A Wide-Band Rotating Coupler for VHF Use

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***Abstract*—A device which transmits wide-band signals in the VHF range across a rotating structure is described. It has potential application to rotating antenna systems and to telemetry systems between stationary and rotating elements.**

No electrical contact is necessary between the stationary and rotating terminals, and bandwidths on the order of 1000:1 are feasible. From the theoretical analysis given here, predicted device behavior agrees well with measurements on a prototype model.

INTRODUCTION

Rotating joints or wrap-around cables, which are often necessary for the transfer of RF energy across rotating structures, are inherently subject to noise, wear, and fatigue. Conventional rotary joints consist of some form of rotating coaxial transmission line or slip-ring configuration. Contact wear or material fatigue caused by device usage introduces noise and discontinuities into an RF system. In the case of wrap-around cables continuous rotation is not possible and cable flexure eventually leads to material failure. Such problems can be reduced if the mechanical connection between the stator and rotor parts of the joint is eliminated.

A wide-band transformer has been investigated by Ruthroff [1] and more recently by Pitzalis *et al.* [2], [3]. This transformer consists of a two-wire transmission line wound upon a ferrite core. The device works well at low frequencies due to the high permeability available with ferrite materials. At higher frequencies the permeability of the core decreases, and conventional transformer action becomes less effective. Nevertheless, the two windings are coupled as a transmission line, and the device still behaves as a transformer.

An extension of the static Ruthroff transformer is to be considered for application as a rotary joint. This device has transformer coupling between a rotating secondary (rotor) winding and a stationary primary (stator) winding. The two windings are arranged so that they form a two-wire transmission-line circuit for high-frequency coupling. A ferrite pot core provides low-frequency coupling. It is the purpose of this short paper to detail the theory and construction of this type of rotating joint. Balanced-current transmission-line theory will be applied to obtain a theoretical analysis.

ROTARY TRANSFORMER CONSTRUCTION AND ANALYSIS

A rotating transformer could be made by putting two separate windings on the center leg of a ferrite pot core, but interwinding capacitance effects would limit the bandwidth severely. Wide-band performance is attainable by use of a bifilar (transmission-line) winding, but then rotation of the secondary with respect to the primary is not possible. To obtain wide-band performance, the transmission-line feature must be preserved while allowing the secondary to rotate with respect to the primary, as illustrated in Figs. 1–4. The primary winding consists of a set of parallel rings connected in series, as shown in Fig. 2. The secondary winding turns are coplanar and concentric with the primary turns, and are also connected in series—thus each turn of the windings forms a parallel-wire transmission line, as shown in Fig. 3(a).

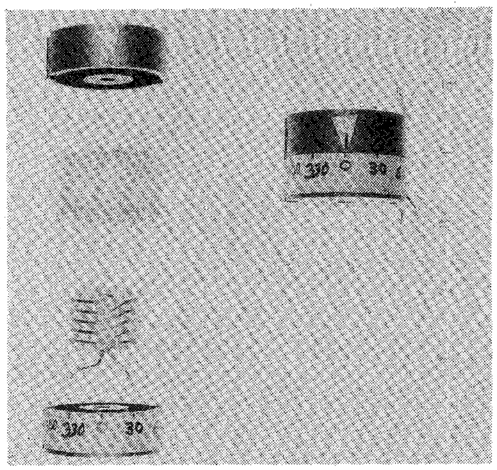

Fig. 1. Photograph of the rotating coupler.

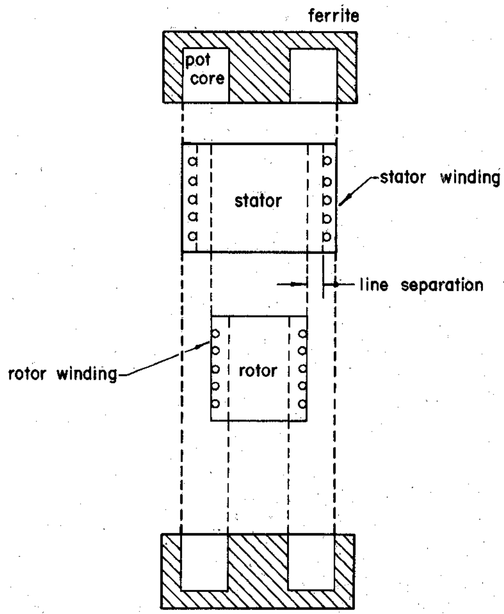

Fig. 2. Sectional view of rotary transformer construction.

To achieve the necessary dimensional stability (particularly the spacing between wires), the windings are mounted in a low-loss dielectric medium such as Nylon or plastic. The characteristic impedance of the line thus formed is a function of the separation of the primary and secondary turns, and of the dielectric constant of the plastic. The characteristic impedance (Z_o) can be approximated [4] by the expression

$$Z_o = \frac{120}{\sqrt{\varepsilon_r}} \cosh^{-1} \frac{D}{d}$$

where

- ε_r relative dielectric permittivity;
- D center-to-center wire separation;
- d wire diameter.

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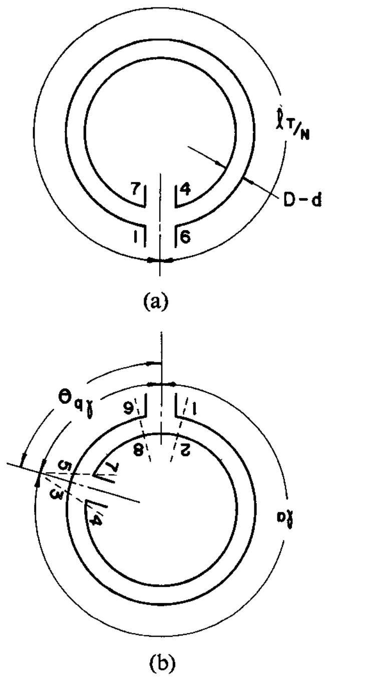

Fig. 3. A single turn of the rotary transformer. (a) No rotation. (b) Rotation through $\theta°$. In the notation of Fig. 4: $V_{1-6} = V_{1-2} + V_{8-6} = V_1 - V_3$ and $V_{7-4} = V_{7-5} + V_{3-4} = V_2 - V_4$.

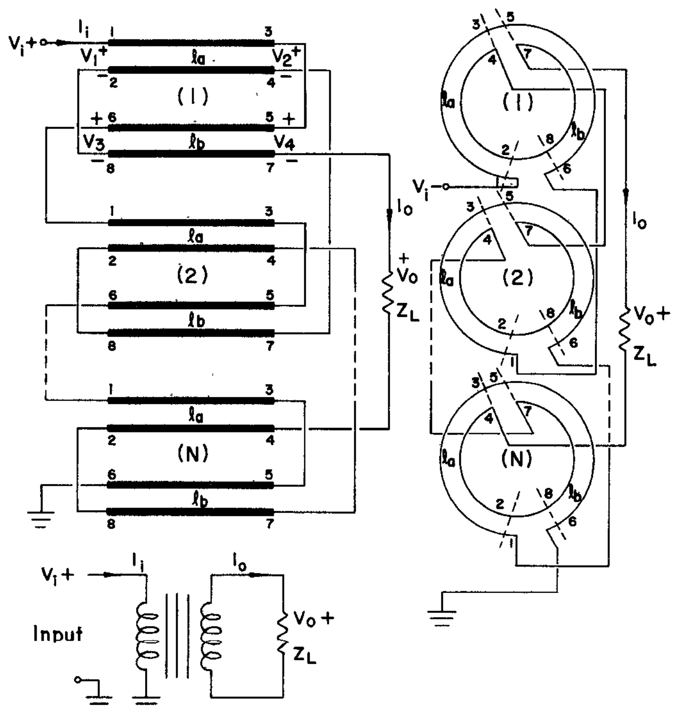

Fig. 4. Illustration of the electrical network formed by an N-turn rotary transformer during rotation.

A ferrite pot core encloses the winding arrangement in order to maintain a tight magnetic coupling at low frequencies. Notice also (see Fig. 1) how the connection leads are attached to the rotor and stator. These leads are fixed to the tops of each coil, hence a short piece of wire must pass longitudinally behind each winding in order to attach to the bottom end of the coil. This configuration was found necessary in order to allow free rotation of the pot core halves.

The analysis of the rotary joint is essentially the same as that for a static wide-band transformer except during rotation. When the transformer is rotated, two transmission-line sections of variable lengths l_a and l_b are formed by each turn (see Fig. 3) because the terminals 7–4 of the rotor turn are no longer coincident with terminals 1–6 of the stator turn. The two transmission lines formed during rotation are interconnected to those formed by other turns, and the interconnection schematic is depicted by Fig. 4. The total line length l_T for an N-turn transformer then is

$$l_T = N(l_a + l_b). \tag{1}$$

If all connecting leads other than those of the transmission lines are short compared with the excitation wavelength, and if the lines are assumed lossless, then two-port equations can be written for each turn of the configuration depicted in Fig. 4. With the assumption that the lines are balanced, the current I_i into terminal 1 must equal the current coming out of terminal 2 etc. From the connection diagram it is apparent that the same value of current I_i flows into the terminal 1 of each turn; and current I_o flows out of terminal 3 of each turn. Examination of the equivalent circuit for a single turn with its two sections of line shows that the input and output ports are respectively connected in series, hence the Z matrix of one turn is the sum of the Z matrices of line a and line b. Furthermore, the N turns of the complete transformer are in series, so from Fig. 4

$$V_i = N(V_1 - V_3) \tag{2}$$

$$V_o = N(V_2 - V_4) \tag{3}$$

and

$$\begin{bmatrix} V_i \\ V_o \end{bmatrix} = -jNZ_o \begin{bmatrix} \cot \beta l_a + \cot \beta l_b & \dfrac{1}{\sin \beta l_a} + \dfrac{1}{\sin \beta l_b} \\ \dfrac{1}{\sin \beta l_a} + \dfrac{1}{\sin \beta l_b} & \cot \beta l_a + \cot \beta l_b \end{bmatrix} \begin{bmatrix} I_i \\ -I_o \end{bmatrix}. \tag{4}$$

Conversion to the transmission matrix yields

$$\begin{bmatrix} V_i \\ I_i \end{bmatrix} = \begin{bmatrix} \dfrac{\sin \beta(l_a + l_b)}{\sin \beta l_a + \sin \beta l_b} & \dfrac{jNZ_o[2 - 2\cos \beta(l_a + l_b)]}{\sin \beta l_a + \sin \beta l_b} \\ \dfrac{j}{NZ_o} \dfrac{\sin \beta l_a \times \sin \beta l_b}{\sin \beta l_a + \sin \beta l_b} & \dfrac{\sin \beta(l_a + l_b)}{\sin \beta l_a + \sin \beta l_b} \end{bmatrix} \cdot \begin{bmatrix} V_o \\ I_o \end{bmatrix}. \tag{5}$$

It can be shown from (5) that the rotary transformer is bilateral and symmetrical. Also, if the output of the rotary coupler is loaded with impedance Z_L, the input impedance Z_i is expressed by

$$Z_i = Z_o \left[\frac{NZ_L \sin \beta(l_a + l_b) + jN^2 Z_o[2 - 2\cos \beta(l_a + l_b)]}{NZ_o \sin \beta(l_a + l_b) + jZ_L \sin \beta l_a \sin \beta l_b} \right]. \tag{6}$$

The insertion loss is calculated to be

$$\frac{P_{av}}{P_o} = \frac{(Z_L + Z_o)^2 N^2 \sin^2 \beta(l_a + l_b) + \{Z_L \sin \beta l_a \sin \beta l_b + Z_o N^2 [2 - 2\cos \beta(l_a + l_b)]\}^2}{4Z_L Z_o \{N^2 \sin^2 \beta(l_a + l_b) - N^2 [2 - 2\cos \beta(l_a + l_b)] \sin \beta l_a \sin \beta l_b\}} \tag{7}$$

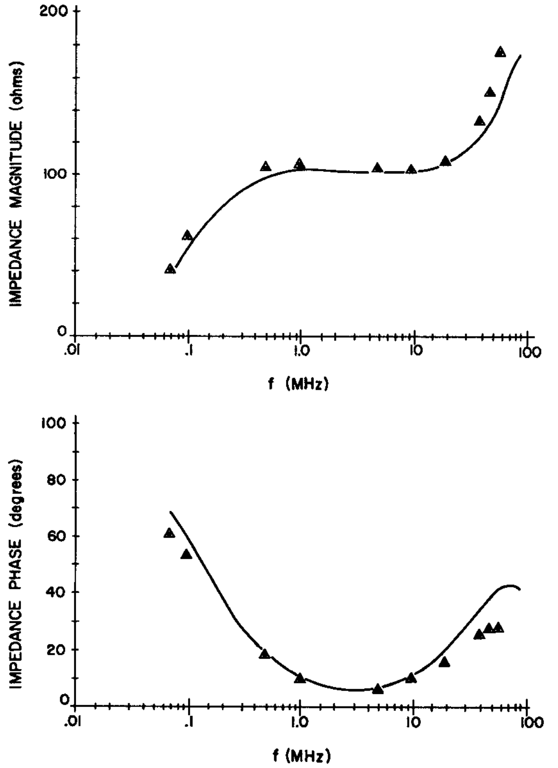

Fig. 5. Input impedance Z_i (theoretical curve is corrected for low-frequency shunt parasitics), $R_L = 110\,\Omega$. ▲: experimental. —: theoretical.

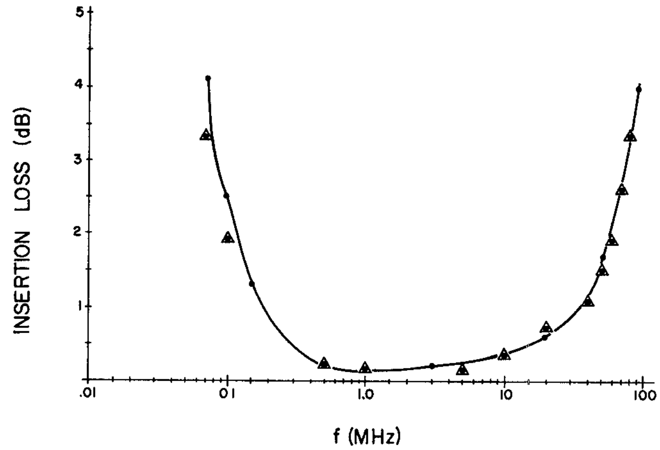

Fig. 6. Insertion loss of the transformer with 110-Ω load. ▲: experimental. —: theoretical.

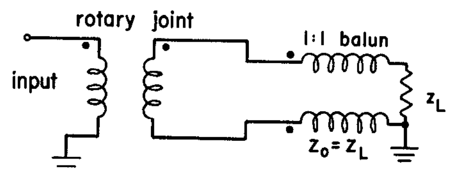

Fig. 7. Connection useful for feeding an unbalanced load impedance.

in which P_o is the output power to load and P_{av} is the available input power.

For minimum insertion loss the optimum load impedance is equal to the line characteristic impedance which is resistive for a lossless line. For this loading the input impedance is expressed by

$$Z_i = Z_o \left[\frac{N \sin \beta(l_a + l_b) + jN^2[2 - 2 \cos \beta(l_a + l_b)]}{N \sin \beta(l_a + l_b) + j \sin \beta l_a \sin \beta l_b} \right]. \quad (8)$$

As long as the total line length per turn $(l_a + l_b)$ represents a small fraction of a wavelength, the terms in (7) and (8) that vary with rotation have small effect on the value of these equations; i.e., the insertion loss and input impedance should remain nearly constant. From (7) the high-frequency point at which the insertion loss is down 3 dB can be shown to occur for $l_T = 0.3\lambda$.

The low-frequency response of the rotary transformer is controlled by the usual transformer shunt parasitics such as magnetizing reaction and core loss. These can be measured or determined from data available from the core manufacturer. If the source resistance is equal to the optimum load resistance and core loss is negligible at low frequencies, as is usually the case with ferrites, the lower 3-dB insertion-loss point is given by

$$f_1 = \frac{R_L \times 10^9}{4\pi N^2 A_L} \text{ Hz} \quad (9)$$

where f_1 is the lower 3-dB cutoff frequency and A_L is the core inductance index expressed in millihenrys per 1000 turns.

The inductance index of a ferrite core is usually available as catalog data. However, it can be determined at low frequencies by winding a small coil with N_p turns on a core and measuring the inductance L_p. The relationship between L_p and A_L is [5]

$$L_p = \frac{N_p^2 A_L}{10^6} \text{ mH}. \quad (10)$$

Experimental Results

The prototype depicted by Fig. 1 was tested. This device had five turns and the following measured electrical characteristics:

$$A_L = 5500 \text{ (core)}$$
$$Z_o = 110\,\Omega$$
$$\beta l_T = 0.02 f \text{ rad } (f \text{ in megahertz}).$$

The input impedance and insertion loss are depicted by Figs. 5 and 6. The 3-dB bandwidth is 80 kHz–80 MHz, and these response curves are accurate for 360° of rotation.

If an unbalanced load is required, a static (nonrotating) wide-band transformer using a toroid core can be used as a 1:1 balun, as shown in Fig. 7. The overall performance is as good as that of the rotary transformer alone, except for the small insertion loss of the balun.

Acknowledgment

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