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Technical Report No. 8
IITRI Project E6357
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VOICE TELEPHONE INTERFERENCE DUE TO SEAFARER GENERATED HARMONICS

Prepared for

U. S. Naval Electronic Systems Command
Washington, D. C.

Prepared by

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FOREWORD

This report was prepared for the Special Communications Project Office of the U. S. Naval Electronic Systems Command by IIT Research Institute, as part of Contract N00039-76-C-0141.

The technical effort reported herein is intended to support development of the Navy's Seafarer ELF Submarine Command and Control Communications System. It provides an analysis and recommended limits for interference to voice telephone communications produced by Seafarer generated harmonic energy which may be present on the antenna and supply power mains. The work was carried out at the direction of Dr. B. Kruger (PME 117-21) and Lt. Cdr. W. Phillips (PME 117-214).

Respectfully submitted,

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(See 1473)

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1. PURPOSE

The purpose of this report is to present an analysis which was performed to specify limits on the interference which may be present in Seafarer transmitter conductors. The study is based on consideration of the maximum permissible interference noise which may be present in voice telephone circuits. Interference limits are specified for both the Seafarer antenna lines and for the 60 Hz service mains which supply power to the transmitter. Methods of measuring these quantities are also discussed.

2. SCOPE

This report initially discusses the usefulness and applicability of a telephone company concept for specifying the potential interference effect on a telephone receiver as a result of current flowing in a nearby conductor. The concept is called "I·TIF", the product of the rms interference current (I) and the "telephone influence factor (TIF)".[1]

Interference to voiceband service is considered. This includes voice communications and voiceband data transmission. Carrier communications and wideband data transmission are not considered here.

Limits for the maximum permissible value of the I·TIF product are specified for (1) the Seafarer antenna cables and (2) the 60 Hz mains supplying power to the transmitter. Methods for measuring the I·TIF product are also given.

3. BACKGROUND

Radio transmitter spurious output limits have usually been specified in terms of minimum suppression of individual components relative to the primary (desired) spectral output. For example, third harmonic must be X dB below fundamental; 5th harmonic, Y dB below fundamental; etc. Thus, each individual transmitter emanation which can possibly cause interference is identified, and a radiation limit is placed on each.

Based on years of inductive coordination work in solving interference problems caused by various forms of interference from the electric power utilities, the telephone companies have developed an alternative method of specifying the interference quality of a waveform. The "Telephone Influence Factor" or TIF is used as a single rating factor for expressing the capability of a current or voltage waveform to cause objectionable interference to the combination of a telephone receiver and listener.

In situations where interference is likely to be coupled to the telephone line predominantly by magnetic coupling, the product of the rms current in the interfering circuit and the TIF of that current is used, i.e., I·TIF, designated I·T. In other situations where capacitive coupling, or "electric coupling" is dominant, the product of the rms voltage of the interfering waveform and the TIF is used, i.e., V·TIF, or kV·TIF, designated kV·T. Thus, a single number (the product I·T or kV·T) expresses the interference capability of the potentially interfering circuit. There is no need for specifying levels of harmonic or other spurious outputs, or even specifying which particular interfering frequencies are present.

For the case of possible interference from Seafarer to telephone systems, coupling is magnetic and, therefore, the I·T product is the appropriate quantity to specify as an interference rating factor for Seafarer currents. The maximum permissible value for the I·T product depends on the strength of the coupling between the Seafarer circuit and the telephone circuit, and also on certain susceptibility parameters of the telephone circuit. Thus, by knowing these telephone circuit parameters and the maximum expected (worst case) coupling between the Seafarer circuit and the telephone circuit, the maximum permissible value of the I·T product not causing objectionable interference can be specified.

This maximum permissible I·T product specified for the transmitter output current assures that the current in a Seafarer antenna cable will not cause objectionable interference to a telephone circuit. Similarly, a maximum I·T product specified for the 60 Hz power mains supplying the Seafarer transmitter assures that the power line current will not cause objectionable interference to a telephone circuit. In each case, the maximum permissible I·T product must be based on the maximum anticipated exposure between the telephone line and the potentially interfering Seafarer transmitter line. The exposure depends on the lengths of telephone line and Seafarer line, the angle between the lines, and their spacing from each other.

For antenna lines which must share the right-of-way (ROW) with telephone lines, the spacing may be only a few meters at most, and the exposure length may be many miles. The 60 Hz supply lines to the transmitter could also share a ROW with a telephone line. This worst-case situation of shared ROW will determine the I·T limits.

4. LIMITS

Since telephone lines sharing a right-of-way with Seafarer lines may be used for any of several types of transmission services, the Seafarer interference specification must be based on the most critical requirements of these services.

Interference to the following two types of telephone transmission service is considered here.

(1) Voice frequency communications

(2) Voiceband data transmission.

Carrier communications and wideband data transmission are not treated in this report.

4.1 Interference Limit for Voice Frequency Communications

The I·T limit is derived by means of the following steps.

(1) Establish a limit for the maximum permissible telephone metallic-circuit noise contribution from Seafarer interference.

(2) By use of the Balance Ratio, determine the maximum allowable longitudinal voltage along the telephone wire pair for the permissible metallic-circuit noise.

(3) Using the fact that the longitudinal voltage on the telephone cable sheath is approximately equal to the longitudinal voltage on a wire pair, establish a limit for the maximum permissible longitudinal sheath voltage.

(4) Express the longitudinal sheath voltage as the product of the sheath current and the sheath resistance.

(5) Derive an expression for the sheath current including the effect of using neutralizing transformers for interference mitigation.

The telephone company objective[2] for metallic-circuit noise at the subscriber is 20 dBrnC.* Allotting one-half of this maximum permissible telephone circuit noise to Seafarer interference, the maximum permissible

*20 dBrnC means 20 dB above reference noise, measured with a C-message-weighting network. Reference noise is -90 dBm at 1000 Hz.

Seafarer interference is 17 dBrnC. At a frequency of 1000 Hz, this would correspond to $0.5(10)^{-10}$ watt. Therefore, for a single interference tone at 1000 Hz, this power would be produced in the 600 ohm resistive telephone termination by a transverse voltage (between the two wires of the pair) given by:

$$V_{t_{1000}} = \sqrt{0.5(10)^{-10}600} = 1.73(10)^{-4} \text{ volts.} \qquad (1)$$

The telephone receiver and listener are most responsive to a frequency of 1000 Hz. However, let us now consider single tone interference at an arbitrary frequency, f. A factor p_f, called the C-message weighting factor,[1] is used for expressing the response of the telephone receiver and listener, at any frequency f, relative to the response at 1000 Hz. The weighting factor is shown graphically in Figure 1. As may be seen, $p_f = 1$ at 1000 Hz, and $p_f < 1$ at other frequencies. Consequently, for telephone circuit noise at any frequency f, the maximum permissible transferse voltage across the circuit pair is

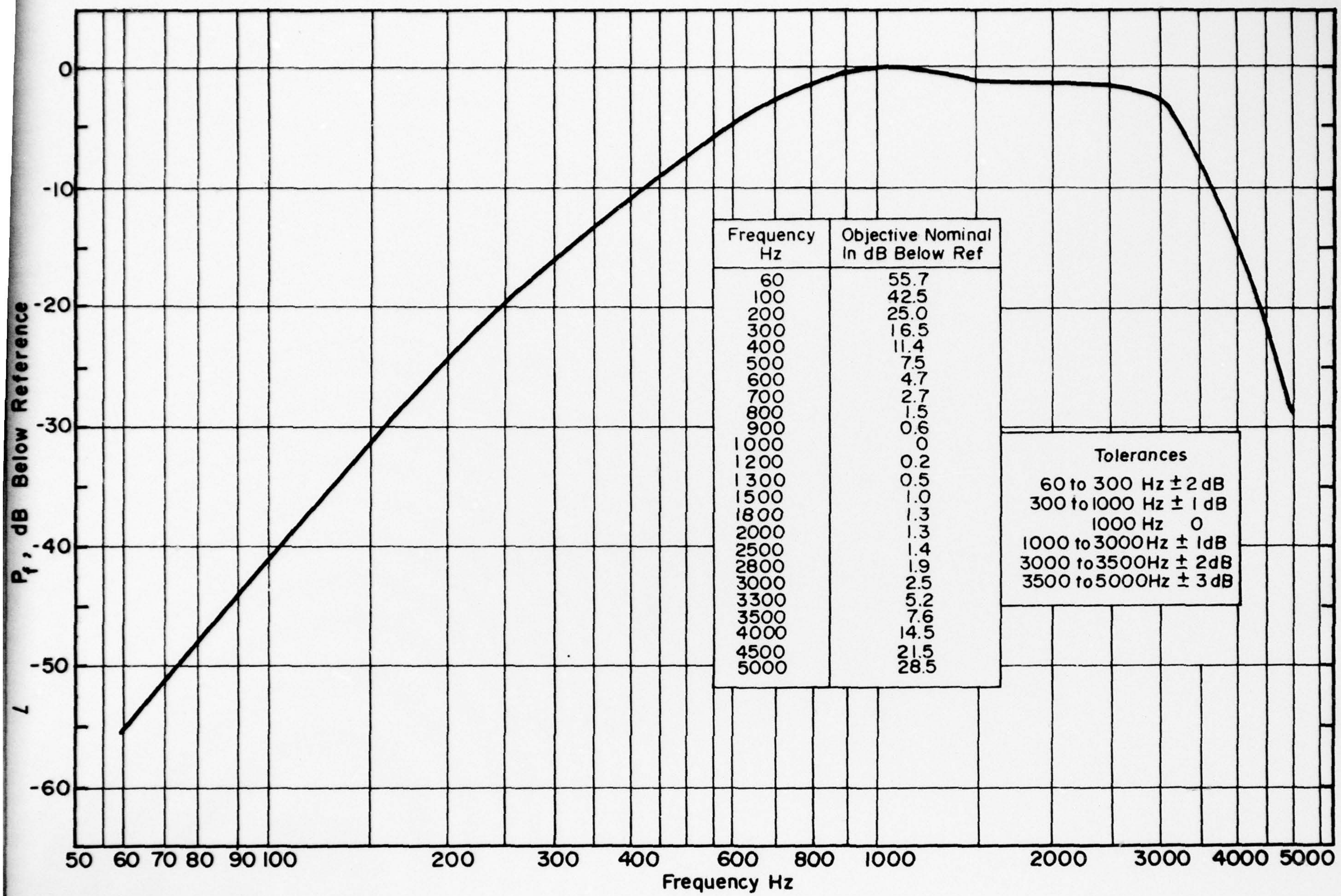
$$V_{t_f} = \frac{1.73(10)^{-4}}{p_f}. \qquad (2)$$

This transverse, or differential, voltage across the circuit pair is due to slight circuit unbalances between the two wires of the pair. A longitudinal or common mode voltage induced along the pair thus produces a small transverse voltage between the two wires. The ratio of longitudinal voltage to transverse voltage is called the Balance Ratio for the wire pair

$$B = \frac{V_{\ell w_f}}{V_{t_f}}. \qquad (3)$$

For modern telephone cable plant, the Balance Ratio is approximately 60 dB at audio frequencies.[2] Therefore

$$V_{\ell w_f} = 1000\ V_{t_f} \qquad (4)$$



Frequency Hz	Objective Nominal In dB Below Ref
60	55.7
100	42.5
200	25.0
300	16.5
400	11.4
500	7.5
600	4.7
700	2.7
800	1.5
900	0.6
1000	0
1200	0.2
1300	0.5
1500	1.0
1800	1.3
2000	1.3
2500	1.4
2800	1.9
3000	2.5
3300	5.2
3500	7.6
4000	14.5
4500	21.5
5000	28.5

P_f = C-Message Weighting Characteristic

Fig. 1 C-MESSAGE WEIGHTING CURVE (FROM REF. 4)

Consequently, at any frequency f, the maximum permissible longitudinal voltage along the length of the wire pair is

$$V_{\ell w_f} = \frac{0.173}{p_f} \qquad (5)$$

It will be assumed that the wire pair is in an aluminum sheath eight mils thick. At voice frequencies (i.e., up to 4 kHz), the 0.008 in. aluminum itself gives no effective shielding to the wire pairs within the cable--the electromagnetic fields inside the sheath are the same as those outside the sheath. Therefore, the longitudinal voltages on the wire pair and on the sheath are equal

$$V_{\ell s_f} = V_{\ell w_f}. \qquad (6)$$

Therefore, the maximum permissible longitudinal voltage along the sheath is

$$V_{\ell s_{f(max)}} = \frac{0.173}{p_f}. \qquad (7)$$

The longitudinal voltage along the sheath, at any frequency f, is equal to the product of I_{s_f}, the current at frequency f flowing along the sheath, and R_s, the total sheath resistance

$$V_{\ell s_f} = I_{sf} R_s, \text{ or}$$

$$V_{\ell s_f} = I_{sf} r_s L \qquad (8)$$

where r_s = sheath resistance per mile

L = sheath length, in miles.

The interference to the telephone cable is assumed to be mitigated with neutralizing transformers, with the cable sheath connected in series with the transformer primaries. Therefore, the sheath current will be approximately equal to the transformer magnetizing current.

Because of the personnel safety limit of 50 V maximum cable-to-ground voltage, one neutralizing transformer must be installed for every 100 volts of accumulated induced voltage on the cable (for the Seafarer fundamental frequency of 76 Hz). Therefore, at 76 Hz, approximately 100 V will be across each transformer primary. From laboratory measurements on neutralizing transformers, the magnetizing impedance is approximately 2000 ohms at 76 Hz, and with 100 V (at 76 Hz) across the primary, the magnetizing current is

$$I_{s_{76}} = \frac{100\ \text{V}}{2000\ \text{ohms}} = 50\ \text{ma.}$$

For right-of-way sharing of the Seafarer antenna and the telephone cable, with a minimum separation of 2 meters between antenna and telephone cable, the electric field (at 76 Hz) along the telephone cable will be

$$E_{76} = 100\ \text{V/mi}$$

when the fundamental antenna current is 100 amperes, i.e.,

$$I_{a_{76}} = 100\ \text{A.}$$

This implies the requirement for one neutralizing transformer per mile of shared ROW. Further, since one circuit with a current of 100 amperes induces a voltage of 100 volts/mile in a second circuit, the mutual impedance between the two circuits is one ohm per mile at 76 Hz:

$$Z_{m_{76}} = \frac{E_{76}}{I_{a_{76}}} = \frac{100}{100} = 1\ \text{ohm/mile.}$$

Next, consider a component of antenna current I_{a_f} at any arbitrary frequency f. Let

Z_{m_f} = mutual impedance (per mile) between antenna and ground return sheath circuit at frequency f, and

I_{s_f} = sheath current at frequency f.

The sheath current will be equal to the total voltage driving the sheath, divided by the total impedance in the sheath circuit:

$$I_{s_f} = \frac{I_{a_f} Z_{m_f} L}{2000\ \text{ohms}\ L}, \qquad (9)$$

where the sheath circuit is considered to have L neutralizing transformers spaced one mile apart over a distance of L miles.

As mentioned previously, the mutual impedance between antenna and sheath at 76 Hz is one ohm/mile for the 2 meter spacing. Since magnetic coupling of two earth return circuits is nearly proportional to frequency,

$$Z_{m_f} = 1 \text{ ohm/mi} \times \frac{f}{76} \text{ for any arbitrary frequency } f.$$

Therefore, the sheath current at any frequency is

$$I_{s_f} = \frac{I_{a_f}}{2000} \times \frac{f}{76}, \tag{10}$$

showing that for a given magnitude of antenna current component at frequency f, i.e., I_{a_f}, the sheath current component at frequency f is proportional to f. This result is partially a consequence of the assumption of a constant transformer impedance of 2000 ohms, even at higher frequencies. The impedance may increase almost proportionally with frequency over some range of frequency. However, no data have been obtained to validate this concept. Therefore, we have assumed a constant transformer impedance which will cause the calculated value of I_{s_f} to be higher than it would for a frequency proportional impedance, and our result will turn out to be somewhat conservative.

Inserting the last expression for I_{s_f} into the Equation (8) for longitudinal sheath voltage:

$$V_{\ell s_f} = I_{s_f} r_s L = \frac{I_{a_f}}{2000} \times \frac{f}{76} r_s L \tag{11}$$

But $V_{\ell s_f}$ must not exceed $V_{\ell s_{f\,(max)}}$. Therefore, from Equations 11 and 7

$$\frac{I_{a_f} f r_s L}{(2000)(76)} \leq \frac{0.173}{p_f} \tag{12}$$

Multiplying both sides of the inequality by 5 and rearranging terms:

$$I_{a_f} \, 5 \, f \, p_f \leq \frac{1.31(10)^5}{r_s \, L} \, . \qquad (13)$$

But 5 f p_f is the TIF weighting factor,[1] T_f. Therefore, Equation 13 can be written

$$I_{a_f} \, T_f \leq \frac{1.31(10)^5}{r_s \, L} \qquad (14)$$

To this point we have been considering interference at a single frequency f. If the antenna current has components at various frequencies, the I·T product for the composite antenna current is defined[1] as the root-sum-square of the single frequency contributions:

$$I_a \, T = \sqrt{\sum_{i=1}^{N} \left(I_{a_{f_i}} \, T_{f_i} \right)^2} \qquad (15)$$

where the sum includes all significant components. The term I_a is the total *rms* antenna current, and T is the TIF for the composite current waveform. Therefore, the interference limitation on the composite antenna current becomes

$$I_a \, T \leq \frac{1.31(10)^5}{r_s \, L} \, . \qquad (16)$$

For a small telephone cable, e.g., 12 pair, the sheath resistance r_s is estimated as 8 ohms/mile. Assuming a maximum exposure distance of 15 miles for the telephone cable in a shared right-of-way with a Seafarer antenna element:

$$I_a \, T \leq 1090 \text{ amperes.} \qquad (17)$$

A similar analysis may be performed for the Seafarer primary power feed lines, with the residual current I_r substituted for I_a in Equations 9-17. The residual current used in these calculations is the phasor sum of all of the 60 Hz conductor currents serving the transmitter.

In summary, Seafarer noise interference to voice telephone circuits can be avoided for both the antenna current I_a and the 60 Hz residual supply current, I_r, if:

$$I \cdot T = \left[\sum_f (I_f \cdot T_f)^2 \right]^{1/2} \leq 1090 \text{ amperes} \qquad (18)$$

where

I_f = interference source current at frequency f.

T_f = 5 p_f f = telephone influence factor at frequency f

p_f = C-message weighting function (shown in Figure 1).

f = frequency in Hz.

As an example, consider a conductor carrying the following currents:

f (Hz)	I(amp)
76	100
228	10
380	0.6

The I·T product is then

$$I \cdot T = \left\{ \left[(100)(5)(0.0033)(76) \right]^2 + \left[(10)(5)(0.0794)(228) \right]^2 + \left[(0.6)(5)(0.251)(380) \right]^2 \right\}^{1/2}$$

$$= \sqrt{(125)^2 + (905)^2 + (286)^2}$$

$$= 957 \text{ amperes.}$$

In this case it is apparent that the largest contribution to the I·T product is from the third harmonic, and the least from the fundamental.

4.2 Voiceband Data Transmission

For standard design voiceband data channels, the maximum noise at the modem receiver is specified[3] as 28 dBrnC for a short transmission distance (0 to 50 miles), with higher levels permitted for longer distances.

If the interference is of the form of a single tone, it must, when measured with C-message weighting at the modem receiver, be at least

3 dB below the specified C-message noise power limit, or 25 dBrnC for short distances.

Therefore, based on these interference limits for voiceband data transmission, use of the 17 dBrnC limit established for voice transmission will be slightly conservative for voiceband data transmission and, therefore, satisfactory. Thus, the I·T limit of 1090 amperes previously derived based on 17 dBrnC noise should be suitable for voiceband data as well as for voice.

5. MEASUREMENT PROCEDURES

Test equipment and procedures are available for determining directly the I·T product for a circuit without ascertaining the spectral distribution of power carried by the circuit. As shown in Figure 2, the following test equipment is required for measuring the I·T product for current carried in a conductor: (1) a current transformer, (2) a current coupler, and (3) a Noise Measuring Set (NMS). The Current Transformer is a device for coupling to the measurement equipment a sample replica of the current in the conductor. The Current Coupler, such as shown in Figure 3, serves to convert the input current components into voltage components, with the conversion factor proportional to frequency. This frequency-proportional conversion simulates the nearly frequency proportional coupling which occurs between two earth return circuits which are magnetically coupled. The Noise Measuring Set (NMS) has a frequency-weighting network with "C-Message Weighting" to simulate the frequency response of a telephone receiver and listener (see Figure 1). The output of the NMS is a reading in dB which can be converted directly into the I·T product by use of a *conversion curve, as given in Figure 4.*

The Current Transformer in Figure 2 can be a conventional two-winding transformer with the primary inserted in series with the conductor, and the secondary connected to the current coupler. Standard TIF current couplers utilize a 0.4 mh inductor with a 5 ampere maximum current, so a suitable step-down ratio must be used for large currents.

Alternately, the Current Transformer may take the form of a clamp-on current probe. Such devices exist with associated inductive shunts for direct use with a noise measuring set to provide a measurement of the I·T product.

Equipment for measuring the I·T product is commercially available from a number of manufacturers, including:

- Wilcom Products, Inc.
- Hewlett Packard Co.
- Western Electric Co.

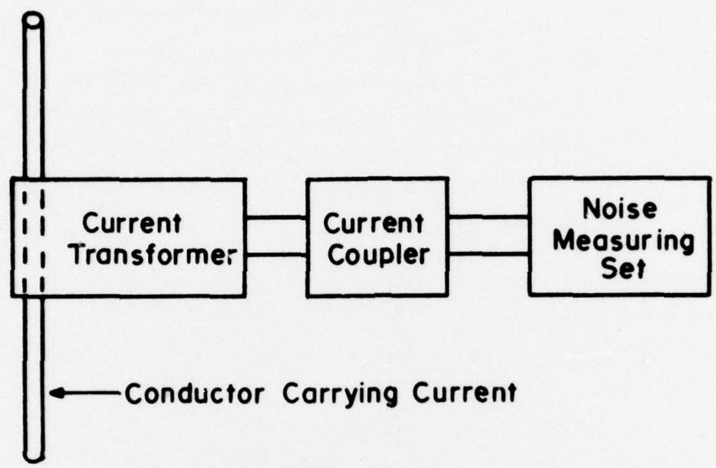


Fig. 2 BASIC TEST CONFIGURATION FOR MEASURING I·T PRODUCT

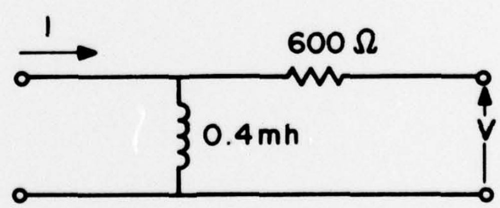


Fig. 3 BASIC TIF CURRENT COUPLER

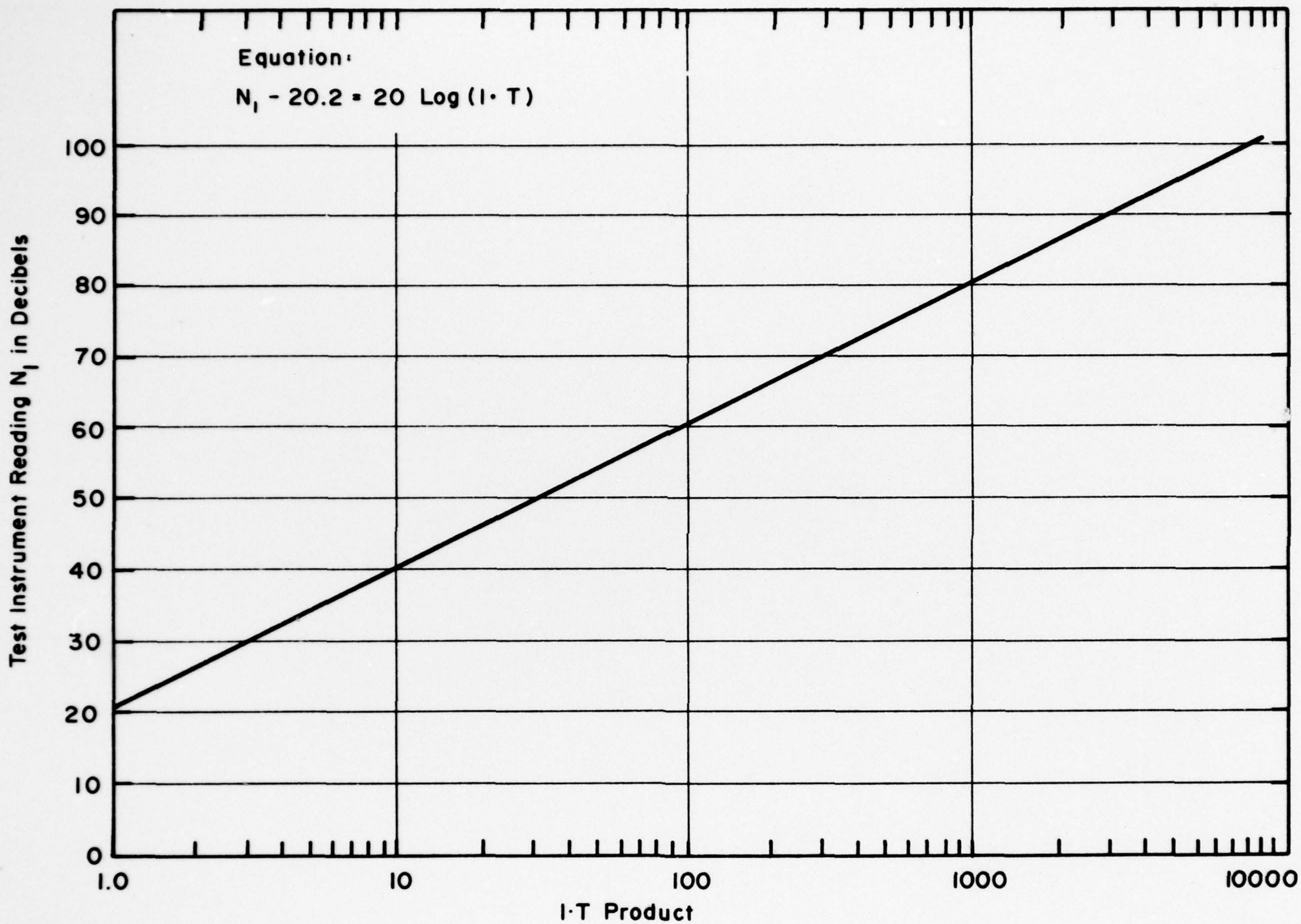


Fig. 4 RELATION BETWEEN NOISE MEASURING SET READING WITH 600 OHM INPUT, C-MESSAGE WEIGHTED, AND I·T ON CT SECONDARY (CURRENT COUPLER INPUT) - FROM REF. 4

5.1 Measurement of I·T Product for Antenna Currents

It is recommended that the I·T product for antenna currents be measured with a clamp-on current probe and standard noise measuring set with C-message weighting as outlined above. The measurement should be performed with various antenna currents, ranging from the minimum to the maximum available current. The measurements should be made directly at the transmitter output and should be performed with operational antenna cable configurations, including antenna tuning capacitors. Measurements should be taken with the transmitter in each of three conditions: (1) unkeyed at 72 Hz, (2) unkeyed at 80 Hz, and (3) keyed between 72 Hz and 80 Hz at the expected operational chip rate of 16 Hz.

5.2 Measurement of I·T Product for 60 Hz Power Mains

The predominant interference from the 3-phase 60 Hz lines supplying power to the transmitter is expected to be the residual current,* i.e., the phasor sum of the conductor currents. A current equal to the residual current returns to the source through a path other than the conductors; e.g., through the earth.

For low voltage power systems, the I·T product can be measured by using several current transformers, inserting one into each of the conductors (3 for delta, 4 for wye) and paralleling the transformer secondaries, thus obtaining the phasor sum of all conductor currents. The sum is then applied to the Current Coupler and the Noise Measuring Set to yield a dB reading which is converted to the I·T product by means of the conversion curve (Figure 4).

The I·T product should be measured for all combinations of the following conditions:

a) Transmitter operating at various levels of output ranging from the minimum to the maximum available current

Unkeyed at 72 Hz
Unkeyed at 80 Hz
Keyed between 72-80 Hz at the expected operational chip rate of 16 Hz.

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*An exception is the case of extremely close, unsymmetrical spacing of telephone and power lines.

b) Input 60 Hz voltage varied over the expected limits in order to determine the I·T product over the widest possible range of operation of transformers, rectifiers, and regulators.

For high voltage power systems, it will not be possible to insert current transformers into the power lines or to clamp current probes onto the lines. In this case, the I·T product of the power line residual current can be measured using a test coil and a noise measuring set with C-message weighting.

For illustrative purposes, Figure 5 shows a 3-phase, 3-wire power line. The residual current I_r is equal to the phasor sum of the currents in the three lines. Any earth return current is assumed to return to the power station via a path deep within the earth.

A flat test coil is oriented vertically within a vertical plane passing through the power line conductors. (The spacing between the conductors is assumed small compared with the height of the conductors.) The coil will be coupled to the magnetic field due to I_r flowing in the conductors, but not coupled to the field caused by I_r flowing in the earth since the earth return current flows deep within the earth and is far from the coil.

The I·T product for the current I_r is determined from measurements performed with a noise measuring set connected to the coil, and by use of an adjustment factor dependent on the height of the power line above the coil.

In general, it would be desirable to make I·T measurements on supply power mains at the point of connection to the Seafarer transmitter. It should be recognized, however, that the residual current is not always constant along the power line, and to assure conformance with the interference specification, additional I·T measurements should be performed at the point where residual current is maximum on the mains.

Since use of a test coil to make measurements on high voltage lines assumes that the coil is coupled to the current in the conductors and not to the return current flowing in the earth, this type of measurement should be performed at some distance from the transmitter (where the return current enters the earth), and away from supporting metal towers, poles, or other magnetic objects.

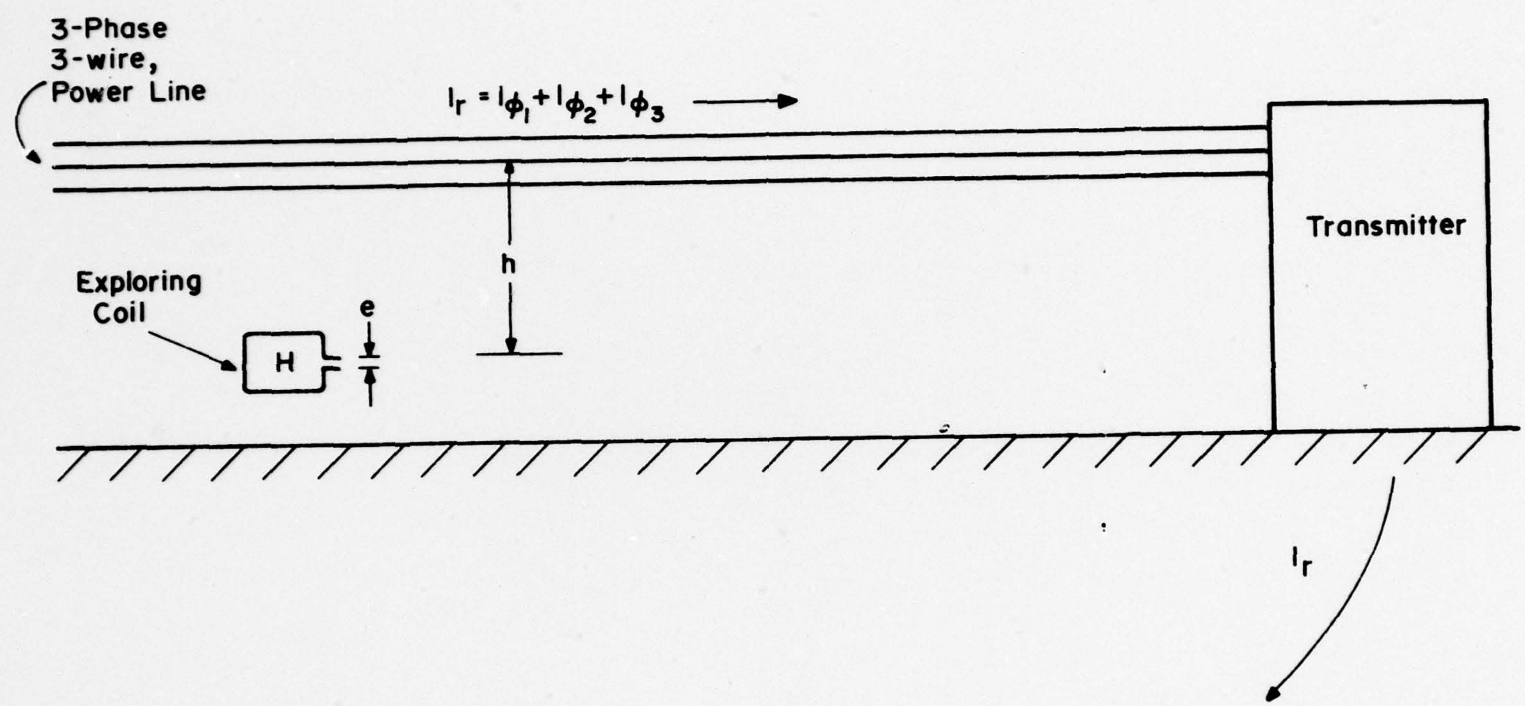

Fig.5 USE OF EXPLORING COIL TO MEASURE I·T OF THE RESIDUAL CURRENT ON A HIGH-VOLTAGE POWER LINE

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The report presents an analysis of telephone noise interference which may be induced by Seafarer transmitter currents. Maximum interference limits are suggested for the Seafarer System, and methods of measuring the effect are discussed

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