Testing the Suitability of an Unenergized Power Line Near Szakony, Hungary for Measuring the Air-Earth Electric Current

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Abstract

The global activity of tropospheric sources of atmospheric electricity can be monitored by near-surface measurements of the parameters of the atmospheric global electric circuit. Measuring the air-Earth vertical electric current on long power transmission lines in fair weather conditions promises an applicable solution for that purpose. The implementation of such a measurement is considered and an unenergized power distribution line of 14.5 km length near western border of Hungary was examined to determine whether it is suitable for further investigations. It was found that a 2.2 km-long segment of the line might be used for that after further testing. This report summarizes the experiences of the first testing of the line, including theoretical considerations on the expected magnitude of the electrical quantities that can be measured on the line and performance of the applied tools and measuring devices. Practical guidelines for selecting the line and the measuring point on the line are derived and recommendations for further tests are given.

Keywords: global electric circuit, air-Earth electric current, power lines.

Introduction

Climate change is one of the global challenges that are critically relevant for humanity as it affects the fundamental areas of prospering of mankind: energy, land, agriculture, as well as basic conditions of living, most notably the temperature (Hardy, 2003). Several elements of the climate are cross-linked via the temperature, e.g. thunderstorm and lightning activity (Williams, 1992), global rainfall (Salzmann, 2016), etc. As thunderstorms and electrified shower clouds are the key drivers of the atmospheric global electric circuit (GEC) (Mach et al., 2011), monitoring of the GEC is a plausible tool for studying the interlinked

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elements of the climate. The DC and AC parts of the GEC (Rycroft et al., 2008), however, have not been effectively utilized so far in this aspect.

Distinction between sources of the DC and AC global circuits is fundamentally important. Beginning with the new theory for the DC global circuit by C.T.R Wilson (1920), electrified shower clouds (precipitating clouds without lightning) are considered as important contributors to the air-earth current. This has been supported by satellite measurements (Liu et al., 2010) and it is also sustained by evidence from measurements of substantial cloud-top current to the DC global circuit by, e.g., Wilson (1920), Mach et al. (2009, 2010, 2011). More than 90% of worldwide precipitating convection (electrified shower clouds and thunderstorms combined) is recognized to contribute to the DC global circuit (Liu and Zipser, 2009). In contrast, only thunderstorms drive the AC global circuit and Schumann resonances (Price et al., 2007).

In attempting to characterize the global climate change via monitoring the GEC, we now focus on the DC part, because quantitative access to the DC global circuit in a globally representative measurement of air-Earth current on a continuous basis would enable access to the continuous variations of rainfall and latent heat release on a continental scale. This achievement would provide unprecedented access to global energetics on both weather and climate time scales. The currently available model-based estimates of the sensitivity of global rainfall to temperature (e.g., Salzmann, 2016) vary by nearly an order of magnitude, largely due to the uncertainty in the role of global aerosol in modulating the rainfall. These model predictions could be checked by this global electrical measurement. The measurements would likely provide a new impetus to global weather forecasting, too.

Reliable continuous access to the DC global circuit, involving all electrified weather worldwide, though pursued for more than a century, is still unsolved. Although some spot attempts have been carried out in special locations, e.g., Vostok, Antarctica (Burns et al., 2017), they are always subject to dominance by local effects and so are generally unsuccessful for continuous monitoring. This is especially true for measurements of the atmospheric electric potential gradient (Nicoll, 2012). Joint analysis of PG measurements recorded in fair weather conditions at well separated monitoring sites can be one workaround for this problem (Bór et al., 2023). The numerous unsuccessful attempts push forward an alternative new approach, which is based on the use of unenergized long transmission lines from an infrastructure already in place. Global representativeness is supposed to be achieved due to the mutual cancellation of local effects that vary along the long line. These lines can be fundamental from a technical point of view, too, because they increase the collection area of the air-Earth current by orders of magnitude over other earlier efforts (Ruhnke, 1969; Ruhnke et al., 1983; Tammet et al., 1996), and so they yield a sufficiently larger electric current which is relatively easier to measure.

This report serves to document the experiences gained during checking the suitability of a segment of an unenergized power line near Szakony, Hungary for making air-Earth current measurement on it.

The tested power line and its environment

We were informed that an unenergized power line runs between two settlements, Szakony and Sopronkövesd near the western border of Hungary (Fig. 1). It used to be a distribution power line of 22 kV. One end of the line (47.432872° N, 16.712734° E) is in Szakony. From there, it runs north-west for about 2.2 km before it takes a sharp turn to head to north-east. Along the first section, it runs quasi-parallel to another active distribution line of 22 kV that lays south-west from it. The distance between the two lines is only 20–100 m. Just before it turns to north-east at the point (47.448574° N, 16.693866° E) (Fig. 2), the unenergized line crosses a high voltage power distribution line of 132 kV (i.e. runs below it) which is running perpendicular to its section back towards Szakony. After turning to the northeast, the unenergized line runs quasi-parallel to the 132 kV active transmission line, partly on its right side, partly on its left side, and literally under it, too, along a short section (Fig. 3b). Close to Sopronkövesd, the tested line crosses an electrified railway line and takes another sharp turn to north-west again right after this (Fig. 1). It runs further in this direction for about 2 km before it terminates. Several active distribution power lines of 22–25 kV crosses the tested line or run parallel to it within a 20–100 m range along some sections.

The total length of the unenergized line is ∼14.5 km. The line consists of 3 wires for the 3 phases of the transmitted electric power. The wires are at about 10 m height above the ground level (pole heights are supposed to be within the 10–15 m range). At most supporting poles, which are placed spaced by 100 m each from one another, the central wire is elevated by 0.8 m from the two, lower running wires. The horizontal distance between the two lower wires is 1.4 m. A diameter of 12 mm can be assumed for each wire (the diameter of the wires applied in such distributing lines is between 9 mm and 14 mm).

It was discovered only in the middle of the testing process that the unenergized line was damaged between two poles, ∼1.3 km after it turns toward north-east. The two lower wires were torn off from the supporting pole at (47.457427° N, 16.704972° E) (Fig. 3a), while the upper wire remained intact. At the next pole towards the northeast at (47.459506° N, 16.707542° E), the two released wires were connected to the top wire and all of them were wound around the metal structure of the pole, i.e., they were more or less grounded (Fig. 3b). This means that all three wires of the rest of the line towards its end at Sopronkövesd were interconnected and were more or less grounded at this pole. On the other hand, from the previous pole all the way back to the end at Szakony, the two lower wires were separated from the rest of the line, while the top wire was connected to the same, including all three wires, and the grounding point.

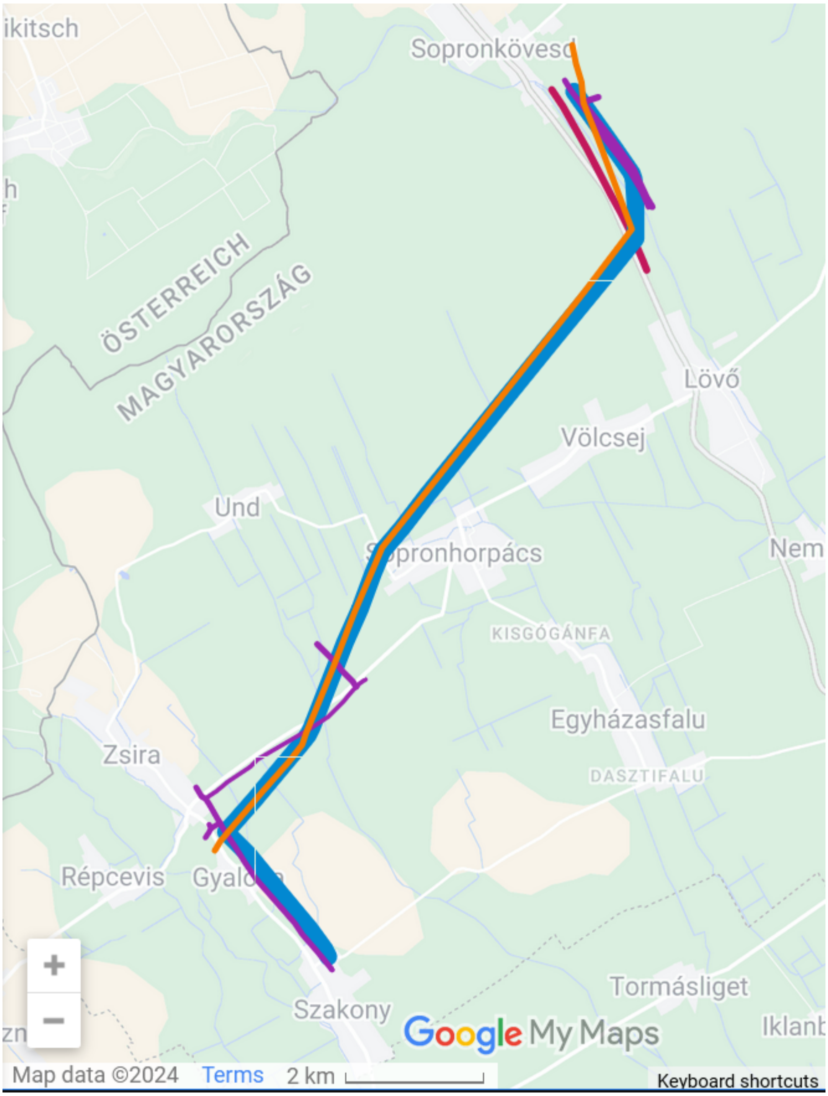

Fig. 1. Map of the tested unenergized power line (thick and blue) and the interfering sections of the power line network. 22 kV distribution lines (purple), 132 kV transmission line (orange), electrified railway line (red). The map is northward oriented. Google maps, 2024.

Fig. 2. Turning point of the tested power line, 2.2 km from its end in Szakony. The pole in the middle is equipped with a mechanical switch that allows breaking the continuity of the line.

Preparations for the testing, methodology

Voltage or current measurement?

The final goal of making measurements on a long transmission line is to infer the global state of the DC GEC. In principle, this can be achieved in two ways. As the power line runs in the air on insulating supporting poles, it acquires the potential of the background field at its elevation level, which, in fair weather conditions, is driven by the potential of the upper equalizing layer in the lower ionosphere (Rycroft et al., 2008). The voltage the line acquires represents the state of the DC GEC. Implementing this approach is both difficult and dangerous. A very long conducting line can collect a significant amount of charge and may come to a very large voltage of several kilovolts compared to the ground. Although the supporting poles are generally good insulators, even a small leakage current through them to the ground can bias the measurement. Given the unavoidable coupling of AC sources, both natural (e.g., lightning) and

Fig. 3. Discontinuity **(a)** and loose grounding **(b)** of the tested unenergized power line. The other line is a high voltage transmission power line of 132 kV.

man-made (e.g., nearby-running active power lines), to the measured line, it can be challenging to extract the DC part of a possibly highly varying voltage. This approach also requires a very sophisticated measuring device exhibiting very low leakage current and so a very high internal resistance that is comparable to the total resistance of the support of the line.

The other concept is to measure electric current that runs between the line and earth through a low-resistance ammeter, i.e., the air-Earth current. Since the line cannot gather a large potential in this approach, this solution is unquestionably safer to test. It also seems easier to realize because one needs to provide only a very good grounding for practically all of the current to flow in the measuring channel towards the ground. Nevertheless, implementing this variant is still challenging. Partly because the DC current to be measured is very small and weak, i.e. it comes from a source that has a very high internal resistance so it cannot drive conventional ammeters. And partly because the direction of the current may change due to the AC coupling to the line, and commercial ammeters in the micro-nanoampere regime normally can handle only monodirectional electric currents. Additionally, large current transients can easily damage electronics designed to be sensitive to very small DC currents. Considering the resources and measuring instruments that were available to us, we opted for checking the suitability of the unenergized line for making air-Earth current measurements on it.

Estimation of the electric parameters of the measured line

Initial calculations were made to estimate what we can expect at the measured line. At the estimation of the air-Earth current, ideal fair weather conditions and no AC coupling to the tested line were assumed. According to Tammet et al. (1996), the effective current collection area A (square meters) of a long horizontal wire of length L (meters), height H (meters) and wire radius R (meters), is given by the following equation

$$A_w = \frac{2\pi LH}{\ln(2H/R)}. \tag{1}$$

For one wire of the tested line, the parameters $L = 14500$ m, $H = 10$ m, and $R = 0.006$ m yield $A_w = 1.1 \cdot 10^5$ m^2. Taking the vertical current density to be $J = 2$ pA $= 2 \cdot 10^{-12}$ A/m^2 (Haldoupis et al., 2017), the air-Earth current on one grounded wire is $I_w = J \cdot A_w = 22.5 \cdot 10^{-6}$ A $= 22.5$ μA. The total current on the interconnected 3 wires will be less than triple of this value, because the wires are close to one another. The reduction due to the geometry of wire arrangement was not estimated, still the magnitude of the expected total current could be inferred. It should be a few tens of microamperes somewhere between 22.5 μA and 67.5 μA.

The voltage of the floating line U is simply the product of the vertical electric field E (the negative of the potential gradient) and the height of the line. In fair weather conditions, E is usually taken to be -130 V/m (Haldoupis et al., 2017). This yields -1300 V for a line at 10 m height. Note that under charged clouds, especially during thunderstorms, E can be more than two orders of magnitude larger which is dangerous both for humans and for the measuring electronics. Therefore, the testing should be carried out in fair weather conditions.

The total charge the line collects (Q) is the product of its voltage U and its capacitance C. Following the formula given by Tammet et al. (1996), the capacitance of a wire can be calculated using the formula

$$C_w = \frac{2\pi\epsilon L}{\ln(2H/R)}, \tag{2}$$

where ϵ is the permittivity of the air. Assuming this to be equal to the permittivity for free space $\epsilon_0 = 8.85 \cdot 10^{-12}$ F/m, the capacity of a wire of the line becomes $C_w = 9.34 \cdot 10^{-8}$ F $= 93.4$ nF. With this value, the largest charge on one wire of the line can acquire is $Q_w = 129$ μC, and so $Q = 388$ μC for the 3 wires combined.

The energy W_w stored on one wire can be calculated as $W_w = \frac{1}{2} C_w \cdot U^2$. For one wire this is ~84 mJ. For the 3 wires combined, the value is $W = 252$ mJ, which is not necessarily lethal in fair weather conditions. However, in stormy weather the voltage can be 1–2 magnitudes larger and the energy can easily be within (or even over) the range applied in defibrillators, namely 120–360 J (Goyal et al., 2023), and so it can be dangerous to human life. This further emphasizes that the test should be made in fair weather conditions and with precaution to avoid any electric shock to people.

On using a spark gap in the measurement

One easy solution for limiting the voltage of the wires is using a spark gap. The spark gap separation d (in mm) can be calculated as the ratio of the maximum allowed voltage U_{max} to the breakdown strength of air $U_{B,air}$. Note that $U_{B,air}$ is usually taken to be 3000 V/mm but it may vary depending on the geometry of the spark gap and environmental conditions, e.g., temperature, pressure, and humidity (Sankar, 2011). For example, if the voltage on the line is to be limited to $U_{max} = 1000$ V, a gap $d = U_{max}/U_{B,air} = 0.33$ mm should be set.

Note that a good spark gap is perhaps the simplest tool to verify whether the floating transmission line functions as expected. Sparks should occur regularly when the separation d is set below the distance that corresponds to the maximum reachable voltage of the line. The time τ (seconds) needed to fully charge the line capacitance from an initially discharged condition can be calculated as

$$\tau = \frac{Q}{I} = \frac{Q}{J \cdot A} = \frac{\frac{2\pi\epsilon LEH}{\ln(2H/R)}}{J\frac{2\pi LH}{\ln(2H/R)}} = \frac{\epsilon E}{J} = \frac{\epsilon}{\sigma}, \tag{3}$$

where $\sigma = J/E$ is the conductivity of air, which can be taken to be $\sigma = 2 \cdot 10^{-12}$ A/m^2 / 130 V/m = $\sim$1.54 $\cdot$ 10^{-14} S/m. With this value, $\tau = 8.85 \cdot 10^{-12}$ F/m / $1.54 \cdot 10^{-14}$ S/m = $\sim$575 s or roughly 9.5 minutes. Note that τ does not depend on the parameters of the line. It is simply the local ambient relaxation time of the atmosphere. Because of the varying conductivity, the actual value of the relaxation time may differ from this estimation, but, depending on the applied spark gap separation, discharges in the spark gap should be observed regularly in every few minutes. Note that good insulation of the spark gap is very important in this application. Since the charging current of the line is very weak, surface current leakage of the spark gap can cause significant deviations from the theoretically expected operation.

Capacitive coupling to the measured line

Capacitive coupling between the tested line and nearby-running active transmission and distribution lines can be expected. The following considerations were made to quantify the conditions for the coupling to remain at a manageable level. Note that such calculations are relevant also from the point of view of safety when work is to be done close to high voltage lines (Luo et al., 2023). An active power line, a single wire of infinite length is assumed to run horizontally at the height H_A above the ground surface. It can be shown that the vertical component of the electric field of this active line and its mirror image under the surface together (E_A) at a horizontal distance D from the line can be given by the formula

$$E_A = \frac{\lambda}{2\pi\varepsilon_0}\left(\frac{H_A - H}{D^2 + (H_A - H)^2} - \frac{H_A + H}{D^2 + (H_A + H)^2}\right) \tag{4}$$

(Reitz et al., 2008), where λ (C/m) is the momentary (but uniform) line charge density of the wire. The line charge density determines the radial electric field E_r at the surface of the wire (cable) through the relation

$$E_r = \frac{\lambda}{2\pi\epsilon R_A}. \tag{5}$$

Here R_A is the radius of the active wire. To obtain an upper limit for the line charge density, we take the radial electric field at the surface of the wire (cable) to be the breakdown strength of air $U_{B,air} = 3$ MV/m. Assuming that R_A is the same as that for the tested line, i.e. 6 mm, solving the relation for the line density yields $\lambda = 1.0 \cdot 10^{-6}$ C/m. We can use this value of λ in the expression for E_A. For the air-Earth current to be monopolar, E_A should not exceed the electric field near the Earths surface, i.e., 130 V/m. This expression can be solved either analytically or numerically for the minimal D which fulfills this condition. Table I contains the E_A values obtained for D varying between 40 m and 50 m, assuming that the active line runs at the same height as the tested line, i.e. at 10 m.

Table I. The vertical component of the electric field (E_A) of an infinite line of charge of 10^{-6} C/m line density at 10 m height at a horizontal distance D from it.

D (m)	40	41	42	43	44	45	46	47	48	49	50
E_A (V/m)	-180	-173	-166	-160	-154	-148	-143	-138	-133	-128	-124

It can be seen that the amplitude of the coupled AC voltage on the line in absolute value is less than the external fair weather field (130 V/m) only further than 49 m from the measurement on the tested line. This means that an active wire, as parameterized above, must be at least ~49 m away from the measured line, but the further the better. If the line consists of 3 wires, with the distance between the phases (wires) taken as negligible compared to the distance between the lines, the minimum required distance is triple this value, i.e. 147 m. Note that this value is an upper limit for the minimum distance, and can be lower if the radial electric field at the surface of the active wire is less than the breakdown field of the air, which is usually so.

If the unenergized line is running parallel to the live line, the AC field estimates apply everywhere along the line. In the much more favorable circumstance that the unenergized line runs perpendicular to the live line, the calculated fields are present only at the end closest to the live line, and diminish substantially further along the line.

Note that an AC signal on the measured line can also be induced by transient electromagnetic wave packets travelling in the air. Such wave packets can originate from both natural (e.g., lightning) and man-made sources (e.g., electric motors or motors with a spark plug). These noise sources may occasionally produce very energetic electromagnetic transients, too. Moving away from areas of human activity can be a solution for eliminating man-made noise sources. Transients of natural origin, however, can always occur, so the measurement must be set up and interpreted accordingly.

Instrumentation used for testing the line

- A spark gap with an adjustable separation distance was manufactured locally. The two ends of the spark gap are separated by a rod of 40 mm diameter made of polyamide for insulation. Note that the surface current leakage of the spark gap could not be measured reliably with the equipment that was available for us.

- The Nanoranger ammeter by Altonovus was intended to be used for measuring small monodirectional currents (https://www.altonovus.com/nanoranger).

- A Voltcraft ET-02 device was used to measure the grounding resistance at the measuring point.

- A Voltcraft M-3860M digital multimeter and an analog oscilloscope (Tektronix 2213) was used to check the level of AC coupling on the measured line.

- All these devices were run on-site either on battery or on a battery-powered 220 V AC inverter.

Timeline of the testing and the observations

Initial measurements at the termination of the tested line in Szakony

The testing took place on January 17, 2024. There was some very weak, practically negligible wind. High level clouds fully covered the sky, but there were no low level clouds so the weather could be described as quasi-fair or semi-fair (Harrison et al., 2020).

The investigation was started at the terminating pole of the tested line (47.432872° N, 16.712734° E) in the village Szakony (Fig. 4). At that point, the line to be tested runs at a distance of about 60 meters from a parallel energized line of 3 phases at 22 kV AC (Fig. 1). The resistance of the grounding attached to the terminating pole was measured to be 13-14 Ω.

Fig. 4. Termination of the tested power line in Szakony. The three wires (phases) coming up from the ground and attached to the supporting pole are under power.

Measurements at the first test point

We learned that an active distribution line, in the continuation of the unenergized line, ends at the terminating pole (Fig. 4). Although it is well separated from the tested line, we were advised that it is not safe to work in the vicinity of the end of this active line. So we moved two pole distances (~200 m) up the test line and made further investigation there at the pole (47.433954° N, 16.711779° E). The ground resistance was found to be 19 Ω at that pole. Using a cherry-picker truck, kindly provided by the energy networks and energy infrastructure company E.ON, high voltage on the wires was checked for safety precautions (Fig. 5a). No significant voltage was found. Then the three phases (wires) of the line were combined using special clamps and all were linked to one down-going cable (Fig. 5b). The wires were combined to increase the total current the line can provide.

The down-going cable from the line was attached to the grounding of the pole at its base through the closed spark gap (Fig. 5c), so the line was separated from the ground by the polyamide insulator of the spark gap. Then the gap was very slightly opened (the exact separation distance was difficult to measure) to

Fig. 5. Preparations at the first test location. **(a)** Testing for high voltage. **(b)** Combining the 3 wires (phases). **(c)** Dániel Piri (to the right) and professor Earle Williams are assembling the oscilloscope, inverter, and car battery. The spark gap (to the left) is fixed to the grounding of the pole and the reel of the down-coming cable from the combined line is already attached to its right side.

see whether any spark occurs. No spark could be observed.

The DC voltage between the two ends of the opened spark gap was measured by the digital multimeter. The value wasnt growing and it was not very stable either, it varied in the range of 13–16 V. This value is much smaller than what was expected (∼1300 V) from the height of the line (10 m) given the fair weather potential gradient is 100–200 V/m.

A car battery of 12 V was connected to the line at the corresponding end of the opened spark gap through the Nanoranger ammeter, serving as a voltage source, to check the leakage current (i.e., the insulation resistance) of the line. The device displayed 150 μA and 110 μA in the two wiring (polarity) configurations. Calculating the leakage resistance by Ohms law $R = U/I =$ 12 V $/110 \cdot 10^{-6}$ A $=$ ∼109.1 $k\Omega$ which is a rather low value indicating a poorly insulated system.

To test the AC signal variations on the line, an analog oscilloscope was connected to the two ends of the closed spark gap with a 10-fold voltage attenuator inserted between the oscilloscope and the tested line. The oscilloscope was powered by an inverter supplied by a 12 V car battery. A strongly and not uniformly varying AC signal was seen in the oscilloscope in the 4–5 V range peak-to-peak (pp). This corresponds to the range 40–50 Vpp on the line taking into account the voltage attenuator.

After this, the oscilloscope was disconnected from the spark gap and the spark gap was bridged by the Nanoranger ammeter. The device displayed 130 nA. Note that this result is most probably biased because the AC component of the signal was larger than the DC voltage on the line, so the actual current was likely not monodirectional. In case of bidirectional currents, the values displayed by the Naoranger device cannot be trusted, because the Nanoranger is specifically designed for the measurement of monodirectional small currents. However, being aware of the relatively strong coupled AC signal on the line, results of the leakage test became questionable, too, since the AC voltage variation on the line (40–50 Vpp) was larger than the DC voltage of the battery (12 V).

The above-described experiences are not surprising now that we know that the combined wires were more or less short-circuited to the ground via the top wire at a location further down the line, but that was not known at the time of those measurements. Nevertheless, the 40–50 Vpp signal variations at 10 m height correspond to an electric field variation of 4–5 V/m pp. This is much smaller than the ambient fair weather vertical electric field (100–200 V/m) so this environment would have allowed making valid measurements in normal conditions.

Measurements at the second test point

It was speculated that the magnitude of the AC signal component might be lowered further if the long section of the test line that is running parallel with the 132 kV transmission line is detached. Segmenting the line is possible at poles where there is a mechanical switch to aid maintenance works. The closest switch was on the pole where the test line turns sharply to the north–east (47.448578° N, 16.693864° E) (Fig. 2). Note that several active power lines run perhaps the closest to the test line at this location.

The measurement took place at the pole with the switch. Ground resistance at this pole was found to be 9 Ω. We were informed that poles with a switch are supposed to have a better grounding. Our measurements confirmed this information (9 Ω vs. 13–19 Ω). The three phases (wires) of the tested line were combined, and the down-going cable was connected to the grounding at the base of the pole through the spark gap. The AC signal measurements were repeated both by the digital multimeter, which showed variations in the 115 Vpp range, and by the oscilloscope, which indicated practically the same range (120 Vpp) and confirmed that the signal waveform includes similar irregularities and mixed frequency content as it was observed at the first testing point.

The 4-fold increased AC amplitude at this location confirms the considerations on the AC coupling in cases when the active line runs perpendicularly to the tested line. This was the configuration here considering the 132 kV high voltage transmission line and the segment of the tested line from this measuring location back to its end in Szakony. The measurements confirmed that the coupled AC signal rings off along the unenergized line further away from the point or region of the strongest coupling. Note that even at its increased level, the coupled AC electric field, 120 Vpp / 10 m = 12 V/m pp is still less than the normal fair weather electric field (100–200 V/m), so usable air–Earth current measurement could have been made on the test line under normal circumstances, at least in theory.

It was around this time when the discontinuity of the lower two wires and the loose grounding of the line (via the top wire and due to the combination of the 3 wires) were discovered.

When the switch was opened and the 2.2 km-long segment of the line back to its end in Szakony was disconnected, the amplitude of the AC component of the signal on the tested line dropped by 75%. Additionally, the waveform of the signal lost its noisy character (Fig. 6) and became apparently sinusoidal at 50 Hz which is the common base frequency of the European continental power line network. This confirmed that a significant fraction of the AC signal component was caused by capacitive coupling from the high voltage transmission line that is running parallel with the tested line in most of its northern part. Detaching that northern segment from the tested line significantly increases the signal to noise ratio in a measurement. On the other hand, it was also realized that the high frequency noise and the irregular, non-sinusoidal character of the signal were caused by the longer segment of the line that included the grounding (Fig. 3b).

The last experiment repeated the leakage current test with the switch opened. This time, the values displayed by the Nanoranger device were 190

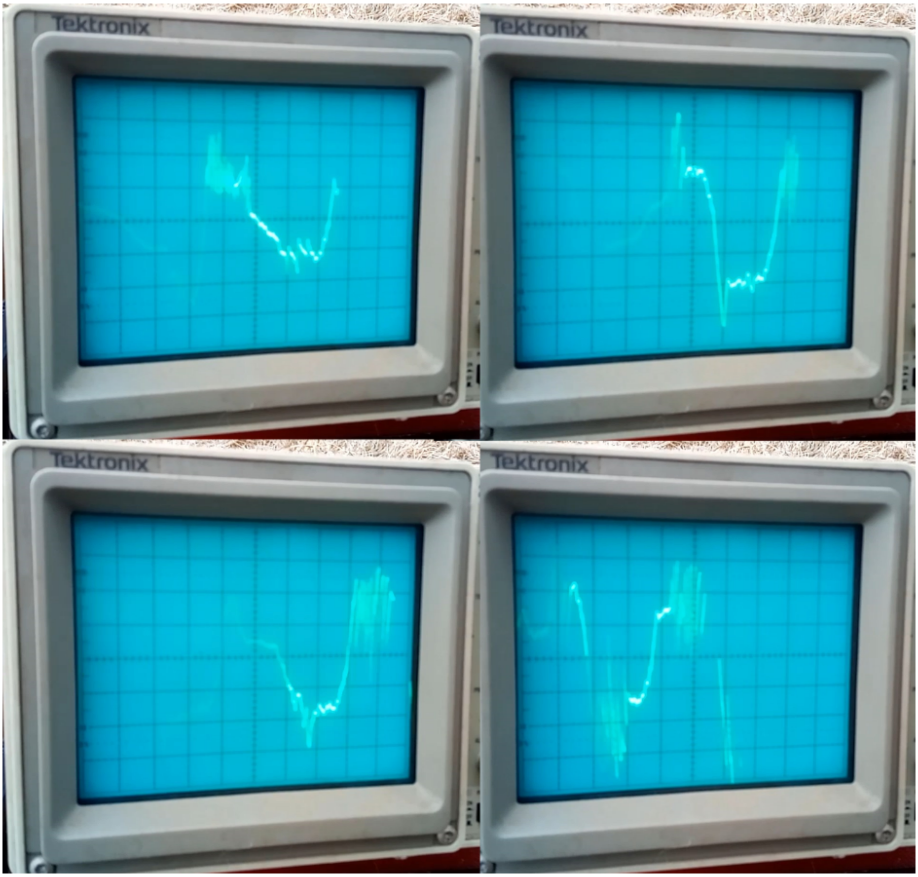

Fig. 6. Screenshots from the oscilloscope when the whole tested line was measured.

μA and 178 μA when it was connected with different polarities and the same 12 V car battery was used as a voltage source. At that point, the testing ended, so these values cannot be evaluated, because the DC voltage was not checked on the 2.2 km-long separated line segment. Note that the insulation resistance of the spark gap wasnt known either. It was observed that the spark gap was practically short-circuited when alcohol was sprayed on the insulator that separates its two ends. This observation emphasizes that the insulation of the spark gap is very much important. It cannot be excluded that dirt and surface moisture caused most of the inferred current leakage during the testing. This would be important especially in the voltage measurement-based research of the DC GEC because leakage currents may significantly bias the measured voltage on the line.

Summary and Conclusions

Supporting our efforts in trying to measure the air–Earth current, E.ON, the energy networks and energy infrastructure company in Hungary kindly made an unenergized power distribution line available for us for testing. The line contained 3 wires for the 3 transmitted power phases, its total length is about 14.5 km and it is located close to the western border of Hungary. Knowing the length and height of the line as well as the approximate diameter of its wires, the potential and the expectable air–Earth current on the line was estimated in section *Estimation of the electric parameters of the measured line.* The benefits of applying an adjustable spark gap in the tests have been discussed, and a method for finding an optimal gap size have been described in section *On using a spark gap in the measurement.* Being aware of the likely AC capacitive coupling of nearby-running active transmission and distribution lines to the tested line, a practical condition for the safe distance from an active line has been worked out in section *Capacitive coupling to the measured line.*

The most important experiences and conclusions of the field test are summarized below.

- Results of the test highlighted the importance of having a good grounding of low resistance at the measuring point. Selection of supporting poles equipped with a maintenance switch at the measuring point is recommended as these poles should have a better grounding.

- Lines of significant current leakage are not suitable for air–Earth current measurements. Checking the leakage resistance of each wire of the tested line separately allows including only the appropriate wires in the measurement. Note that measurement of the current leakage must be made using an appropriate measuring device and voltage source so that the possible capacitive AC coupling from external sources to the tested line is taken into account. Caveats and pitfalls of leakage current measurements are discussed in section *Measurements at the first test point.*

- There were several active, high-voltage power lines in the 20–100 m vicinity of the tested line, so capacitive AC coupling to the tested line could be expected. The AC component is a noise in DC air–Earth current measurements and makes the processing of the recorded data more difficult. Therefore, selection of a line that is away from the known active local power sources is recommended. Lines which are perpendicular to a crossing active power line are favored over lines which are parallel to the nearby active power lines. In case of a perpendicular line, the measurements should be made as far from the cross point with the active line as possible. In addition to keeping a distance from active power lines, low pass filtering the current would provide a solution to cope with unwanted effects of the AC coupling in any measuring environment.

- Although the test line in this report was much exposed to AC capacitive coupling, the performed test did not exclude the possibility that the air–Earth current can be measured on a separated segment of the line. Quantitative survey of the external AC field via the AC signal component on the line and its evaluation of its ratio to the fair weather electric field should be made at each line which is considered for measuring the air–Earth current.

- Having appropriate instrumentation for both checking the line and making measurements on it is of fundamental importance. The spark gap, if applied, should be verified to have a very good insulation to prevent current leakage. The ammeter device intended for measuring the air–Earth current should impose as little load on the line current as possible due to the extremely high internal resistance of the atmospheric current source. If the monodirectionality of the measured current cannot be guaranteed, a non-polarity-specific ammeter should be applied. Additionally, the internal resistance of the ammeter must be at least 2 orders of magnitude less than the total leakage resistance to ground of the line being used.

It has been demonstrated that a rough evaluation of the suitability of an unenergized power line for measuring the air–Earth current can be made with the relatively simple tools applied in this testing. Some of the tools should be improved for the follow-up tests to be more reliable. This includes improving the leakage resistance of the spark gap, and making leakage current measurements with a voltage source of a much higher power. Perhaps the most needed addition would be an universal, polarity-independent solution with which the digital time series of the air–Earth current can be recorded for an in-depth analysis.

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