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ELF FIELD IN THE PROXIMITY OF COMPLEX POWER LINE CONFIGURATION MEASUREMENT PROCEDURES

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The issue of how to measure magnetic induction fields generated by various power line configurations, when there are several power lines that run across the same exposure area, has become a matter of interest and study within the Regional Environment Protection Agency of Friuli Venezia Giulia. In classifying the various power line typologies the definition of double circuit line was given: in this instance the magnetic field is determined by knowing the electrical and geometric parameters of the line. In the case of independent lines instead, the field is undetermined. It is therefore pointed out how, in the latter case, extracting previsional information from a set of measurements of the magnetic field alone is impossible. Making measurements throughout the territory of service has in several cases offered the opportunity to define standard operational procedures.

INTRODUCTION

Whether prolonged exposure to extremely low frequency (ELF) magnetic fields generated by power lines has a significant impact on human health is still an open issue. Several evaluation studies carried out in laboratories concerning this frequency range have given effects that are obscure or difficult to interpreta, while others have yielded significant effects from *in vivo* and *in vitro* experiments. Epidemiological studies have returned mixed results, and a recent evaluation of the combined results of the major studies conducted in this connection, shows a statistically significant correlation between childhood leukaemia and residential proximity to power lines[1].

The concern to protect the framework of human life may legitimately lead to ensuring that anyone who proposes a decision has undertaken an in depth *a priori* analysis of all the implications, advantages and disadvantages of the latter, calling upon all the scientific and technical knowledge of the day. Such a rule could be understood as the Principle of Precaution (PP).

In Italy, regulations limiting exposure of the general public to electromagnetic fields are set under a framework law[2]. This was intended to set out the basic principles for promotion of scientific research for the assessment of long-term side-effects and adopting precautionary measures in compliance with the PP provided for by Paragraph 2 of Article 174 of the Treaty on European Union.

Cautionary permissible exposure limits, attention values and quality objectives, for the general public, are set out in a regulation under the framework law[3] as follows.

In case of exposure to electric and magnetic fields generated by power lines, the following exposure limits must not be exceeded: 100 μT for magnetic induction fields and 5 kV m^{-1} for electric field strength, both expressed as root-mean-square (r.m.s.) values (short-term effects).

As a cautionary measure to protect against any possible long-term effects that might be related to power frequency (50 Hz) magnetic fields, an attention value of 10 μT is adopted in children's playgrounds, residential dwellings, school premises, and in areas where the duration of people's stay is $\geq$4 h per day. The attention value is the median of values recorded over a 24 h period, under normal power line operational conditions.

In designing new power lines as well as in planning developments in the proximity of existing electric power lines, for the categories mentioned above, a quality goal of 3 μT is adopted for the purpose of progressively minimising exposures. Also, this limit is intended to serve the purpose as described above.

Among the institutional tasks of the Regional Environment Protection Agency of Friuli Venezia Giulia (ARPA FVG) one is also to carry out measurements of magnetic induction fields in the proximity of power lines. In order to meet the requirements of Italian legislation, information concerning the induction value—which is the median value over a 24 h period under normal working conditions of the power line—must be acquired through measurements. CEI[4] rules and IEEE[5] standard procedures, however, only supply qualitative indications on how to carry out measurements, without

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determining the measurement duration as well, so as not refer to more complex cases.

After giving a short introduction to electrotechnics, this work will define the typologies of lines that can be found in the area of service. A series of performed measurements concerning both a trivial situation and more complex cases will be presented as well as the procedures adopted by the ARPA FVG.

A SHORT OUTLINE OF ELECTROTECHNICS

The plants considered in this work are three-phase alternating tension and current system transmission and distribution power lines operating at industrial frequency (50 Hz in Italy).

The tension is represented by phasor $e^{i(\omega t+\theta_k)}$, where ω is the angular speed which corresponds to a rotation frequency of 50 Hz, and the three-phase angles θ_k can assume are the values 0°, 120° and 240°. The phases are usually indicated with *R*, *S* and *T*.

The conventions adopted in the following part of this work are shown in Figures 1 and 2.

Currents and tensions are generally out of phase of an angle ϕ_i, as shown in the conventional phasor diagram in Figure 1. In the instance of currents of the same intensity ($I_R = I_S = I_T$) the circuit is defined as balanced, in the instance of identical phase shifts ($\phi_R = \phi_S = \phi_T$) it is defined as symmetric.

The conditions outlined below will be assumed as valid, as generally fulfilled when high voltage (HV, 132 kV) and very high voltage (VHV, 220 e 380 kV) (voltage values of the power lines in Friuli Venezia Giulia), power lines are concerned.

In the hypothesis of HV and VHV balanced lines the earth wire current is null.

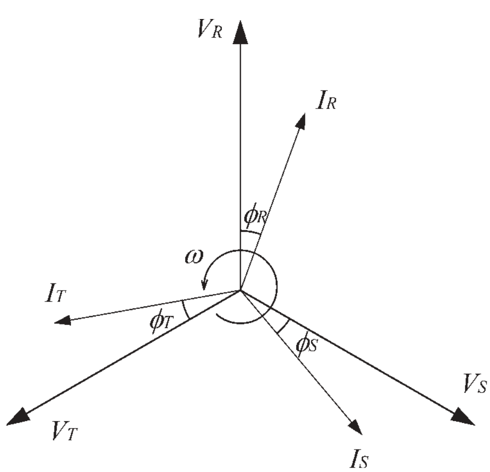

Figure 1. Phasors *V–I* diagram.

In Figure 2, which, for the sake of simplicity, refers to a monophase case, *S* indicates the apparent power, *P* the active power, *Q* the reactive power, *V* the line-to-line voltage and *I* the line current.

When the load is capacitive, the current has a phase lead compared to the voltage, and *Q* is conventionally assumed as negative. Whereas, when the load is inductive, the current has a phase lag compared to the voltage and *Q* is assumed as positive.

It is possible to demonstrate $P = \sqrt{3}VI\cos\phi$ and $Q = \sqrt{3}VI\sin\phi$ in the case of a three-phase power line.

In the case of VHV power lines, *P* and *Q* are measured at the power-conversion stations. The sign of *P* depends on the phase shift amplitude between current and voltage (it is positive when $|\phi| < 90°$, negative when $|\phi| > 90°$), and it can be correlated to the power flow (and, therefore, to the energy flow).

Current flow, instead, in this specific case of alternate current, has no physical meaning, as erroneously indicated in Ref. (6).

DEFINITION OF POWER LINE TYPOLOGIES

The various power line typologies which can be found on the service area will, now, briefly be outlined. The adopted terminology admittedly refers to aerial lines, although, the concepts are also pertinent to underground cables.

Single-circuit line (SCL)

The pylons carry one single conductor per phase (or each phase is divided in a group of cables, and in this case we refer to twin conductors, triple conductors, etc.) (Figure 3a).

Split-phase line (SPL)

This is where some of the phases are shared among different conductors, which therefore sustain a lower load. If the three phases are split and set in an

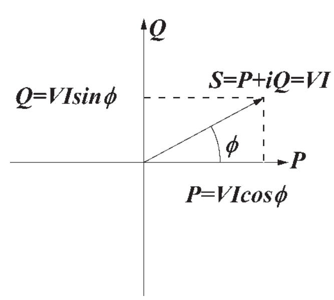

Figure 2. Scalar *P–Q* diagram.

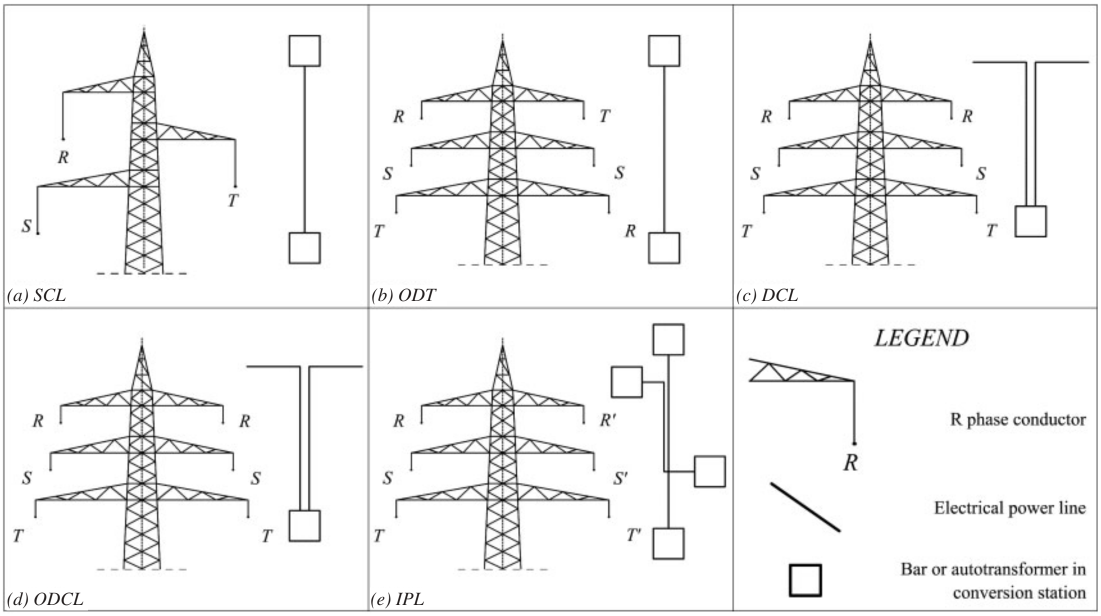

Figure 3. (a–e) Schematic representation of power line typologies.

antisymmetric manner, the generated field is consequently minimised (optimised double tern-ODT configuration) (Figure 3b).

Double circuit line (DCL)

This is a system made up of two distinct power lines, which share the same pylons for a section of their length and have homologous (i.e. at the same phase: R, S or T) conductor voltages out of phase of a known quantity: in order to fulfil this condition, the homologous conductors must end on the same bar in a transformation power station (in the case of same nominal voltage) or to the primary and secondary winding, respectively, of an autotransformer (in case of distinct nominal voltages) (Figure 3c).

Optimised double circuit line (ODCL)

This is a type of double-circuit line (DCL), which is characterised by a particular disposition of the phases in order to minimise the magnetic field generated[7] (Figure 3d).

Independent power lines (IPL)

Independent power lines are conductors which derive from and end at different power stations. In this case, it is not possible to formulate any hypotheses on a relation between the phase shifts concerning the homologous conductors (Figure 3e).

The distinction between DCL and ODT has been introduced to make the following exposition more clear; the DCL is made up of two power lines having different currents and voltage typologies (therefore different phase shifts ϕ), while the ODT is a line having only one current and the same ϕ for homologous conductors. The condition required to optimise a DCL, or in general a system made up of more lines, is that the homologous voltages have a determined phase shift. This condition is not fulfilled in the case of independent power lines.

The phase shifts between the homologous voltages of two lines having different nominal voltages are known when the type of autotransformer used in the conversion station is also known. For example, a ‘YNa0’ (‘Y’ indicates the star connection of the conductors, ‘N’ that the neutral conductor is accessible, ‘a’ that input and output windings are autoconnected, and ‘0’ no phase shift between the input and the output voltage) autotransformer does not create any phase shift between input and output voltages. Therefore, if two or more lines of this type run across the same site, the situation is determined by knowing V, P and Q; it is then possible to optimise the system of lines in order to obtain an optimised DCL.

Licitra *et al.*[6] take the case of two independent lines, which do not end at the same conversion station and have no electrical characteristic in common. The lines under consideration are not in phase, and the phase shift between homologous conductor currents, hereinafter referred to as $\Delta\phi$, in time changes in an unpredictable manner. The said authors state

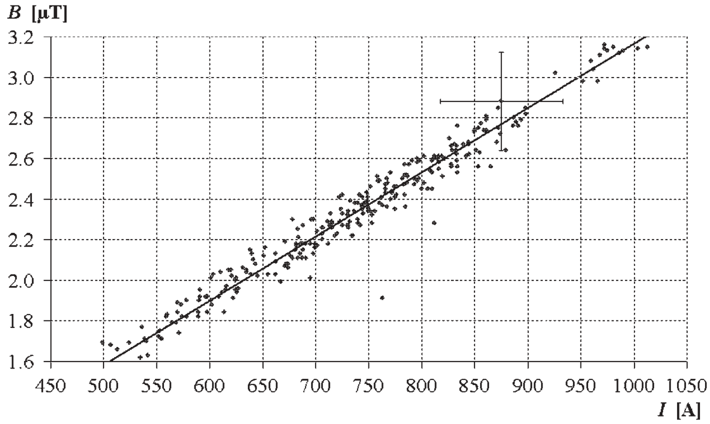

Figure 4. Relationship between measured induction and line current for a single line case (n. 356, 380 kV).

that the sense of the energy flow is supplied by the line owner; nevertheless, these data cannot be used to evaluate $\Delta\phi$, and therefore to extrapolate the alleged conclusions, precisely because they are independent lines. Energy flow sense has effective meaning only if there is a common reference frame, for the two lines, as could be the voltages shown in Figure 1. This reference frame does not exist in the case of independent lines: the two voltage sets (and consequently the current sets) are uncorrelated, out of phase by an unknown and undefined amplitude; therefore, it cannot be obtained by the line owner even having the values of P and Q. In the following part of the present work, a similar argument to Ref. (6) will be discussed but it will treat the case of a DCL where the system is altogether determined by the readings of V, P and Q.

EXPERIMENTAL ASPECTS

Before measuring a magnetic induction field proximate to power lines, it is necessary to individuate the specific cases they fall under. When more power lines run across the same site, it is necessary to obtain information from the line owner on the existing relationship between the homologous voltages, which is, whether the lines are independent or whether the voltages have fixed phase shifts. This information is essential to correctly interpret the results of the measurements, or to calculate statistical predictions starting from the set of acquired data. The readings obtained close to single, double and triple circuit lines are presented in the next paragraph.

Single circuit line

In this case the magnetic induction field is proportional to the circulating current (according to Biot–Savart's law), so it is sufficient to carry out a spot measurement, as described further on. Knowing the transiting current at the time of measurement, it is possible to calculate the field at that specific point at every other moment of the current time chart. Figure 4 shows the relationship between line current intensity and measured magnetic induction in the proximity of a 380 kV single line (the n. 356, Planais-Redipuglia). The measurement was carried out over a three-day period by means of a PMM 8055S continuous area monitor station, powered by photovoltaic cells and remotely queried using a GSM modem. The field meter was placed close to the line and the probe fixed 1.5 m away from the ground, and the acquisition time set at 1 min in the AVG mode. The arithmetical average result was chosen because the induced currents in the human body are proportional to the field intensity, and not to the power for which the r.m.s. would have been chosen.

Considering an error of 6.6% on the data supplied by the owner and a measurement error of 8.4%, the result is a reduced χ^2 with 272 degrees of freedom $\tilde{\chi}^2_{272} = 0.08$; this value does not allow rejecting the proportionality hypothesis. Collected and fitted data are shown in Figure 4. The computation of the efficient magnetic induction field was performed by Phidel®, an innovative software(7), once the electrical and geometric data relating to the concerned power line were supplied by the owner.

In the case of split-phase lines, the situation does not change, as the phases are simply carried by a larger number of conductors.

Double circuit line

Measurements were carried out close to two 380 kV power lines (347 Planais-Salgareda and 356 Planais-Redipuglia), at 5 km from conversion station, using

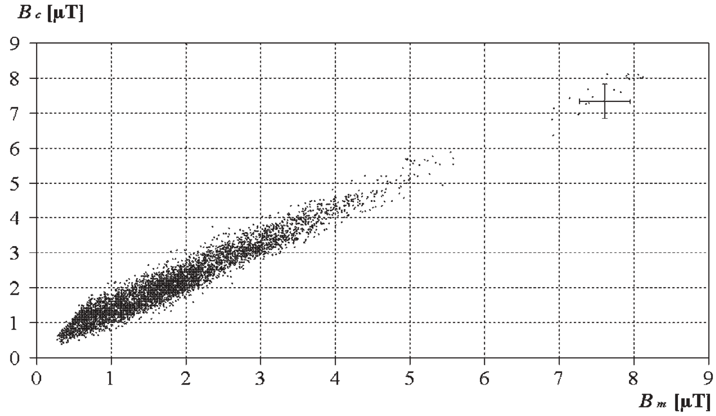

Figure 5. Relationship between induction measured (B_m) in proximity to a double line and that calculated by Phidel® (B_c).

the earlier mentioned field meter at the same settings. The two lines reach the same bar at the conversion station, so the homologous voltages are in phase; the magnetic induction value at a specific point therefore can be obtained by the measurements of V, P and Q, whose values are recorded every 15 min.

In order to calculate the value of the measured magnetic induction field the above described convention, used to determine the phase shift between the currents of the two lines, was taken into account. Using that assumption, the area monitor station measurements on a 60 d basis and the computation performed by Phidel® were compared. Figure 5 shows the relationship between the measured field and the results returned by the software.

To test the validity of Phidel®, the results were compared with experimental measurements, obtaining the value of the reduced chi-square with 5182 degrees of freedom $\tilde{\chi}^2_{5182} = 0.6$, which does not allow rejection of the hypothesis on the validity of the software.

In Ref. (6), the authors' purpose is to find a way to determine the field produced by a multi-line system, assuming a linear dependence between the induction and the current of the line closest to the point of measurement, while the field created by the remaining ones is considered as a constant background.

Taking into consideration the above described measurements, in the following passage it will be demonstrated that the field trend in function of the current of each of the two lines presents features that do not accord with the said hypothesis.

According to Figure 6, in which the collected data are shown, it is not possible to set a relationship as $B = B_0 + kI$ with $B_0 > 0$; in one case there is an absence of linearity as evidenced by the light grey dots, in the other a 'negative background' as shown by the dark grey dots.

Consequently, in order to determine the field value in proximity to several power lines, it is necessary to consider the relative phase shift between the currents, and more superficial approximations can be due to a poor statistical data collection or to the particular geometry of the system, for which the effect produced by one line is predominant.

In fact, in Figure 6a a measured magnetic field of 2 μT is generated by a current of ~100 A circulating in the 347-line combined with a current of ~750 A due to the 356-line.

Figure 6b shows the sketch of a pylon head for the DCL in question with the indication of the point of measurement. On the right side of the figure the circuit scheme is displayed. It is possible to note the un-optimised phases disposition.

Triple circuit lines

The case of a 220 kV DCL (283 Monfalcone Z. I.—Redipuglia and 277 Redipuglia—Monfalcone Z. I. AL.) and of a 380 kV line (343 Monfalcone C. TE—Redipuglia) was taken up for consideration. For a certain length, at 5 km from the generating station, they run parallel and only a few meters distant from one another. The three lines come from the same conversion station, and a 'YNa0' autotransformer is placed in the midst of them. Also in this case, the system is fully determined by knowing V, P and Q, and the field can be calculated as in the previous case.

Independent lines

In the general case of independent lines, or when the readings of P and Q are not available, it is impossible—even on the part of the line owner—to formulate any hypothesis on $\Delta\phi$ when the

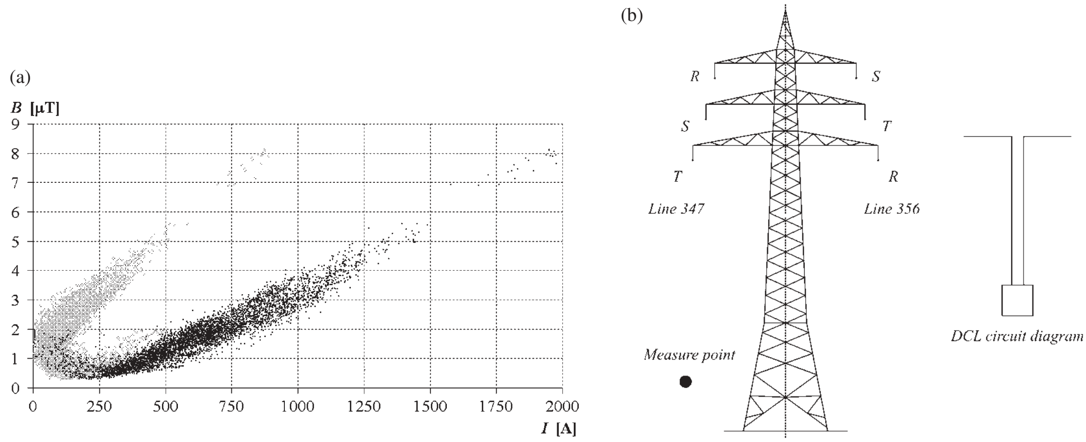

Figure 6. (a) Magnetic induction in function of current for lines 347 (light dots) and 356 (dark dots). (b) Disposition of the phases on a pylon of the 347–356 DCL and relative circuit diagram.

measurement is carried out, or also make a statistical prevision on the power flow directions in order to reproduce or to interpret the measurements. In these cases, the only possibility to extrapolate precautionary considerations on the intensity of a magnetic induction field is to resort to a computation of the worst phase configuration using Phidel® software, or continuously monitor over a long period the field from which statistical information is extracted.

CONCLUSIONS

The nomenclature related to the different line typologies has been made clear by defining the concept of DCL, and a measurement procedure set up starting from the simple case of the single circuit line, considering then that of a DCL, and finally taking in consideration a system of independent lines. In the cases where P and Q are not available, or when considering independent lines, it is evident how the aid of specific software computation can become fundamental. The alternative is to resort to a continuous area monitor station. The purpose of the present study is to point out how inappropriate it is to hazard statistic previsions on independent lines starting from a mere measurement of magnetic induction.

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