accuracy, of course, was far better than needed to generate 0.1 percent delays. The overall module accuracy was measured to be better than 1 percent of reading, ± 0.5 ns.

VI. Conclusion

The folded-ramp circuit is an example of a measurement module designed specifically for use in computer-controlled systems. The circuit allows single-range time measurements over a range greater than 10^9 to 1. Freezing the ramp, as opposed to sampling, has allowed the accuracy to be better than 1 percent of reading ± 0.5 ns. The circuit is preferable for computer control since the processor is not tied up in repeating measurements for the simulation of an autoranging module.

Glaser
#2445

Accuracy Limitation in Measurements of HF Field Intensities for Protection Against Radiation Hazards

HENRYK R. KUCIA

Abstract—The desired measurement accuracy; the relationships between field intensity, absorbed power, and hazards; and the usefulness of *E* and *H* field intensity measurements are discussed. Measurement accuracy versus the dimensions of the *E*-field antenna; measurement accuracy versus the capacitive coupling of the antenna with its surroundings; and measurement accuracy versus instrument calibration accuracy are all considered. A block diagram and the basic parameters of a universal measuring instrument now under development are included.

THE Polish Central Research Institute for Labor Protection has, for a couple of years, dealt with some technical and biophysical aspects of the protection of human beings against the energy of electric and magnetic fields within the frequency range of 0.1-300 MHz.

Special attention is paid to the accuracy evaluation of field intensity measurements in the Fresnel zone in the vicinity (decimeters, meters) of energy sources, and to a determination of a closer relation between electric field intensity and the electric energy absorbed inside the human body.

Desired Measurement Accuracy

The concern with accuracy evaluation is caused by the fact that results of measuring the same near-field intensities with the different measuring instruments [1],[2] we have used are in many cases incomparable, as differences among them exceed 100 percent. We wanted to explain the reasons for this situation, starting first with this question: "What accuracy of the measurement should be met from the point of view of medical protection against electromagnetic fields?" We have found that this question cannot be answered as there is no universally applicable relation between intensities of electromagnetic fields and the biological effects they may cause.

Manuscript received June 8, 1972; revised July 5, 1972.
The author is with the Central Research Institute for Labor Protection, Warsaw, Poland.

Relations Between Field Intensity, Absorbed Power, and Hazards

Biological effects depend rather upon the amount of electromagnetic field power dissipated in the human body which is not strictly related to field intensity. For example, for the same frequencies and intensities of electric fields below 100 MHz, the amount of power dissipated in the human body can take at least any values in an approximate range 1 : 4 due to the influence of an actual capacitive coupling of the human body to the HF source. For general orientation only, a simplified calculation of that effect was made in two cases with the following assumptions (see [3] for an analysis of the mechanism of local increase in the intensity of a hazardous HF electromagnetic field caused by the presence in it of a human being).

1) For frequencies below 100 MHz a human body absorbs electric field energy in the same manner as homogeneous muscle tissue with resistivity $\rho \cong \text{constant} \approx 1.2\ \Omega \cdot \text{m}$, permittivity $k' \cong \text{constant} \cong 100$, dissipation factor $\tan \delta \cong \text{constant} \approx 4$.

2) A quasistationary electric field of intensity E in volts per meter is parallel to the axis of a human body that can be considered as a solid cylinder 1.8 m long and 0.3 m in diameter.

3) The cylinder has an electric equivalent circuit in the form of series connections of a 0.33-μH inductance in series with a parallel network of resistance 30 Ω and capacitance 34 pF.

4) The cylinder is situated in a vertical position on a conductive grounded plane.

The cylinder is considered separately under the influence of two different types of electric field of the same intensity. In the first case, a source of the field is far away from the cylinder and there is not any practical capacitive coupling between the cylinder and the source. In the second case, the cylinder is situated inside a parallel plate capacitor and does have capacitive coupling with the upper plate.

For both cases, the same formulas were reached for the power absorbed in the solid cylinder as a function of frequency

$$P \approx \frac{P_0}{1 + \left(\frac{f_0}{f} Q_0\right)^2 \left(\frac{f^2}{f_0^2} - 1\right)}$$

where P_0, Q_0, and f_0 are the power, Q factor, and frequency at resonance of the circuit which includes the solid cylinder and its capacity to surrounding space. Calculations done with the aid of the preceding equation show that a human body seen as a solid cylinder has the first resonant frequency in the region of 60 MHz.

In both cases discussed, the Q factor of the circuit $Q_0 \cong 4$ and the resonant frequency $f_0 \cong 60$ MHz.

However, in the second case, values of Q_0 and f_0 are reduced about 10 percent, and P_0 is increased, but the relative power absorbed in the solid cylinder goes up 1.5–2.2 times at frequencies lower than the resonant ones. It is, undoubtedly, a significant variation. These results are shown in Fig. 1.

Therefore, knowledge of field intensity and frequency does not yet give unequivocal characteristics of the electric field as a harmful factor for human health. Protection against harmful electromagnetic fields requires then not as much striving for accurate field intensity measurement as for precise determination of the power which is dissipated in a human body and its time function.

As measurements of that power are not yet possible, measurements of electromagnetic field intensity, or derivative magnitudes, are to be used as substitutes. Obviously, these measurements should be done with a measuring technique whose measurement accuracy is unequivocally determined and adequate for actual measurements standards applied in science and technology. To get this measurement accuracy in the case of hazardous fields, properties of near-zone fields should be carefully studied.

USEFULNESS OF THE E AND H INTENSITY MEASUREMENTS

Results of the biological investigations lead to the conclusion [4] (which could probably be confirmed by, for example, measurements of a complex permittivity and permeability of the human tissues), that in order to produce comparable harmful effects to human health, the density of the magnetic field energy W_H should be about 10 000 times the density of the electric field energy W_E. Practically, it means that for fields in the radiation zone, and for so-called high-impedance fields, where $W_E = W_H$ or $W_E > W_H$, the harmful effect of the electric field dominates definitely over the magnetic field effects.

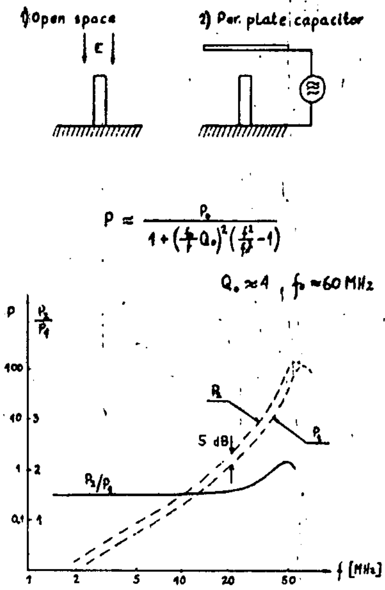

Fig. 1. The absorbed power as a function of frequency for a cylinder simulating a human body when exposed to 1) a distant source and 2) a field in a parallel-plate capacitor.

For this kind of field, measurement of electric field intensity is quite adequate. For so-called low-impedance fields with $W_H > W_E$, both measurements of electric and magnetic components of the field should be carried out. Considering the present applications of HF electric currents, the last-mentioned fields occur with inductive heating devices which operate usually at frequencies below 1 MHz. Seldom do these devices work at higher frequencies up to 10 MHz.

Concluding the above, measurements of electric field intensities at frequencies up to 300 MHz are of fundamental importance and should be made in the vicinity of any one field source, while the measurement of magnetic field intensities is less useful and is usually restricted to some sources of fields which operate at frequencies up to 1 MHz (10 MHz). Because of this fact, the remaining part of the paper is mostly devoted to electric field measurements.

MEASUREMENT ACCURACY VERSUS DIMENSIONS OF E-FIELD ANTENNA

On the basis of our own investigation carried out during the past few years concerning field patterns in the vicinity of various HF sources, it may be stated that electric fields, intensities of which are harmful to health, generally occur in the near zone which implies an inductive component, the vector of which is in a radial direction from the source.

To determine its value, usually it is sufficient to use a field intensity measuring instrument equipped with a directional antenna.

However, dipole antennas ought to be used since they have, in comparison with monopole antennas, much smaller sensitivity to capacitive coupling with surrounding objects.

The main factor limiting the length of a dipole is the nonuniformity of the electric field which exists in the immediate vicinity of field sources [2], [4], [5]. In this zone, the intensity of an electric field decreases approximately with the third power of the distance from an HF source. Therefore, to limit the error of measurement caused by the finite length of a dipole, the dipole should not exceed a value calculated according to the equation [2],[4]

$$2L \leqslant 2R_0\sqrt{1-\frac{1}{\sqrt{p+1}}}$$

where R_0 is the distance from the center of a dipole to the electric field source and p is the permissible measurement error caused by the finite length of a dipole. The formula sharply limits the dimensions of dipole antennas at distances less than 50 cm. For example, if there is a need to measure field intensity at distances $R_0 = 10$–50 cm with a permissible error $p = 0.05$ (5 percent), then the length of a dipole antenna should not exceed 3.16 cm.

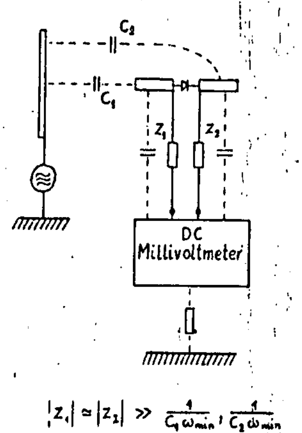

Fig. 2. Near-field capacitive coupling between a dipole antenna, its surroundings, and a source.

Measurement Accuracy Versus Capacitive Coupling Between the Antenna and Its Surroundings

Potentials of electric field which produce a capacitive current flow between the field source and the earth may exert an important influence upon a measuring instrument of near-zone fields, since the instrument may respond to the capacitive current in addition to the field intensity being measured [2],[4]-[6]. Currents of this type may flow in the following circuits of a dipole antenna: capacitance coupling of a dipole arm with the HF source, coupling between the dipole arms and the instrument housing, and coupling between the instrument and the earth (housing of the field source). The coupling paths are illustrated in Fig. 2.

To make negligible the influence of these currents on the indications of the instrument, they should not produce a voltage at the output terminals of the dipole which is comparable with the voltage produced at this terminal by the measured intensity of the electric field. Therefore, the capacitive currents I_1 and I_2 flowing through both arms of a dipole under the influence of the field potential should be small and if possible, equal to each other. As the capacitances C_1 and C_2, which couple the arms of a dipole with a source are usually not equal, equality of the currents I_1 and I_2 can be reached with a required accuracy by placing correspondingly high impedances Z_1 and Z_2 ($Z_1 = Z_2 = Z$) on current paths going from the arms of the dipole toward the housing of the instrument. Simultaneously, the following conditions should be satisfied:

$$|Z| \gg \frac{1}{C_1\omega_{\min}}, \frac{1}{C_2\omega_{\min}}.$$

It should be noted that impedances Z_1 and Z_2 may consist of resistances R_1 and $R_2 = R$ placed purposely in series with wires connecting the arms of a dipole and the input of the measuring circuit, and of stray capacitances appearing between the arms of a dipole and instrument housing or grounded objects surrounding the dipole. So, to maintain the proper balancing effect of resistors R_1 and R_2, values of the aforementioned capacitances should be reduced to a minimum, which may require removing the main body of the instrument away from the dipole a distance at least 20 times the dipole length. Also, the wires connecting the dipole with the measuring circuit should not be shielded.

With the properly chosen resistances R_1 and R_2 and sufficient distance between the dipole and the instrument housing, touching the housing by a person carrying out measurements should not have considerable influence upon the measurement results.

In order to limit the values of currents I_1 and I_2, the impedance between the housing of the instrument and the earth should be high. Therefore, the instrument housing should not be grounded and the instrument should have an internal power supply.

It is worth emphasizing that high values of the resistances R_1 and R_2 also limit variations of the instrument indications due to the differences in the potentials which may exist between the arms of a dipole and the housing of the instrument.

Obviously, a large distance between a dipole and the instrument housing also reduces the influence of the housing upon the field pattern in the dipole region.

Experimental investigation carried out in typical electric fields have proven that the presence of a person at a distance of approximately 1 m from the line connecting the field source with a measuring antenna does not produce a measuring error greater than 5 percent in the case of an instrument where a dipole antenna of 5-cm length was used and compensation had been made for the influence of external capacitive coupling [2],[7].

Measurement Accuracy Versus Instrument Calibration Accuracy

In many cases poor calibration accuracy can also be an important source of measurement errors, often exceeding 10 percent. There is need for low cost and accurate calibration test stands, ready to use during production and exploitation of the instruments. It is believed that this kind of stand will be developed.

For calibration of electric field intensity instruments in the frequency range up to 30 (50) MHz, a simple parallel plate capacitor fed by a generator of 5-W power output can be successfully used [2],[5],[8]-[11]. For higher frequencies, however, this method is not recommended because of calibra-

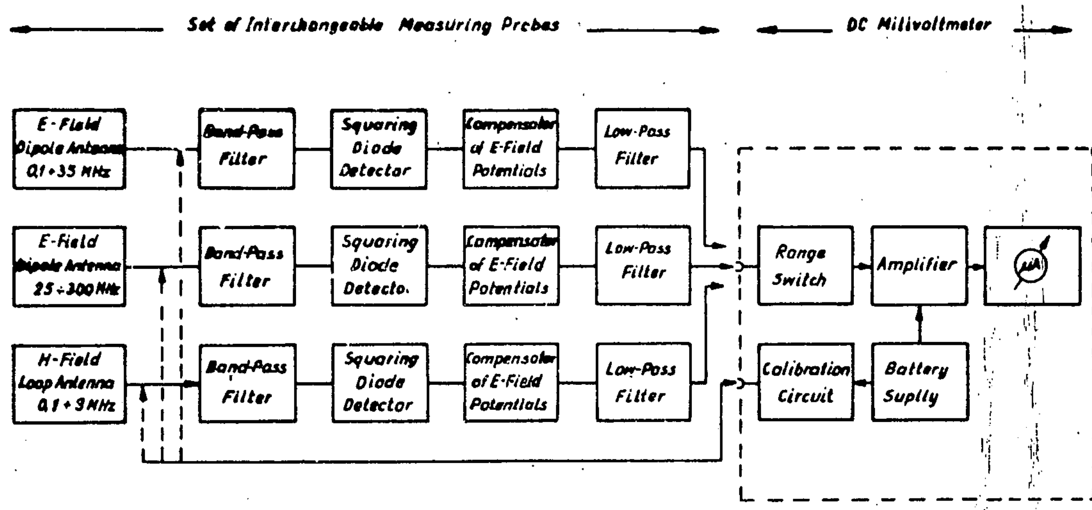

Fig. 3. Block-diagram of a portable instrument for measuring intensities of both electric and magnetic fields.

TABLE I
BASIC PARAMETERS OF THE MEASURING INSTRUMENT UNDER DEVELOPMENT

Parameter	Electric Field	Magnetic Field
Measuring range	0.5–2000 V/m	0.5–500 A/m
Frequency band	0.1–300 MHz	0.1–3 MHz
Maximum influence of an electric HF potential of 2000 V	20 V/m	0.5 A/m
Linear dimensions of the antenna	4 cm	5 cm
Antenna: instrument housing distance	2 m	2 m

tion errors caused by resonant phenomena of the test stands and standing waves which arise between plates and on the plates of the capacitor.

During instrument calibration some additional measurements should be made to evaluate the influence of other field factors which could change the instrument indications. For these purposes, unique test stands become a necessity, too.

It seems reasonable to list separately, in a technical description of the instrument, those errors which are proportional to the measured field intensities and those errors which do not obey this proportionality and are caused, for example, by the mentioned capacitive coupling of the antenna with surrounding objects.

The observed practice of stating an overall percentage accuracy of the measuring instrument without giving a description of measuring conditions leads to confusion during measurements of field intensity.

Calculations of the measuring accuracy of the noxious fields, according to general principles of safety, should be so carried out as to ensure only positive errors in the measurements.

BLOCK DIAGRAM AND BASIC PARAMETERS OF A UNIVERSAL MEASURING INSTRUMENT UNDER DEVELOPMENT

It is believed that the aforementioned factors are the fundamental ones to be considered when dealing with accuracy of electric field intensity measurements. Similar factors also limit the accuracy of magnetic field intensity measurements. The above factors have been examined [5]-[12], and we have made appropriate preparations to develop a portable instrument that can measure the intensities of both electric and magnetic fields.

A block diagram and basic parameters of the instrument are shown in Fig. 3 and in Table I.

REFERENCES

[1] H. R. Kucia, "Problem of improving the working conditions in electromagnetic fields," *Wiadomości CIOP* (*CIOP News*), nos. 10–12, 1967.

[2] H. R. Kucia and A. Koperski, "Problems in the measurement of hazardous electromagnetic fields" (in Polish), *Prace Central. Res. Inst. Labor Protection*, vol. 20, no. 67, 1970.

[3] H. R. Kucia, "Summary of theoretical and experimental research, pt. I," unpublished.

[4] —, "Proposed laboratory setup for measuring industrial HF electromagnetic fields," Cen. Res. Inst. Labor Protection, Warsaw, Poland, unpublished project 43-ZEL, 1965.

[5] V. A. Franke, "Measuring the electric and the magnetic component of 0.1–30 MHz HF field in the induction region and development of an instrument for this purpose," in *Trudy Laboratorii Elektrobezopasnosti LIOT.* Leningrad, USSR: LIOT, 1958, pp. 14–47.

[6] —, "A pickup head for the IEMP-LIOT instrument to measure electric field intensities in the frequency range 20–300 MHz," in *Sbornik Rabot Laboratorii Elektrobezopasnosti LIOT.* Leningrad, USSR: LIOT, 1963, pp. 111–114.

[7] H. R. Kucia and A. Koperski, "Summary of theoretical and experimental research, pt. II," Cen. Res. Inst. Labor Protection, Warsaw, Poland, 60–2FD, 1969.

[8] V. S. Buzinov, "Standard test stand for checking and calibrating small dipole antennas," *Izmer. Tekh.* (*Meas. Eng.*), no. 6, pp. 50–53, 1967.

[9] V. S. Buzinov, B. Ye. Kinber, and V. B. Ceytlin, "Calibration of small dipole antennas in the field of parallel-plate capacitor," *Trudy Institutov Komiteta Standartov Mer i Izmerital'nykh Priborov pri Soviete Ministrov ZSRR*, (Izd. Standartov) (Trans. Inst., Committee of Measures and Measuring Instrum., Ministerial Council of the USSR, Standards Publ.), 81 (141), pp. 49–53, 1966.

[10] H. R. Kucia, "Summary of theoretical and experimental research–pt. III: Calibration of small dipole antennas used in measurements of HF fields," Cen. Res. Inst. Labor Protection, Warsaw, Poland, unpublished project 60–ZFD.

[11] —, "Accuracy of calibrating short dipoles in a capacitor field," *Przeg. Telekomun.* (*Telecommun. Rev.*), no. 1, 1970.

[12] H. R. Kucia, A. Koperski, and A. Maslag, "Universal HF electromagnetic hazardous fields meter–pt. 1: Basic electrical and mechanical parameters," Cen. Res. Inst. Labor Protection, Warsaw, Poland, unpublished project BF-101-112, 1971.