Short-Step-Stub Chebyshev Impedance Transformers

PIETER W. VAN DER WALT, MEMBER, IEEE

***Abstract*—A transfer function for short-step impedance transforming filters consisting of short cascaded TEM transmission-line sections and at least one commensurate length open-circuit stub is described. Element values are given for a particular family of octave-bandwidth short-step transformers that are much more compact than existing short-step transformers.**

I. Introduction

THE well-known quarter-wave impedance transformer [1] provides a convenient way to match a resistive load to a generator with a resistive output impedance. The transformer is easy to implement since the line characteristic impedances all lie within the range defined by the port resistances. The transformer is relatively long, which can be a disadvantage in microwave integrated circuits, especially those working at the lower microwave frequencies. For purposes of comparison, the stripline layout of a second-order quarter-wave transformer providing a match between resistances of 1 and 10 Ω over a relative bandwidth of 60 percent is shown in Fig. 1(a). Element values from the quoted references are shown in Table I for this, as well as the other transformers mentioned below.

Matthaei [2] described a short-step transformer which consists of an even number of cascaded unit elements. The transformers are usually constructed from lines with a length of 1/12 or 1/16 of a wavelength at the center frequency of the response. Since the passband performance of a short-step transformer of order $2n$ is roughly comparable to the performance of a quarter-wave transformer of order n, the quarter-wave transformer is twice as long as an equivalent short-step transformer with $\lambda/16$ lines.

Short-step transformers are, in general, more difficult to realize than quarter-wave transformers because of large step discontinuities between sections and the large range of impedance values within the transformer. For example, a four-section $\lambda/16$ Chebyshev transformer which matches resistances with a ratio of 10:1 over a fractional bandwidth of 60 percent, with a layout as shown in Fig. 1(b), has lines with a ratio of 15.4 between highest and lowest characteristic impedance [2]. This makes the transformer unsuitable for many microstrip and stripline applications.

A remarkable short-step impedance transformer proposed by Levy [3] reduces the realizability problems to a great extent, as the spread in line impedances is decreased considerably. Fig. 1(c) shows the stripline layout of this transformer with a matching ratio of 10:1, a relative bandwidth of 67 percent (one octave), and a shortest line length of $\lambda/16$. The length of the transformer is about the same as Matthaei's short-step transformer, but the ratio of highest to lowest line impedance is only 6.4.

A new and very compact fourth-order $\lambda/16$ short-step-stub transformer, providing a match between 1 and 10 Ω over an octave bandwidth, is shown in Fig. 1(d). The transformer can be implemented with transmission lines with a ratio of 14 between the highest and lowest characteristic impedances. Since the stub lines can each be fabricated in the form of two stubs with twice the characteristic impedance connected in parallel, the ratio be-

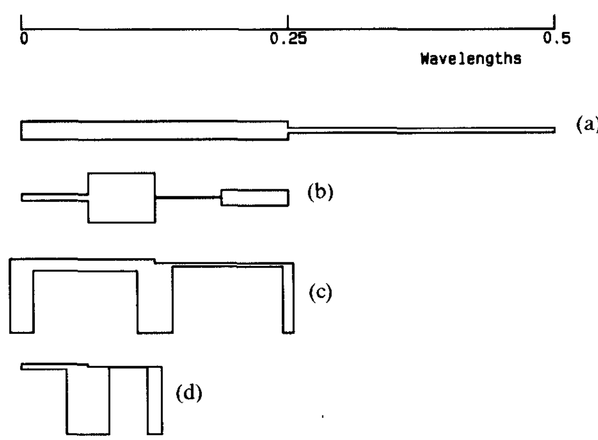

Fig. 1. Stripline layouts of impedance transformers with comparable performance. (a) Quarter-wave. (b) $\lambda/16$ Matthaei short-step. (c) $\lambda/16$ Levy short-step. (d) $\lambda/16$ short-step-stub.

TABLE I
ELEMENT VALUES OF THE TRANSFORMERS IN FIG. 1 FOR A MATCH BETWEEN 15 AND 150 Ω

Transformer Type	Figure	Element Values from left to right Ohms				
Quarter Wave	1(a)	28.94	77.96			
Matthaei Short-step	1(b)	66.63	12.09	186.1	33.77	
Levy Short-step	1(c)	23.01	43.10	16.50	105.0	45.23
Short-step-stub	1(d)	74.06	13.76	193.9	36.03	

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The author is with the Department of Electrical and Electronic Engineering, University of Stellenbosch, Stellenbosch 7600, South Africa.
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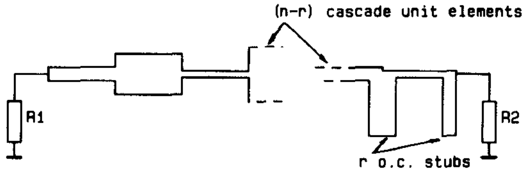

Fig. 2. General form of short-step-stub transformers with r open-circuit stubs and $(n-r)$ cascade-connected unit elements.

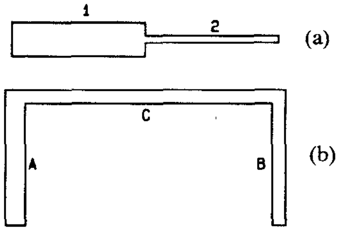

Fig. 3. Equivalent commensurate networks used for transforming a transformer with one or two stubs into Levy's short-step transformer. The stubs in the equivalent network, one with negative and one with positive characteristic impedance, are degenerate and do not contribute a transmission zero.

tween the highest and lowest characteristic impedance can be reduced to 7. The transformer is therefore easier to realize than the short-step transformer in Fig. 1(b). The nth-order transformer (with n even) of this type consists of $n/2$ unit elements in cascade and $n/2$ open-circuit stubs.

In this paper, a general transfer function for the design of short-step transformers is developed. It may be used to synthesize short-step transformers of even-order n with r (where $r \leqslant n/2$) open-circuit stubs and $n-r$ cascaded unit elements, as shown in Fig. 2, to provide a match between resistance loads R_1 and R_2. This class includes Matthaei's transformer with $r=0$, as well as Levy's transformer, which is designed with $r=1$ or $r=2$, and then transformed into its final form with the network equivalence of Fig. 3. The characteristic immittances of the equivalent network in Fig. 3(b) are given in terms of the immittances of the prototype in Fig. 3(a) by

$$Z_C = \frac{Z_1 + Z_2}{2} \tag{1a}$$

$$Y_A = \frac{Y_1 Z_2 - 1}{Z_1 + Z_2} \tag{1b}$$

$$Y_B = \frac{Z_1 Y_2 - 1}{Z_1 + Z_2}. \tag{1c}$$

This transformation accounts for the very low impedance spread in this transformer, as the cascade sections of the transformed filter take on the average impedance values of the lines in the prototype filter. This averages out the high–low impedance topology usually found in short-step transformers. As the characteristic impedance of one of the stubs in the equivalent network is always negative, the prototype network must contain a stub with positive characteristic impedance to absorb the negative element. The transformation also accounts for Levy's remark that under certain conditions, negative element values result for this transformer. It should be noted that in this paper, n, the order of the transfer function approximation, is equal to the total number of elements in the different prototypes. It corresponds to $2n$ for single-ordered zeros and $2n+2$ for double-ordered zeros in Levy's paper.

II. Chebyshev Transfer Function Approximation

Suitable transfer functions are derived by first transforming the s-plane response to the p-plane using Richard's transformation; the p-plane bandpass response is then transformed to the z-plane where a Chebyshev general parameter characteristic function is found. This function is transformed back to the p-plane where the transformers are synthesized.

A typical frequency response for the short-step impedance transformer of Fig. 2 is shown in Fig. 4(a). The relative bandwidth for which $|S_{11}| \leqslant S_{\max}$, with $S_{\max}$ the maximum magnitude of the reflection coefficient in the passband, is defined as

$$B = \frac{\omega_2 - \omega_1}{\omega_m} \tag{2}$$

where the frequencies ω_1 and ω_2 define the lower and upper passband edges, and ω_m is the center frequency of the response, defined by

$$\omega_m = \frac{\omega_2 + \omega_1}{2}. \tag{3}$$

The transformer consists of lines with an electrical length of a quarter wavelength at frequency ω_0. The ratio t, where

$$t = \frac{\omega_0}{\omega_m} \tag{4}$$

and $t > (1 + B/2)$, determines the length of the lines used in the transformer. The transformation [4]

$$p = u + jv = \tanh(sT) = \tanh\left(\frac{s\pi}{2\omega_0}\right) \tag{5}$$

(where p is Richard's variable, $s = \sigma + j\omega$ is the Laplace variable, and T is the delay time of the lines) transforms the response into the p-plane response shown in Fig. 4(b). The frequencies v_1, v_2, and v_m are given by

$$v_{1,2} = \tan\left[\left(1 \pm \frac{B}{2}\right)\frac{\pi}{2t}\right] \tag{6}$$

$$v_m = \tan\left(\frac{\pi}{2t}\right). \tag{7}$$

An impedance transformer of even-order n with r open-circuit stubs and $(n-r)$ unit elements, as shown in Fig. 2, has r transmission zeros at $p \to \infty$, corresponding to the open-circuit stubs, and $(n-r)$ transmission zeros at $p^2 = 1$, corresponding to the unit elements.

To find a family of characteristic functions [4] with equiripple properties in the passband and poles at the frequencies of the transmission zeros, the p-plane response

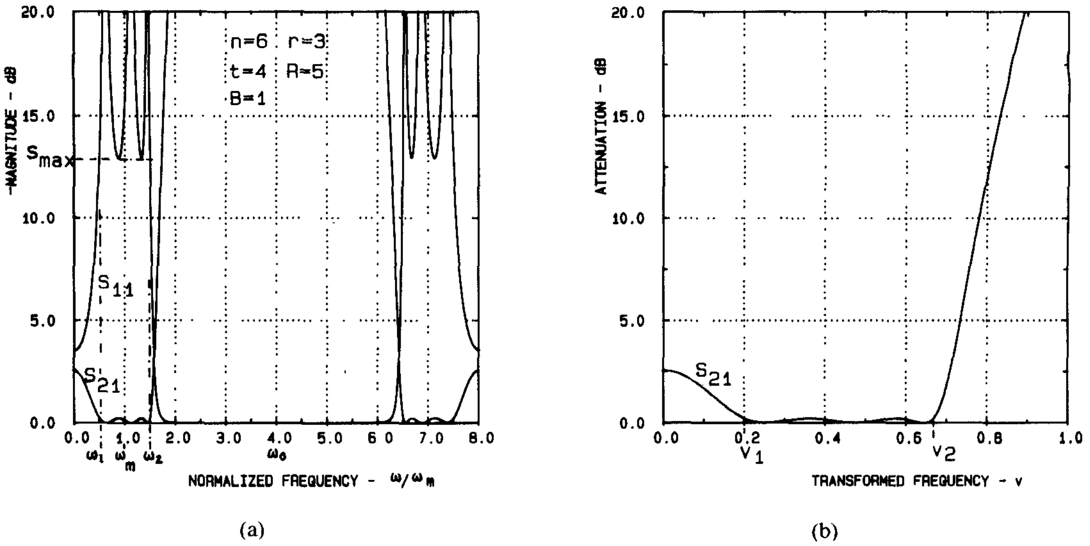

Fig. 4. Frequency response of a general short-step-stub transformer in (a) the s-plane (real frequency) and (b) the p-plane (Richard's variable).

is transformed to the z-plane with the transformation [5]

$$z^2 = \frac{p^2 + v_2^2}{p^2 + v_1^2}. \tag{8}$$

The general parameter Chebyshev function in the z-plane [4], [5] is defined by

$$F(z)F(-z) = \frac{[P(z) + P(-z)]^2}{4P(z)P(-z)} \tag{9}$$

where the polynomial $P(z)$ is given by

$$P(z) = (1+z)^r \left(\sqrt{\frac{1+v_2^2}{1+v_1^2}} + z \right)^{n-r}. \tag{10}$$

The two factors in (10) correspond to transmission zeros at $p \to \infty$ and $p^2 = 1$. The function $F(z)F(-z)$ is now transformed back to the p-plane to find the required transmission coefficient

$$|S_{21}|^2 = \frac{1}{1 + k^2 F(z)F(-z)}\bigg|_{z^2 = (v_2^2 - v^2)/(v_1^2 - v^2)} \tag{11}$$

which is in a form suitable for synthesis. For $r = 0$, $r = n/2$, and $r = n$, simple closed-form solutions exist for the poles and zeros of the transmission coefficient.

III. Matching Performance of Short-Step Transformers

The maximum voltage standing-wave ratio in the passband of an impedance transformer can be found from the value of the characteristic function at the frequency $s = 0$, which corresponds to $p = 0$ and therefore to $z = z_0 = \pm v_2/v_1$. At this frequency, no impedance transformation takes place, and the reflection coefficient is determined by the ratio of the terminating resistances of the transformer. Application of the identity $|S_{11}|^2 + |S_{21}|^2 = 1$ for lossless networks leads to

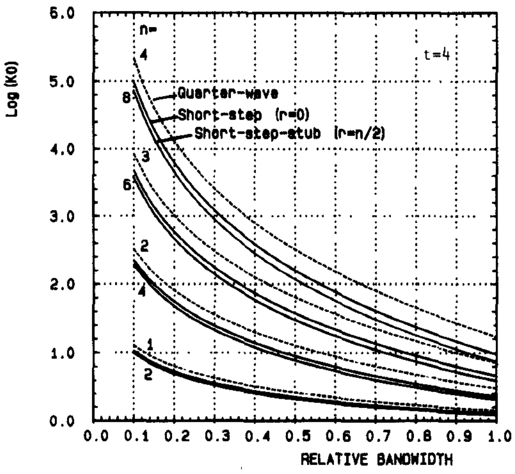

Fig. 5. The performance parameter K_0 as a function of bandwidth for short-step transformers (solid lines) and quarter-wave transformers (broken lines).

$$S_{21}(0) = \left| \frac{R_2 - R_1}{R_2 + R_1} \right| = \frac{kK_0}{\sqrt{1 + k^2 K_0^2}} \tag{12}$$

where

$$K_0^2 = F(z_0)F(-z_0). \tag{13}$$

For a given relative bandwidth, order, and resistance ratio $R = R_2/R_1$, (12) can be solved for k, resulting in

$$k^2 = \frac{(R-1)^2}{4RK_0^2}. \tag{14}$$

The passband ripple of the transformer is given by

$$L_m = 10\log(1 + k^2) \tag{15}$$

and the maximum passband voltage standing-wave ratio is given by

$$\mathrm{VSWR} = \left(\sqrt{1+k^2} + k\right)^2. \tag{16}$$

The value of K_0 determines the passband performance of the transformer. Fig. 5 shows the logarithm of K_0 as a function of the relative bandwidth for transformers of orders $n=2$ to $n=8$, for $r=0$ and $r=n/2$, and $t=4$. (For transformers with other values of r, K_0 lies between the curves for $r=0$ and $r=n/2$.) For purposes of comparison, the logarithm of K_0 is also shown for quarter-wave transformers of order $n/2$. The figure shows that the performance of a short-step transformer is roughly comparable with that of a quarter-wave transformer of order $n/2$, regardless of the specific topology of the short-step transformer.

IV. Element Values

Element values were calculated with a simple synthesis procedure, which is an extension to distributed networks of a synthesis procedure for lumped-element networks which was described by Lind [6]. It is outlined below.

The transmission parameters ($ABCD$) of the transformer are found by standard parameter identification procedures, e.g., [7]. Also, the inverse transmission parameter matrices of a general open-circuit stub and a unit element, the basic sections from which the transformer is assembled, are determined. Synthesis is carried out by inspecting the poles of the transmission parameters of the transformer to determine the types of section which can be extracted. A section is then extracted by pre- or postmultiplying the transmission matrix of the transformer with the inverse matrix of the section. The characteristic impedance of the section is chosen such that order of the relevant transformer parameters in the resultant matrix is reduced, either by cancellation with poles of the parameters or by cancellation of the coefficients of the highest or lowest term of the numerators. The procedure is repeated until the order of the transmission matrix is reduced to zero and only an ideal transformer remains. Since the order of two parameters are reduced at each step, numerical accuracy can be verified by ensuring that the order of both parameters are indeed reduced simultaneously. An example, the synthesis of a fourth-order short-step-stub transformer, is given in the Appendix.

Element values are shown in Table II for octave-bandwidth short-step-stub transformers with $r=n/2$ and line lengths of $\lambda_m/8$ ($t=2$) and $\lambda_m/16$ ($t=4$). The termination R_1 (see Fig. 2) is normalized to 1 Ω, and the other port is terminated in a resistance of R Ω.

TABLE II
OCTAVE-BANDWIDTH SHORT-STEP-STUB IMPEDANCE TRANSFORMERS

Line length: $\lambda_m/8$	B = 0,67				
N = 4					
R	2	3	5	7	10
LINE 1	1.4690	1.7428	2.1300	2.4230	2.7776
STUB 1	2.4203	2.4868	2.7745	3.0490	3.4110
LINE 2	2.1878	2.9277	4.1495	5.1848	6.5320
STUB 2	3.6045	4.1774	5.4049	6.5244	8.0215
VSWR	1.2043	1.3536	1.5946	1.8011	2.0806
N = 6					
R	2	3	5	7	10
LINE 1	1.2962	1.4482	1.6486	1.7916	1.9567
STUB 1	2.3056	2.2784	2.3752	2.4840	2.6308
LINE 2	2.0125	2.4915	3.2217	3.8045	4.5323
STUB 2	1.9633	2.3302	2.9944	3.5632	4.2993
LINE 3	2.4104	3.3882	5.1378	6.7251	8.9117
STUB 3	4.2875	5.3306	7.4021	9.3245	11.9818
VSWR	1.0716	1.1195	1.1910	1.2479	1.3199
N = 8					
R	2	3	5	7	10
LINE 1	1.1876	1.2766	1.3889	1.4660	1.5525
STUB 1	2.4141	2.3117	2.2968	2.3214	2.3678
LINE 2	1.8106	2.1092	2.5315	2.8494	3.2296
STUB 2	1.6798	1.9023	2.2824	2.5918	2.9766
LINE 3	2.2951	2.9994	4.1657	5.1572	6.4554
STUB 3	2.1293	2.7051	3.7557	4.6910	5.9496
LINE 4	2.5124	3.6478	5.7770	7.7898	10.6636
STUB 4	5.1071	6.6061	9.5533	12.3357	16.2642
VSWR	1.0257	1.0423	1.0663	1.0848	1.1075
Line length $\lambda_m/16$	B = 0,67				
N = 4					
R	2	3	5	7	10
LINE 1	2.3775	2.9548	3.7198	4.2772	4.9370
STUB 1	0.5926	0.6378	0.7330	0.8142	0.9172
LINE 2	4.2162	5.7189	8.1655	10.2335	12.9284
STUB 2	1.0509	1.2345	1.6090	1.9481	2.4019
VSWR	1.1760	1.3025	1.5035	1.6735	1.9008
N = 6					
R	2	3	5	7	10
LINE 1	1.9950	2.3333	2.7462	3.0271	3.3417
STUB 1	0.5558	0.5701	0.6105	0.6456	0.6894
LINE 2	4.0552	5.0219	6.4637	7.6024	9.0154
STUB 2	0.5615	0.6781	0.8787	1.0477	1.2648
LINE 3	4.6008	6.5479	10.0111	13.1549	17.4970
STUB 3	1.2819	1.5999	2.2253	2.8059	3.6096
VSWR	1.0576	1.0958	1.1521	1.1966	1.2524
N = 8					
R	2	3	5	7	10
LINE 1	1.7272	1.9420	2.1907	2.3524	2.5275
STUB 1	0.5640	0.5577	0.5686	0.5819	0.5997
LINE 2	3.6560	4.2571	5.0825	5.6939	6.4183
STUB 2	0.4851	0.5564	0.6708	0.7618	0.8737
LINE 3	4.6702	6.0967	8.4369	10.4170	13.0026
STUB 3	0.6192	0.7966	1.1132	1.3934	1.7697
LINE 4	4.7060	6.9249	11.0754	15.0046	20.6283
STUB 4	1.5390	1.9898	2.8772	3.7147	4.8981
VSWR	1.0193	1.0317	1.0496	1.0633	1.0800

Comparison of element values with those of short-step transformers [2] shows that the $\lambda_m/8$ short-step-stub transformers, which are comparable in size to the $\lambda_m/16$ short-step transformers, exhibit a much smaller spread in element values than the short-step transformers, and a slightly smaller spread than Levy's transformers. The $\lambda_m/16$ short-step-stub transformers have an element value spread similar to that of the short-step transformers, but are more practical when parallel-connected stubs are used to reduce the ratio of element values in the transformer.

As t is increased, the elements of the short-step transformers become shorter and the impedance range within the transformer increases, so that the transformer becomes more difficult to implement in distributed form. As the lines become shorter, however, the short-step-stub transformer with $r=n/2$ in particular increasingly reminds one of a direct semi-lumped-element implementation of Matthaei's classic LC impedance matching filter [8].

This filter can, in fact, be synthesized directly from (11) as an LC network in the p-plane with $r=n$ (i.e., all p-plane transmission zeros at infinity). The transmission zeros at $p^2=1$ in a short-step transformer lie increasingly farther away from the passband in the p-plane as t is increased; with t large enough, whether these transmission zeros lie at $p^2=1$ or $p \to \infty$ makes little difference to the shape of the transformer's passband frequency response since (8) maps both sets of transmission zeros to very nearly the same point in the z-plane. The relation of (5) also becomes linear in the vicinity of the passband.

For large values of t, the performance parameter K_0 is the same for the different short-step topologies. The lumped-element matching network will therefore have a passband response similar to that of a short-step transformer since the tangent function in (5) is approximately equal to its argument for small angles. Low-impedance stubs and high-impedance unit elements, which are difficult to realize, may therefore be replaced by lumped-element capacitors and inductors without significant effect on the passband response. (The stopband response will be affected, and the response will no longer be a periodic function of frequency.)

The $r=n/2$ short-step-stub design therefore provides an exact procedure for the semi-lumped-element implementation of lumped-element impedance transformers, and helps to develop an understanding of the relationship between lumped- and distributed-element filters.

V. Conclusion

A general procedure for the synthesis of short-step impedance transformers has been presented. In particular, one member of the short-step family, with $r=n/2$, is very compact and relatively easy to implement. Simple expressions for evaluating the passband performance of impedance transformers have been derived, and element values are given for a selection of compact octave-bandwidth transformers.

The relationship between short-step transformers and lumped-element impedance matching networks has been pointed out, leading to an exact procedure for the semi-lumped implementation of lumped-element transformers.

Appendix

For a fourth-order short-step-stub impedance transformer with $\lambda_m/12$ lines ($t=3$), a relative bandwidth B of 20 percent, and a transformation ratio $R=5$, it follows (to five significant digits) from (6), (8), (10), and (12)–(16) that $v_1=0.50953$, $v_2=0.64941$, $K_0^2=2083.2$, $k^2=0.00038403$, $L_m=0.0017$ dB, VSWR $=1.040$. The maximum value of the reflection coefficient $S_{\max}$ in the passband is -34.16 dB. The transmission parameters for the transformer doubly terminated with unit resistors are [7]

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \frac{1}{1-p^2} \cdot \begin{bmatrix} 2.2361+15.117p^2+15.980p^4 & 4.2783p+8.2586p^3 \\ 4.2783p+8.2586p^3 & 0.4472+4.2680p^2 \end{bmatrix}. \tag{A1}$$

The transmission parameters have two common factors $\sqrt{1-p^2}$ in their denominators, implying that unit elements may be removed at any time from any port. The parameter A, the inverse of the open-circuit voltage ratio of the impedance transformer, has one more transmission zero at infinity than parameters B and C, and two more than parameter D. This implies a parallel shunt open-circuit stub at port 2, and a series-shorted stub at port 1. From Kuroda's identities [4], we know that such a series stub followed by a unit element is equivalent to a unit element followed by a shunt open-circuit stub. The parameters are therefore compatible with the topology of Fig. 1(d).

It is noted that the inverse transmission parameters of a unit element with characteristic impedance Z_0 are given by

$$\frac{1}{\sqrt{1-p^2}}\begin{bmatrix} 1 & pZ_0 \\ \dfrac{p}{Z_0} & 1 \end{bmatrix}^{-1} = \frac{1}{\sqrt{1-p^2}}\begin{bmatrix} 1 & -pZ_0 \\ \dfrac{-p}{Z_0} & 1 \end{bmatrix} \tag{A2}$$

and those of a shunt open-circuit stub with characteristic admittance Y_0 are given by

$$\begin{bmatrix} 1 & 0 \\ pY_0 & 1 \end{bmatrix}^{-1} = \begin{bmatrix} 1 & 0 \\ -pY_0 & 1 \end{bmatrix}. \tag{A3}$$

To extract a unit element from the left side of the impedance transformer, it is noted that when a set of transmission parameters with a common factor $\sqrt{1-p^2}$ in their denominators are premultiplied with the inverse transmission matrix of a unit element, the result is of the form

$$(1-p^2)^{-1}\begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix} = (1-p^2)^{-1}\begin{bmatrix} A-pB/Z_0 & B-pZ_0A \\ C-pD/Z_0 & D-pZ_0C \end{bmatrix}. \tag{A4}$$

A reduction in order is possible if the factor $(1-p^2)$ in the denominator cancels with a similar factor in the numerators of the parameters. To create zeros at $p^2=1$ in the numerators, an element with characteristic impedance $Z_0=B(1)/A(1)=D(1)/C(1)$ must be extracted. Note that the extraction is possible only if both conditions for Z_0 are met. Also note that this simple extraction corresponds to the conventional extraction with Richard's theorem. Extraction of an element with characteristic impedance 2.6588 Ω from (A1) leaves the matrix

$$\frac{1}{\sqrt{1-p^2}}\begin{bmatrix} 2.2361+5.9777p^2 & 3.0893p \\ 3.4373p+6.0103p^3 & 0.44722+3.1061p^2 \end{bmatrix}. \tag{A5}$$

From this matrix, a shunt open-circuit stub may be extracted from the left or the right side as the parameter C, the inverse of the open-circuit transfer impedance, has two transmission zeros at infinity, while the parameter B, the inverse of the short-circuit transfer admittance, has none. For an extraction from the left side, it is noted that premultiplication of a set of transmission parameters with the inverse matrix of a shunt open-circuit stub with characteristic admittance Y_0 results in

$$\begin{bmatrix} A' & B' \\ C' & D' \end{bmatrix} = \begin{bmatrix} A & B \\ C - pY_0A & D - pY_0B \end{bmatrix}. \quad (A6)$$

The transmission zero at infinity is removed, and the order of the matrix reduced by a cancellation of highest-order coefficients in C' and D'. Therefore

$$Y_0 = \lim_{p \to \infty} \left\{ \frac{C}{pA} \right\} = \lim_{p \to \infty} \left\{ \frac{D}{pB} \right\}. \quad (A7)$$

Removal of an element with characteristic admittance $Y_0 = 1.0055$ S leaves the matrix

$$\frac{1}{\sqrt{1-p^2}} \begin{bmatrix} 2.2361 + 5.9777p^2 & 3.0893p \\ 1.18907p & 0.44722 \end{bmatrix}. \quad (A8)$$

Further extraction of a unit element $Z_0 = 6.9077\ \Omega$ and a shunt stub $Y_0 = 0.3870$ S leaves the matrix

$$\begin{bmatrix} 2.2361 & 0 \\ 0 & 0.44722 \end{bmatrix} \quad (A9)$$

which represents an ideal transformer with a turns ratio of 2.2361:1. The transformer transforms the normalized 1-Ω load resistor to the specified 5-Ω load.

Acknowledgment

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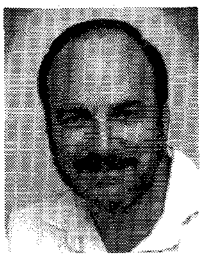

Pieter W. van der Walt (M'80) was born in Germiston, South Africa, on April 12, 1947. He received the B.Sc., B.Eng., M.Eng., and Ph.D. degrees in electronic engineering from the University of Stellenbosch in 1970, 1973, and 1982, respectively.

He joined the Department of Electrical and Electronic Engineering of the University of Stellenbosch in 1971 as a Junior Lecturer. He was appointed Professor in 1980 and served as Chairman of the Department in 1980, 1981, and 1984. His main interests include network synthesis and linear and nonlinear circuit design.

Dr. van der Walt is a member of the South African Institute of Electrical Engineers, and is currently Vice-Chairman of the South Africa section of the IEEE.