keywords:** maintenance, diagnosis, piezoelectric transducer, charge amplifier, voltage amplifier.

1. **INTRODUCTION**

The unpredicted faults, occurring in the component elements of the wind generators could determine negative effects on their economic operation. A promising approach on avoiding the occurrence of major faults consists in real time monitoring of the mechanical vibrations. Monitoring the vibrations of wind turbine generators might detect faults in incipient stages, avoiding large non operational time periods. Together with the new wind turbine generators, capable of generating megawatts in power, new and efficient detection of faults and maintenance methods are required. Online monitoring systems offer a new perspective upon the prevention and the maintenance of the faults.

Using monitoring systems, the faults’ detection in incipient stages is possible, even before they could visible or acoustically audible. This way, preventive maintenance measures may be performed, in order that the first fault should not degenerate in a major fault, reducing consequently the total cost of the maintenance process.

At the same time, these monitoring systems can extend the maintenance planning for large time intervals, avoiding thus the use of new spare parts for the functional elements.

Because the replacement of the main components represents an extremely high time and cost effort, an online monitoring system can offer several advantages, namely:

- prevents secondary and major faults;
- reduces the cost of the maintenance by applying the conditional maintenance;
- permits remote surveillance and diagnosis performed on the ground at the basis of the wind turbine tower;
- offers detailed information on the performances and on vibrations, in order to optimize the wind turbine operation.

Modern wind turbine generators are provided with several embedded fault correction systems, based on the measurements of the rotor speed, of the electric power and of the generator’s temperature, etc. There are available also generators permitting the transmission of the measured data and consequently a remote control system.

![Fig.1. The component elements of a vibration measuring system.](image)

The monitoring system of the wind turbine condition is complementary to the existing systems and measures the vibration components and the oscillation of the structure. As a consequence of these measurements, one can determine the condition of the wind turbine generator like the staggering and the frazzle of the rotor, faults in the systems controlling the
gyration, imminent cracking of the bearings and of the
gearwheels and of the gearboxes in incipient stages.

A vibration measuring system includes an element
sensitive to vibrations (sensor, transducer), an
electrometric amplifier (signal converter) and an
adapter having the role of matching the impedance with
the processing circuits of the measured signals (Fig. 1).

2. VIBRATION TRANSDUCERS

The vibration transducers represent devices
converting mechanical chokes and vibrations into
optic, mechanic or electric quantities, proportional with
the measured input quantity.

In application that are monitoring vibrations the
main quantity used is the acceleration, measured by vibration transducers, i.e. accelerometers, which may be:

- piezoelectric accelerometers;
- variable electric capacity accelerometers;
- piezoresistive accelerometers.

In the domain of the vibration monitoring, the
signal performed by the accelerometers is integrated in
time, in order to obtain the vibration velocity. However,
the double integration, in order to obtain the
displacement, must be performed carefully, due to the
errors that occur frequently in the low frequency range.

The choice of the transducer’s type depends
mainly on the environment and on the frequency range
where the device is used. One of the major advantages
of the piezoelectric transducers consists in the
possibility of using them in a very large interval of
temperature (from $-196 \, ^\circ C$ to $+620 \, ^\circ C$), and in the
capacity of operating for high frequency vibrations, up
to 20 kHz.

A piezoelectric sensor is merely modeled as an
electric charge source, namely a capacitor and parallel
resistance, or as voltage source in series with a
capacitor and a resistor.

For the two models depicted in Fig. 2, the
generated electric charge depends on the piezoelectric
constant of the transducer and the capacitance is
determined by the surface area and the dielectric
constant of the piezoelectric material. The resistance is
used for the discharge of the static charge.

![Fig. 2 Electrical modelling of the vibration sensors.](image)

The complex structure of a piezoelectric sensor
with seismic mass and unidirectional movement on
vertical direction is depicted in Fig. 3 [1]. It consists in
the ensemble seismic mass – spring – damper and
displacement transducer. The acceleration $\frac{d^2 x_i}{dt^2}$ of the
structure represents the physical quantity detected by
the above depicted ensemble. The displacement transducer takes over the mechanical signal and
converts it into an electrical quantity.

The model of the accelerometer has in its structure
a mechanical system $G_m$ and an electrical system $G_e$.

For the mechanical system are important the
transfer functions in the frequency range of the relative
displacement $x_{si}$ of the seismic mass and of the
acceleration $\frac{d^2 x_i}{dt^2}$.

Accordingly to the second Newton’s law, the
seismic mass $M$ presents for small displacements a time
variable value that represents the solution of eq. (1):

$$ M \cdot x_i = M \cdot x_{si} + B \cdot x_{si} + K \cdot x_{si}, \quad (1) $$

where

- $B$ is the viscous friction coefficient
- $K$ is the elastic constant.

Setting the initial time conditions $x_{si}(0)=0$ and
$dx_{si}/dt (0)=0$ and using the Laplace transform, the
transfer function of the mechanical system of the
piezoelectric transducer is obtained (eq. 2):

$$ G_m(s) = \frac{x_i(s)}{x_{si}(s)} = S_m \cdot \frac{\omega _0^2}{s^2 + 2 \cdot \zeta \cdot s + \omega _0^2}, \quad (2) $$

in which

- $\omega _0 = \sqrt{K/M}$ is the resonance frequency of the
structure,
- $\zeta = B / 2\sqrt{K \cdot M}$ is the damping factor,
- $S_m=M/K$ is the mechanical sensitivity.

The square of the resonance frequency $\omega _0^2$ is
direct proportional to the rigidity $K$ and inverse
proportional to the seismic mass $M$. The mechanical
sensitivity $S_m$ is direct proportional to the seismic mass
$M$ and inverse proportional to the $K$.

The design of the piezoelectric transducers has to
take into account the increase of the resonance
frequency, the enlargement of the operation frequency
range and the increase of the mechanical sensitivity, all
of them in order to increase the resolution of the transducer.

The transfer functions of the electric system are:
- the frequency response of the relative displacement \( x_0 \)
- the output voltage \( e_0 \) versus displacement.

Generally, the electric system of the transducer has in its structure the proper transducer, the connectors and the charge amplifier.

The piezoelectric transducer performs a linear conversion between the relative displacement \( x_0 \) and the displacement of the seismic mass, according to the relation (3):

\[
Q = K_q \cdot x_0
\]

where \( K_q \) represents the output signal value for a unitary displacement.

Fig. 4 depicts the equivalent circuitry of the electric system of the transducer and fig. 5 depicts the simplified version of the model [2].

![Fig. 4. The equivalent circuitry of the piezoelectric transducer.](image)

![Fig. 5. Simplified version of the electric model.](image)

Both the transducer and the amplifier circuit present high input impedances, in order to perform a non losses charge-voltage conversion. In this case the resistance and the capacity of the model are determined using the relationships (4) and (5):

\[
R = \frac{R_{\text{pzt}} \cdot R_{\text{ampl}}}{R_{\text{pzt}} + R_{\text{ampl}}} \approx R_{\text{pzt}}
\]

\[
C = C_{\text{pzt}} + C_{\text{ampl}} + C_{\text{wire}}
\]

In the relationship (4), it is assumed that the value of the loss resistance \( R_{\text{pzt}} \) is much higher than the value of resistance \( R_{\text{ampl}} \) of the amplifier circuitry.

The equivalent simplified model permits to write the operating equation of the electrical system, eq. (6):

\[
C \cdot \frac{de_0}{dt} = i_{\text{pzt}} - i_R = K_q \cdot \frac{dx_0}{dt} = e_x
\]

(6)

\[
\frac{de_0}{dt} = K_x \cdot \frac{dx_0}{dt} = \frac{e_x}{\tau}
\]

(7)

where \( \tau = RC \) represents the time constant of the circuitry.

The transfer function of the electric system of the transducer is depicted in eq. (8):

\[
G_e(s) = \frac{e_x(s)}{x_p(s)} = S_e \cdot \frac{\tau \cdot s}{\tau \cdot s + 1}
\]

(8)

where \( S_e = K_q/C \) represents the electrical sensitivity.

![Fig. 6. Frequency response of the piezoelectric transducer.](image)

If both systems, namely the electrical system and the mechanical system are taken into account, the transfer function of the transducer is given by eq. (9):

\[
\frac{e_x(s)}{d^2x_p / dt^2} = S_e \cdot \frac{\tau \cdot s}{\tau \cdot s + 1} \cdot \frac{\omega_n^2}{s^2 + 2 \cdot \zeta \cdot \omega_n \cdot s + \omega_n^2}
\]

(9)

in which \( S_e = S_m = K_q M/CK \) represents the sensitivity factor of the transducer.

The frequency response of a piezoelectric accelerometer, for which a precision of \( \pm 5 \% \) to the central frequency is imposed, can be considered as linear in the frequency range \( 3/\tau \) to \( \omega_n/5 \) (Fig. 6).

The frequency response is limited by the time constant \( \tau \) of the transducer, and in high frequency by the mechanical resonance frequency \( \omega_n \).

3. CHARGE AMPLIFIERS

The charge amplifiers [5] balance the injected charge on the negative input port of the operational amplifier, by charging the capacitor in the negative
reaction loop $C_f$. The high value associated resistance $R_f$ in the negative reaction loop, slow down the discharge of the capacitor $C_f$ in order to prevent the saturation of the operational amplifier. The values of the resistance $R_f$ and of the capacitor $C_f$ set the low cutoff frequency of the amplifier.

The amplifier maintains 0 V at its input, thus the dispersion capacity associated to the interface cables should not be an important issue.

Fig. 7 depicts a basic schematic diagram of a classical charge amplifier that may be used as a signal conditioning circuit. Usually in a sensor modeling, a current source is chosen, in order to highlight the high value of the output impedance.

The output signal processing circuit has to have very low input impedance in order to collect the maximum from the output charge of the sensor. Consequently, the charge amplifier represents the ideal solution, presenting a virtual ground for the sensor’s signal, while the gain of the amplifier stands at a high value. In other terms, any charge developed in the sensor will determine a voltage at the amplifier input.

The high frequency gain is set by the adjustment of the value of the capacitance $C_f$, thus mitigating the effect of the resistance $R_f$ placed in the negative reaction loop. Lesser the capacitor value is, higher the gain will become.

![Image of charge amplifier diagram](image)

An approximate value $A_S$ of the gain is given by the relationship (10):

$$A_S = \frac{1}{C_f}$$  

(10)

It results, from the above relationship that the gain increases when the value of the capacitance decreases. Although the gain is not depending on the internal capacitance of the sensor, it is worthy to take into account its effect on the electromagnetic noise.

In lower frequencies the capacitive circuit from the negative reaction path is charging, being limited by the reaction resistance $R_f$ which determines the reduction of the gain. In higher frequencies, the impedance of the capacitive circuit decreases, cancelling the effect of the resistive path of the negative reaction loop.

![Gain-frequency characteristic of the charge amplifier](image)

The response of the circuit is similar to the response of a high-pass filter, having the cutoff frequency, given by the relationship (11):

$$f = \frac{1}{2\pi \cdot R_f \cdot C_f}$$  

(11)

The bandwidth of the signal is set according to the application. Therefore, increasing the capacitance means the increase of the gain, in order to obtain a decrease of the cutoff frequency and the resistance should be increased as well. But the increase of the resistance has negative consequences on the noise. The increase of the resistance makes practically impossible a practical setup, due to the associated noise. Another limiting factor of the increasing of the resistance is the bias current of the circuit. The input current of the amplifier is closing by the series resistance of the negative port, determining an output offset voltage. This issue can be minimized by using an operational amplifier with low values of the input currents, e.g. a FET input amplifier. The input currents of this type of amplifier are usually lower than 100 pA and if the value of the resistance from the negative reaction loop will be less than 1 GHz, the offset would be filtrated.

Due to the difficulty of maintaining the pole of the high pass filter at a lower value, the use of the piezoelectric sensors becomes more difficult, especially in direct current applications (even if the leakage currents through the sensor have very low values).

In order to mitigate the response of the circuits to undesired signals at the resonance frequency of the sensor and in order to reduce the total amount of the noise in the frequency range, an additional low pass filter is needed.

The internal noise of the charge amplifier increases when the capacitance increases and the input resistance decreases.

**4. VOLTAGE AMPLIFIERS**

For a voltage amplifier [7], the output voltage depends on the capacitance “seen” by the sensor. The capacitance associated to the interface cables will affect the output voltage, and in case of cables replacement or in changing their position, the variations of the capacitance $C_c$ could be significant, determining major modifications in the measured signal.

The resistance $R_b$ offers a current path parallel to the operational amplifier input for the direct current signals.
component of the input stage of the amplifier. The value of the resistance $R_b$ must be chosen as high as possible and the cable length should be reduced at the minimum.

The internal noise of the voltage amplifiers is not dependent on the input capacitance.

The low and high cutoff frequencies are set by choosing the values of the resistance $R_f$ and of the capacitance $C_f$. In Fig. 9 the resistance $R_p$ represents the transversal stray resistance of the sensor and $R_b$ represents the transversal stray resistance at the input of the operational amplifier. $R_g$ represents the series resistance on the negative port of the operational amplifier. Fig. 10 presents the attenuation versus frequency characteristics of the amplifier.

Note that it is impossible to use an accelerometer to measure the static acceleration, due to the fact that the electric charge should not be converted into voltage and transmitted to the circuit, but will be dissipated through the parallel resistance of the circuitry. Consequently, a proper design of piezoelectric transducers, make them suitable for use in very low frequency [3]. Alternatively, the ratio $K_q/C$ and the inverse of the square of the mechanic resonance frequency $1/\omega_n^2$ determine the sensitivity of the transducer. In this respect, several trade-off’s should be performed in order to obtain the proper response in high frequency ranges [4].

5. EXPERIMENTAL RESULTS

The charge amplifier manufactured by the authors for the application presented has in its structure a non inverting amplifier, symbolized by U1A, a high pass filter, symbolized by U1B and a low pass filter with adjustable amplification, symbolized by U2A.

The circuit U1A, Fig. 11, represents a non inverting amplifier having a high value of the input resistance, $R= 60 \, \Omega$. Limiting the input impedance to a finite value represents a very important issue, in order to mitigate the noises specific to high values of this impedance.

Due to the high value of the resistance $R$, a high output offset voltage will be generated. This issue can be fixed by the use of FET operational amplifiers. The operational amplifiers that have been used are of TL082 type, having in their structure two JFET transistors with very low input currents, usually smaller than 100 pA.

The resistance $R_1$ and the capacitor $C_1$ determine a low pass filter, having a protection role against the possibly perturbing signals that might be transmitted from the transducer to the input of the amplifier.

The gain of the non inverting circuit is given by the relationship (12):

$$A = 1 + \frac{R_1}{R_i}$$

The U1B circuitry, Fig. 12, represents a high pass filter.

The circuitry U2A is also a high pass active filter having the same cutoff frequency and an adjustable gain using the band commutator JP1. The gain can be selected using the transfer gates having also a commutator role.

In order to achieve the needed bandwidth of approximately 100 kHz, a few filtering stages have been used, the needed bandwidth couldn’t be achieved within a single amplifier circuit.
The use of several series filtering stages was also necessary in order to reduce the offset introduced by the operational amplifiers.

The charge amplifier is supplied from a differential supply source having the voltages of ± 8V.

The three amplifier circuits, the supply source and an acquisition board are mounted together in a case (see Fig. 14).

The signals provided by the charge amplifiers are transmitted to an acquisition board National Instruments NI PCI-6110 and processed (Fig. 15).

6. CONCLUSIONS

The design of the piezoelectric-charge amplifier systems for the diagnosis and the monitoring of the wind turbines, implies a series of technical problems, that the designer has to keep in mind and which are:

- The processing of the output signal of the piezoelectric transducer is an important issue, because the output signal could be proportional to the amplitude, the velocity or the acceleration of the vibrations of the wind turbine generator. If the output quantity from the transducer is the acceleration of the vibration and the quantity of interest is the amplitude, two successive integrations are needed. The reverse situation is a bit more complicated from the point of view of the electronic involved, two successive derivations being necessary.
  - The frequency response of the piezoelectric transducers is limited by the time constant of the transducer and in the high frequency range by the mechanical resonance frequency;
  - The signal processing circuit from the output of the piezoelectric transducer has to have a very low value of the impedance in order to collect the maximum of the output charge from the output of the sensor.
  - In the case of charge amplifiers, at low range frequencies, the reaction resistance determines a reduction of the gain, and at high range frequencies the impedance of the circuit becomes lower, cancelling the effect of the resistive path of the reaction loop.
  - From the point of view of the internal noise of the charge amplifier, it increases with the increase of the capacitance and with the decrease of the input resistance.
  - For the voltage amplifiers the cutoff frequencies at low and high frequencies are set by the choice of the resistance $R_f$ and of the capacitance $C_f$.
  - For voltage amplifiers, the output voltage depends on the capacitance seen by the sensor and that is why the length of the interface cables must be reduced to a minimum length.

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