MODELLING OF BROADBAND POWERLINE COMMUNICATION CHANNELS

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Abstract: This paper develops a new PLC model and investigates the impact of the load, line length, and diameter of the transmission line on the channel transfer function over the frequency range of 1-20 MHz. The results show that with 42 degrees of freedom, the proposed model leads to an average RMSE value of approximately 5.2 dB. With the same conditions, the Phillips model leads to an average RMSE value of approximately 1.62 dB.

Keywords: Power Line Telecommunication, PLC Channel Transfer function, Broadband PLC

1. INTRODUCTION

Considerable effort has been recently devoted to the determination of accurate channel models for the Power Line Communication (PLC) environment, both for indoor and outdoor cases. Power lines have been used as a communication medium for many years in low bit-rate applications like automation of power distribution and remote meter reading [1-2]. However, the characterization of the transfer function is a non-trivial task to achieve since PLC characteristics change depending on the particular topology of a given link. The attenuation depends much more on network topology and connected loads. The amplitude characteristics show, even at short distances, deep narrowband notches of high attenuation, which can even be higher than those for longer distances. These notches result from reflections and multipath propagation. This behaviour is very similar to the one of mobile radio channels.

The conversion of networks designed to distribute electric power into communication media has been the subject of extensive research carried out over the last few years. The growing demand for information exchange calls for high rate data transmission, which in turn requires the utilization of the power grid in the frequency range up to 30 MHz. Several problems are caused by the frequency-dependent nature of the power grid, the presence of time varying loads, as well as by the structure of the grid itself. The solutions for these problems can be achieved through proper modelling of the power grid as a communication medium with a time-varying delay.

Several channel models from multipath propagation principles have been proposed [3], [4], [5]. The works presented in [4] and [6] are very close to the approach introduced herein. Models proposed in the literature focus on the subject of in-home networks, i.e. the power distribution networks inside consumer premises. In this paper, the model parameters are derived from the lumped-circuit transmission line model to obtain the transfer function of the channel, as shown in Fig.1, using equations (1) and (2) below:

$$\frac{\partial v(x,t)}{\partial x} + R \cdot i(x,t) + L\frac{\partial i(x,t)}{\partial t} = 0 \qquad (1)$$

$$\frac{\partial i(x,t)}{\partial x} + G \cdot v(x,t) + G\frac{\partial v(x,t)}{\partial t} = 0 \qquad (2)$$

In these equations x denotes the longitudinal direction of the line, while R, L, G and C are the per-unit length resistance (Ω/m), inductance (H/m), conductance (S/m) and capacitance (F/m), respectively.

2. TRANSMISSION LINE PARAMETERS

Anatory et *al*., [7], have defined the transmission parameters for the PLC system from a primary substation to the customer bracket. They assumed that the separation distance D, between conductors is much greater than the radius, a of the conductors; hence the capacitance C, inductance L, and AC resistance R per loop meter are given by [1], [2]:

$$c = \frac{\pi\varepsilon}{cosh^{-1}\left(D/_{2a}\right)} \qquad [F/_m] \qquad (3)$$

$$L = \frac{\mu}{\pi} cosh^{-1}\left(D/_{2a}\right) \qquad [H/_m] \qquad (4)$$

$$R = 2\left(\frac{R_s}{2\pi a}\right) = \frac{1}{\pi a}\sqrt{\frac{\pi f \mu}{\sigma}} \qquad [\Omega] \qquad (5)$$

Here μ and σ are the permeability and conductivity of the metal conductors, respectively. The propagation coefficient γ is given by:

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \qquad (6)$$

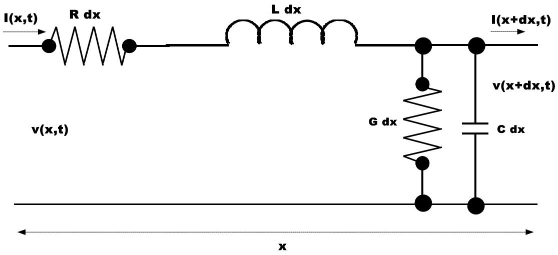

Figure1: Two-conductor distributed transmission line

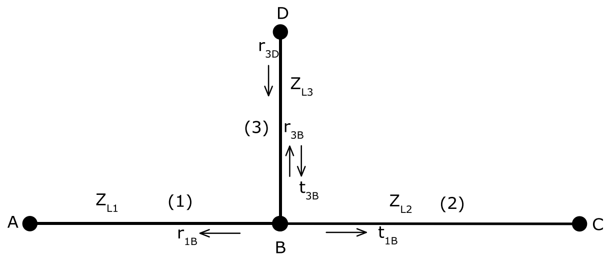

Figure 2: One-tap cable multipath signal propagation

Where α is the attenuation coefficient and β is the phase coefficient. Also the attenuation function is given by equation (7) below, where l is the length of the cable:

$$A(f, l) = \exp(-\gamma\, l) \tag{7}$$

The characteristic impedance Z_0 can be expressed as:

$$Z_o = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \tag{8}$$

The impedance seen looking into a generalized transmission line terminated in the load Z_L is:

$$Z_{in} = Z_0 \left(\frac{Z_L + Z_0 \tanh(\gamma l)}{Z_0 + Z_L \tanh(\gamma l)} \right) \tag{9}$$

If the load terminal is short-circuited, i.e. $Z_L = 0$, equation (9) becomes:

$$Z_{in} = Z_{sc} = Z_o \tanh(\gamma l) \tag{10}$$

Similarly, if the load terminal is open-circuited, i.e. $ZL \rightarrow \infty$, equation (9) becomes:

$$Z_{in} = Z_{os} = Z_o \cot h(\gamma l) \tag{11}$$

From equations (8) and (10), we obtain:

$$Z_o = \sqrt{Z_{sc} Z_{os}} \tag{12}$$

$$\gamma = \frac{1}{l} \tanh^{-1} \sqrt{\frac{Z_{sc}}{Z_{os}}} \tag{13}$$

In the lossless transmission line, Z_{in} can be expressed as:

$$Z_{in} = Z_0 \left(\frac{Z_L + jZ_0 \tanh(\beta l)}{Z_0 + jZ_L \tanh(\beta l)} \right) \tag{14}$$

3. TRANSFER CHANNEL FUNCTION

The transfer function *H(f)* is the well-known multipath model proposed by Phillips [7] and Zimmerman and Dostert [8]. The echo model of Phillips presents the channel impulse response as the superposition of *N* Dirac pulses representing the superposition of signals from *N* different paths, that is:

$$H(f) = \sum_{i=1}^{N} \rho_i e^{-j2\pi f \tau_i} \tag{15}$$

Here, ρ_i is a complex factor and τ_i is the delay time. Zimmerman proposed an adapted echo model that contains an additional attenuation factor. The multipath signal illustrated in Fig. 2 is investigated and analyzed simply as the link that consists of three segments (1), (2) and (3) with the lengths L_1, L_2 *and* L_3, and the characteristic impedances Z_{L1}, Z_{L2} *and* Z_{L3}, respectively. We assume that terminals *A* and *C* are matched, which means $Z_A = Z_{L1}$ *and* $Z_C = Z_{L2}$. *B and D* are reflection points, with reflection coefficients r_{1B} , r_{3B}, r_{3D} respectively, and the corresponding transmission coefficients denoted as t_{1B}, t_{3B} ,respectively. Therefore, with these assumptions, the link can have an infinite number of propagation paths due to multiple reflections. Each path *i* has a weighting factor g_i, representing the product of the reflection and transmission coefficients along the path, with the standard condition:

$$|g_i| < 1 \tag{16}$$

Therefore the transfer function *H(f)* in the frequency range from 500 kHz to 20MHz can be expressed as:

$$H(f) = \sum_{i=1}^{N} g_i (e^{-(a_o + a_1) \cdot d_i}) e^{-j2\pi f \frac{d_i}{v_p}} \tag{17}$$

where *N* is the number of paths of propagation, a_0, a_1 and k are parameters from frequency-dependent attenuation. The relevant parameters are not derived from component properties, but from channel measurements with d_i its length and v_p the propagation speed.

Consider the transfer function *H(f)* in (17); using the parameters in Table 1, we come up with simulation model shown in Figure 3 [5,7]. The model of Figure 3 is an example of with four paths. Table 2 shows the parameters of the model [5-7]. In an earlier work by Anatory *et al.,* [8-13], they proposed a generalized transfer function represented by:

Table 1: Parameters of the multipath model [5,7]

Path No	1	2	3	4
Delay in μ-seconds	**1.0**	**1.25**	**1.76**	**2.64**
Equivalent length in m	**150**	**188**	**264**	**397**
Weighting factor g_i	**0.4**	**-0.4**	**-0.8**	**-1.5**
K=0.5	**$a_0 = 0$**		**$a_1 = 0$**	

Table 2: Parameters of series-resonance circuit model

Branch No	R in Ohm	L in μH	C in nF	f_{res} in MHz	Q
1	21.4	0.137	10.890	4.122	0.165
2	12.1	8.264	0.1334	4.793	20.640
3	67.9	18.919	0.0197	8.238	14.431
4	46.4	11.948	0.0103	14.324	23.183
5	19.6	1.008	0.0273	30.357	9.799

Table 3: Set of parameters of proposed model

Branch	Length in m	Lm in μH/m	Cm in nF/m	f_m in MHz	Q	R in Ohm/m
AB	70	20.69	2.635	0.596	3.67	0.008
BC	10	2.668	0.417	4.77	2.04	0.001
BD	12	3.201	0.501	4.77	1.22	0.0016
BF	10	2.667	0.418	4.77	3.67	0.0013
BE	3	0.880	0.137	14.37	9.767	0.0004

$$H_m(f) = \prod_{d=1}^{M_T} \sum_{M=1}^{L} \sum_{n=1}^{N_T} T_{LM} \alpha_{mn} H_{mn}(f) \quad n \neq m \quad (18)$$

$$\alpha_{mn} = P_{Ln}^{M-1} \rho_{nm}^{M-1} e^{-\gamma_n (2(M-1)l_n)} \quad (19a)$$

$$P_{Ln} = \begin{cases} \rho_s & n = 1(source) \\ \rho_{Ln}, & otherwise \end{cases} \quad (19b)$$

where, N_T is the total number of branches connected at the node and terminated in any arbitrary load. This was achieved by letting *n, m M, $H_{mn}(f)$* and T_{LM}, represent, respectively, a branch number, a referenced (terminated) load, the number of reflections (with total *L* number of reflections), the transfer function between line *n* to a referenced load *m,* and the transmission factor at the referenced load *m* (see details in [8]). They also proposed the signal contribution factor α_{mn} as given by (19a), where ρ_{nm} is the reflection factor at node *B,* between line *n* and the referenced load *m.* γ_n is the propagation constant of line *n* that has line length l_n. All terminal reflection factors P_{Ln} in general are given by (19b), except at the source where $\rho_{L1}=\rho_s$ is the source reflection factor.

Phillips' measurements give the impedance of the electrical loads described by one or several resonant circuits (*SRC*) that consist of resistance *R,* capacitance *C,*

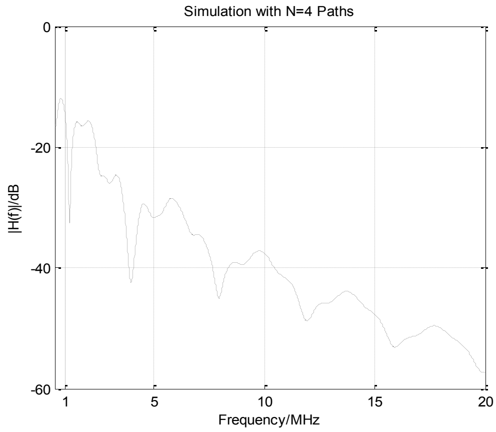

Figure 3: Multipath model from (17)

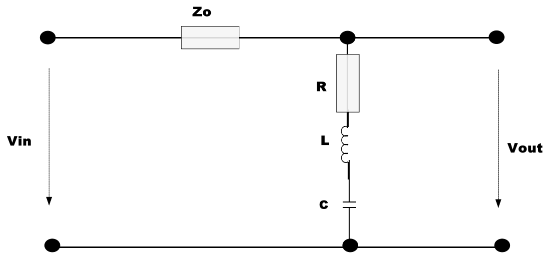

Figure 4: Series resonant circuit

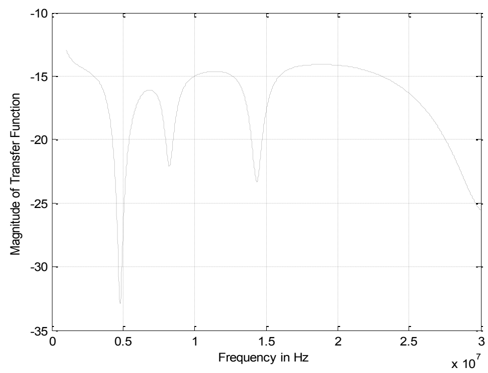

Figure 5: Transfer function of the series resonance model

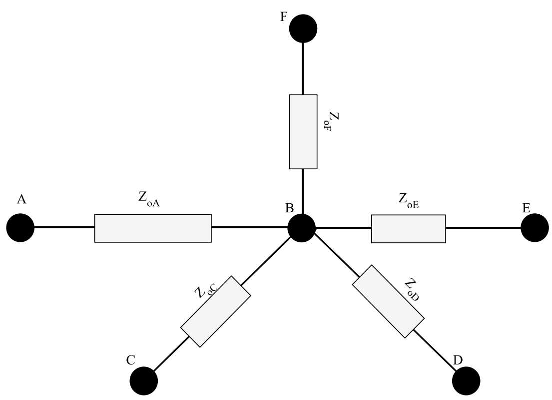

Figure 6: Simulation network model

and inductance L, as shown in Fig. 4, where, Zo is the characteristic impedance of the line. The impedance Zs of the resonant circuit is frequency-dependent and can be described by:

$$Z_s(f) = R + j2\pi fL + \frac{1}{j2\pi fC} \quad (20)$$

At resonance frequency, f_m we have:

$$f_m = \frac{1}{2\pi\sqrt{LC}} \quad (21)$$

The impedance is then minimal with an imaginary part equal to zero and a real part equal to R. The transfer function $H(f)$ is:

$$H(f) = \frac{1}{1 + \frac{Z_0}{Z_s(f)}} \quad (22)$$

The quality factor of the resonant circuit is defined by:

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}} \quad (23)$$

Q is a function of the width of the notch: the higher the Q, the narrower is the notch. Phillips [3] describes the transfer function $H(f)$ as the overall function of each resonant circuit transfer function $H_i(f)$, and derives the expression as:

$$H(f) = \prod_{i=1}^{N} H_i(f) \quad (24)$$

Each resonant circuit can thus be described by three parameters: resistance R, inductance L and capacitance C. In addition, the characteristic impedance Z has to be defined - in this case, it corresponds to his own measurement in [4], where Z is 90 *Ohm*. Also in order to fit a model with N resonant circuits to a measured transfer function, $3xN$ parameters have to be optimized. The author carried out the optimization by means of an evolutionary strategy. Table 2 summarizes the values of the parameters and the resulting resonance frequencies and Q factor. Fig. 3 shows the resulting simulation of the Phillips model.

4. PROPOSED TRANSFER FUNCTION

The Phillips model is based on evolutionary strategy to get lumped circuit parameters of the SRC load. The model we are proposing is based on transmission line parameters as shown Fig. 1. Once we have defined all parameters of the branch, we use equations (20) and (22) to generate the transfer function of the transmission line. Here we consider multiple branches at a single node as shown in Figure 6, where AB is the distributing branch from the distribution transformer to the customer's pole.

Here, BC, BD, BE and BF are branches to the customers and the AB branch is from the distribution transformer. Z_{oA}, Z_{oC}, Z_{oD}, Z_{oE} and Z_{oF} represent characteristic impedances of each one of the branches which are terminated by loads R_C, R_D, R_E, and R_F, respectively. The link AB is the customer pole with a length of $70\ m$, conductor radius r_m of $7\ mm$, and the spacing between the conductors d_m is 18 mm. The end user branches are $BD = 12\ m$; $BF = 10\ m$; $BC = 10\ m$; $BE=3\ m$, radius r of the conductor is 6.5 mm, and the space between conductors D is $17\ mm$. Based on equations (3), (4) and (5) and the network parameters, we determine the lump circuit parameters at the customers end, with $L= 26.677\ \mu H/m$, $C = 16.683\ nF/m$ and R is given for different frequencies as shown in the Table 3. As R is small compared to the resistive load terminated by each branch, it is neglected.

Consider the network shown in Fig. 6 from the first configuration, as shown in Table 3. We observe that by varying the length of the branch, we also vary the position of the resonance frequency of the transfer function, meaning the position of the notch. The lower the length of the line, the higher is the resonance frequency. To fit our model into the existing one, we fixed the loads as follow: $R_{AB} = 95\ \Omega$ at distance of 35 m, $R_{BC} = 20\ \Omega$ at distance of 10 m, $R_{BD} = 75\ \Omega$ at distance of 10 m, $R_{BE}=25\ \Omega$ at distance of $3.32\ m$ and $R_{BF} = 8.4\ \Omega$ at distance of 10 m. By setting the number of degrees of freedom at 42, the proposed model leads to an average root-mean-square error (*RMSE*) test statistic value of approximately 5.2 dB. Under the same conditions, the Phillips model leads to an average *RMSE* value of approximately 1.62 dB, where:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - x_n')^2} \quad (25)$$

The chi-square (χ^2) statistic is given by:

$$\chi^2 = \sum_{i=1}^{n}\frac{(x_i - x_n')^2}{x_n'} \quad (26)$$

Here $\{x_1, x_2, x_3, ..., x_n\}$ is experiment data set; $\{x_1', x_2', x_3', ..., x_n'\}$ is theoretical model data set; and, the number of degrees of freedom $df=n-1$. In our case, $n = 42$, $df = 41$, then $\chi^2 = 71.63$. From the table, the value of then χ^2 for 41 df at 1% level of significance is 74.75.

The second configuration consists of changing the radius r_m of the main cable, the space between conductors D, radius r at the customer end. It is observed that notches become narrow. This implies that the quality factor Q is lower at resonance frequencies such of 0.5, 4.77 and 14.6

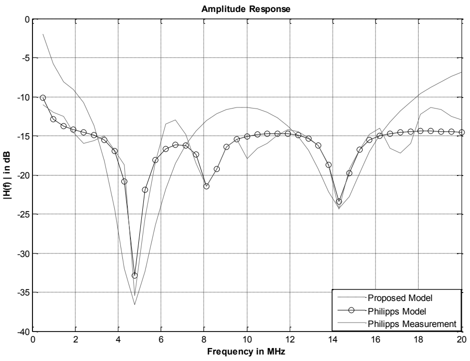

Figure 7: Amplitude Response of the model in (17)

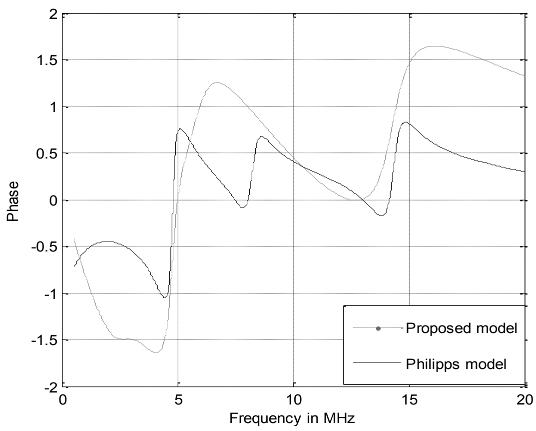

Figure 8: Phase response of the model in (17)

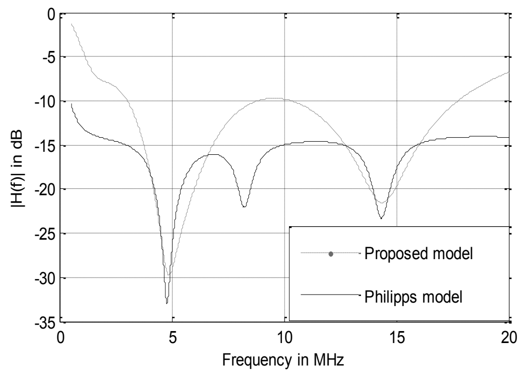

Figure 9: Amplitude response with a and D varying

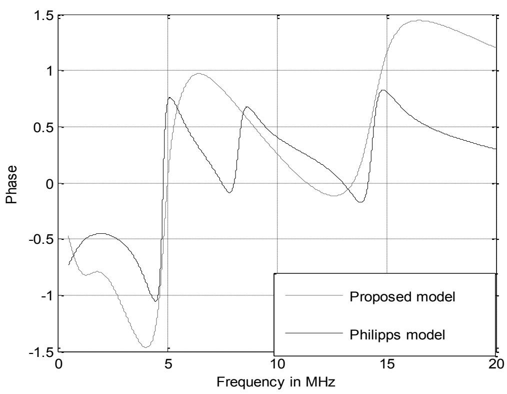

Figure 10: Phase response with r and D varying

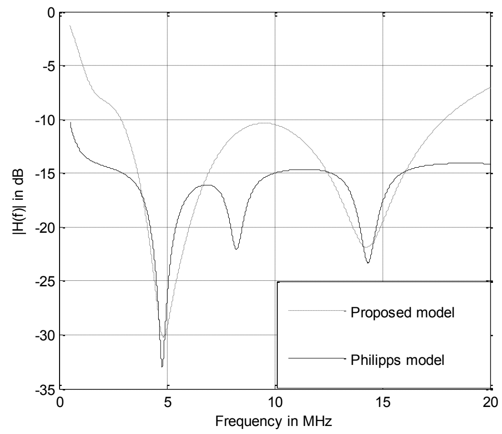

Figure 11: Amplitude response with resistance loads increased

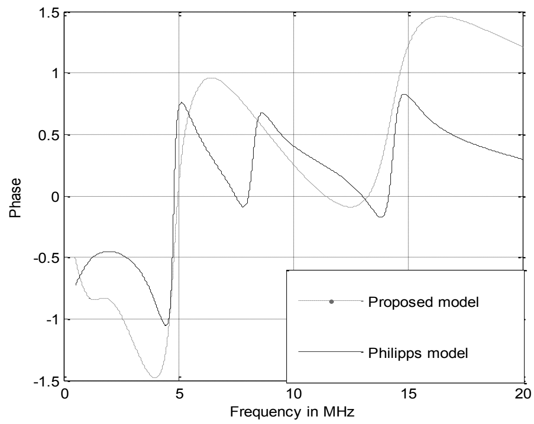

Figure 12: Phase response with resistance loads increased

We vary the radius r_m of the main cable, from 7 mm to 9 mm and the spacing between conductors D from 18 mm to 20 mm, at the user customer end; and radius r from 6.5 mm to 7 mm and the space between conductors D from 17 mm to 19 mm. Figures 9 and 10 show that the amplitudes of the notches increase, which implies that the transfer function also depends on these two parameters.

For the third configuration, we vary the loads only. First of all, we increase all five resistive loads as follows: $R_{AB} = 350\ \Omega$, $R_{BC} = 65\ \Omega$, $R_{BD} = 80\ \Omega$, $R_{BE} = 12\ \Omega$ and $R_{BF} = 30\ \Omega$. It is observed that the sharpness of the curve reduces as indicated in Fig.11 and Fig.12, thus meaning that the quality factor Q decreases when resistive load connected is increased. Also, the notches recede backwards in frequency compared to Phillips model.

5. CONCLUSIONS

Currently there is no universal model for the transfer function of the power line as there are many parameters that need to be known or measured before determining the transfer function. The model suggested here of

MHz as the loads are higher according to equation (21).

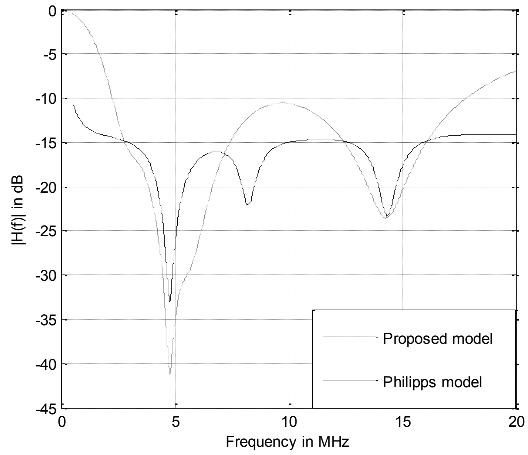

Figure 13: Amplitude response with resistance loads decreased

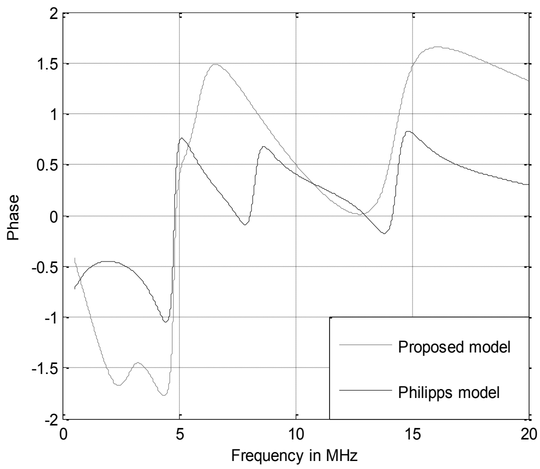

Figure 14: Phase response with resistance loads decreased

transmission line parameters is comparable to the *SRC* model of Phillips, which is based on the evolutionary strategy. In addition the model is dynamic with lengths of branches and load. The Phillips model does not give enough information about the influence of length on the transfer function. By setting the number of degrees of freedom to 42, the proposed model leads to an average RMS value of approximately 5.2 dB. With the same conditions, the Phillips model leads to an average RMS value of approximately 1.62 dB.

6. ACKNOWLEDGEMENT

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