Introduction

The knowledge of overhead line and cable impedances is very important for the correct setting of impedance protection relays. Line-to-line impedances can be calculated with acceptable accuracy, but line-to-ground impedances have to be measured because the calculation does not fit within the real condition of the specific ground resistance with metallic pipes, cables, and other metallic parts in the ground. Also, the mutual coupling between power lines has to be measured. Conventional measurement principles are:

- Beat frequency method
- Test with normal and reverse polarity.

These methods need high-test currents to get an acceptable signal-to-noise ratio, and they are not very precise. This article describes a new test method using frequencies different from the line frequency. The resulting excellent noise suppression allows for precise measurements under difficult conditions.

Measuring Principle

The measuring principle is shown in Figure 1. A digital signal processor generates sinusoidal signals in a frequency range of 15 to 400 hertz. This signal is fed to a switched-mode power amplifier. A transformer at the output matches the internal amplifier impedance with the test object impedance. A multiplication of the measured signals with the generated signal, \( \sin(\omega t) \), and the 90° shifted signal, \( \cos(\omega t) \), enables an excellent filtering of the noise and a measurement of the real and imaginary parts with high precision. Thus, complex impedances \( Z=R+jX \) can be measured. When the measurements are made at frequencies different from the line frequency, they also can be made under difficult conditions without any interference problems. The impedance value
at line frequency can be determined by interpolating the curve impedance versus frequency. The described method is also ideal for ground impedance and coupling measurements.

**Capacitive and Inductive Coupling**

Without special equipment, measurements on overhead lines can be quite dangerous. A calculation for 220 kilovolts was made. The capacitive coupled voltage was approximately 48 kilovolts (both ends open), and the current through the coupling capacitance (one end grounded) was approximately 280 milliamperes per kilometer.

If a second system on the tower had a fault current of 3000 amperes, the induced voltage in the measured system would be calculated to 400 volts per kilometer, or four kilovolts for the whole length of 10 kilometers.

To avoid any danger during the measurements, a special coupling unit was used between the test equipment and the overhead line. A separation transformer with reinforced insulation and measuring transformers allowed a complete potential separation. The coupling unit was situated near the overhead line, far away from the operation unit. Overvoltage arresters made the operation as safe as possible. For such situations, test currents up to 20 amperes can be generated.

**Line Impedance Measurement**

For determination of the symmetric line impedance, ground impedance, and ground factor (k0), the following measurements are necessary:

- L1-L2, L2-L3, and L3-L1 loops
- L1+L2+L3 (in parallel) to ground.

The symmetric line impedance $Z_{1,sym}$ can be easily determined out of the line-to-line impedances (see Figure 2).

The ground impedance $Z_m$ can be calculated by subtracting $Z_{1,sym}/3$ from the ground loop impedance (see Figure 3).

![Figure 3](image)

**On-Site Tests**

In the first example, a measurement was made on a 220-kilovolt overhead line with a length of 80 kilometers (Figure 4).

![Figure 4](image)
The whole test could be prepared ahead of time, so the actual measurements of all parameters would take approximately 30 minutes of on-site time. The calculation of $Z_{1,sym}$, $Z_{m}$, and the ground factor $k_0$ was done automatically (Figure 5).

Very often the ground factor is set to one. In this case, a ground factor of 0.47 was measured. If a fault had occurred in the first part of the second zone, the relay would have tripped instantaneously, so the selectivity of the protection was not provided.

A second example was measured on a high-voltage cable connection. The length was nine kilometers, and the cable screens were “cross-bonded.” The ground factor of the protection relay was set to 0.8. The measured ground factor was 0.3. It is also interesting to note that the inductive component ($X$) of the ground impedance was negative. The reason for this was the relatively big inductance between the inner cable conductors (distance between the phases $=30$ cm) compared to the small inductance between inner conductor and screen, so the difference became negative.

**Noise Suppression**

All the measured results in Figures 5 and 6 are interpolated values. The real measurement was made at different frequencies to get the impedance curve over the frequency. In Figure 7, the noise at 50 hertz can be seen clearly. By interpolating the impedance curve for 50 hertz, this value can be determined with high precision. Although high, 50 hertz noise is around. Also, the impedance values at the harmonics can be determined.
Ground Impedance of Large Substations

For measuring the ground impedance of substations, the auxiliary line for the current loop should be at least 10 times the maximum longitude of the substation. Otherwise, the potential gradient area of the auxiliary electrode would influence the potential gradient area of the substation ground system, which is measured. For large substations, out-of-service overhead lines or cables are used as auxiliary line. The principle is shown in Figures 8 and 9.

Figure 10 shows the ground impedance curve. A distance of more than 2000 meters is needed between the measuring electrode and the substation ground to get the complete impedance value. Due to the measurement of the complex impedance, voltages, which may be induced in the voltage-measuring path, can be eliminated.

Normally, not only the ground feeds the current flowing back to the substation, but also all metallic line, tubes, pipes, the ground cable on the tower top, and cable screens feed parts of the current flowing back. Sometimes it is important to determine the current balance of all described paths. This can be done, if the paths are accessible, by using current clamps, which are put around the line.
In Figure 11, the principle of ground grid measurement is shown. With this measurement, contact resistances of ground grid connections can be measured and corrosion of the grid itself can be detected.

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