Measurement of Telephone Line Parameters using the Three Voltmeter Method

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ABSTRACT
Telecom Egypt Company (TE) is the unique fixed telephone line company in Egypt. Due to the huge demand for high data rates for personals and companies, the performance of the copper network needs to be evaluated to assess its capability for transmitting high data rates to meet the increased demand on data transmission. The most commonly used testing and measuring instrument in TE is "Dynatel 965DSP", which has some drawbacks.

This paper introduces a new methodology for measuring the telephone line parameters. This method is based on the three voltmeter method for measuring resistors, capacitor, inductors and vector impedances. This method is automated by using NI-6008 USB data acquisition DAQ card. The frequency range of interest extends from 0.8 KHz to 196 KHz. The experimental results of the transmission line parameters, R, C, characteristic impedance, phase constant and attenuation constant have acceptable accuracy, while the results of the inductance and conductance have errors greater than the acceptable values.

General Terms
A new methodology for measuring the twisted pair transmission line parameters, three voltmeter method, Data Acquisition System

Keywords
Telecom Egypt company; "Dynatel 965DSP"; Three Voltmeter method; Data Acquisition Card; Telephone line parameters measurement.

1. INTRODUCTION
Because of increasing demand on the data communication across the public telephone network, it is required to assess the capability of the copper network for high data rates transmission especially as part of this network is old. This required evaluation of the copper network is accomplished by measuring representative samples of transmission line parameters [1-4]. These parameters are: the resistance (*R*) per kilometer km, the capacitance (*C*) per km, the inductance (*L*) per km, the conductance (*G*) per km, the characteristic impedance (Z_0), the attenuation constant *Alpha* (α) and the phase constant *Beta* (β). In TE company, "Dynatel 965DSP" instrument is used to measure some of these transmission line parameters (*R, C* and α). This instrument is an expensive in addition, it cannot measure all the required transmission parameters. In our work, a new cheap, reliable and sufficiently accurate automatic measurement method is introduced to carry out all these measurements. This method is the three voltmeter method [5-10]. By using this method with the Data Acquisition System (DAS) [11-14], all the RLCG transmission parameters can be measured.

In this paper, we develop an automatic testing method of the transmission line parameters based on the three voltmeter method with DAQ card and a PC. The paper is organized as follows: section 2 contains RLCG parameterized model of the transmission line, section 3 contains the three voltmeter method principle and the setup circuit. Section 4 presents the experimental results and the comparison with "Dynatel 965DSP" results and the RLCG parameterized model. Section 5 and section 6 contain the comments on the results and finally the conclusions.

2. RLCG PARAMETERIZED MODEL
In this section, the analytical model is described and the equations of the different parameters are illustrated [7]. The model equation of the resistance is:

$$R(f) = \frac{1}{\frac{1}{\sqrt[4]{r_{oc}^4 + a_c.f^2}} + \frac{1}{\sqrt[4]{r_{os}^4 + a_s.f^2}}} \quad (1)$$

Where r_{oc} is the copper DC resistance and r_{os} is (any) steel DC resistance, while a_c and a_s are constants characterizing the rise of resistance with frequency in the "skin effect".

$$L(f) = \frac{l_0 + l_\infty \left(\frac{f}{f_m}\right)^b}{1 + \left(\frac{f}{f_m}\right)^b} \quad (2)$$

Where l_0 and l_∞ are the low frequency and high frequency inductance, respectively and b is a parameter chosen to characterize the transition between low and high frequencies in the measured inductance values.

$$C(f) = C_\infty + C_0.f^{-c_e} \quad (3)$$

Where C_∞ is the contact capacitance and C_0 and C_e are constants chosen to fit the measurements.

$$G(F) = g_0.f^{+g_e} \quad (4)$$

Where g_0 and g_e are constants chosen to fit measurements. Referring to [17], the values of 26-AWG parameters are presented. It is noticed that, the parameterized RLCG model values coincide well with the TE standard values.

3. THREE VOLTMETER METHOD AND SETUP CIRCUIT
The three voltmeter method is primarily suited for power and energy measurements, but it is also well suited for impedance measurements provided that suitable reference impedance and three highly-accurate voltmeters are available [5-10]. Recently the three voltmeter method has been found very convenient for routine calibration of standards of self-inductance, inductor losses, and it has also been applied to calibration of

the mutual inductance. The basic arrangement of the measurement method is shown in Figure 1, where $Z_x = R_x + jX_x$ is the Device Under Test (DUT) and $Z_s = R_s + jX_s$ is the reference impedance standard. Using three highly-accurate voltmeters, the peak voltage values of voltages V_X, V_S and V_T can be measured across Z_X, Z_S and the signal source respectively. Practically, a known resistor is used as the known impedance for simplicity and more accuracy.

$$\alpha = \left({}^{V_T}/_{V_S}\right) \tag{5}$$

$$\alpha_X = \left({}^{V_X}/_{V_S}\right) \tag{6}$$

$$\alpha_B = \frac{\alpha^2 - \alpha_X^2 - 1}{2} \tag{7}$$

$$\alpha_A = \frac{1}{2}\sqrt{[1 - (\alpha - \alpha_X)^2][(\alpha + \alpha_X)^2 - 1]} \tag{8}$$

Thus, the values of the unknown impedance real and imaginary parts are determined using equation (9)

$$R_X = \alpha_B R_S$$
$$X_X = \alpha_A R_S \tag{9}$$

To be sure of the unknown impedance imaginary part; inductive or capacitive, a slight change in the usable frequency is made. If the imaginary part value increases; or the total impedance absolute value, so it is inductive. If the imaginary part value decreases, so it is capacitive.

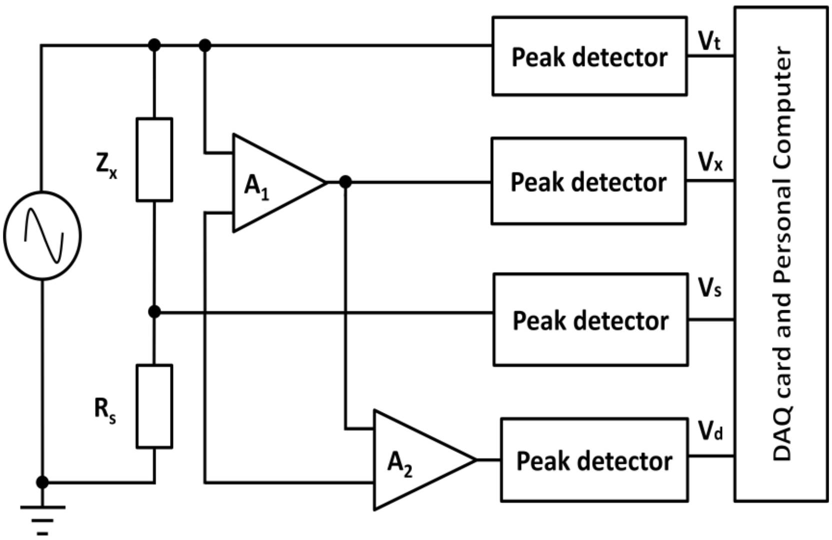

Fig 1: The modified three voltmeter method measuring circuit

Actually, we are not interested in knowing the exact measured values of these voltages; rather we really concerned about the weighted magnitude values i.e. the relative magnitudes with respect to, e.g. the applied signal. Accordingly, we can replace ac voltmeters by three peak detectors. The output voltages of the peak detectors are measured automatically by the DAQ card.

Both of the two amplifiers A_1 and A_2 are differential amplifiers. The used amplifiers are of type LM318 and diodes (*D*) of type 1N4148 which are commercially available. Figure 2 demonstrates the used peak detector circuit. This peak detector circuit has some limitations. First, the circuit accuracy is severely deteriorates unless the amplifiers have high slew rate and frequency response extending to tens or even hundreds of megahertz. Second, the circuit performance is limited by the characteristics of used op-amps.

The voltages of interest are measured using DAS system which is explained in the next section. The used DAQ card is NI-6008 USB [15, 16] which has 12-bit resolution, maximum input analog voltage of 10 V and sampling rate of 10 Ks/second.

4. EXPERIMENTAL RESULTS

A cable length of 20m, 26-AWG is used in the test with known resistance of 10 KΩ as the standard (known) impedance.

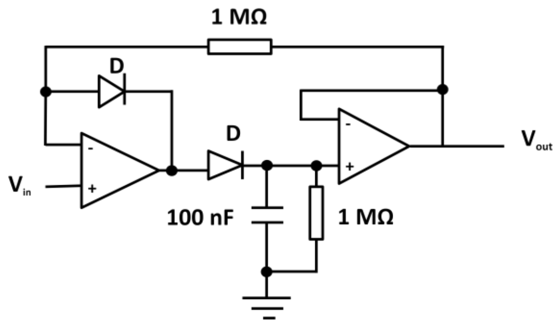

Fig 2: Peak detector circuit

The experiment is interested in the frequency band starting from 0.8 KHz to 196 KHz. All connections were performed on a bread board and using commercially available components. First, the open circuit transmission line input impedance Z_{ioc} is measured then the short circuit transmission line input impedance Z_{isc} is measured. Substituting both Z_{ioc} and Z_{isc} in the transmission line equations (10) and (11),

the transmission line parameters are calculated.

$$Z_{ioc} = Z_0/\tanh(\gamma d) \tag{10}$$

$$Z_{isc} = Z_0 \tanh(\gamma d) \tag{11}$$

After measuring both Z_{ioc} and Z_{isc}, characteristic impedance Z_0, and propagation constant γ are calculated. Substituting γ

and Z_0 in equations (12), (13), (14) and (15), then *R*, *L*, *C* and *G* are calculated.

$$R = \Re(\gamma Z_0) \tag{12}$$

$$L = (1/\omega)\Im(\gamma Z_0) \tag{13}$$

$$C = (1/\omega)\Im\left(\frac{\gamma}{Z_0}\right) \tag{14}$$

$$G = \Re\left(\frac{\gamma}{Z_0}\right) \tag{15}$$

The simulation results of the transmission line parameters are shown in "Table 1". The experimental results of the transmission line parameters are shown in "Table 2".

Table 1. Transmission line parameters simulation results

Frequency (KHz)	R (Ω/Km)	L (μH/Km)	C (nF/Km)	G (μS/Km)	Z_0 (Ω)	α (nep/Km)	β (rad/Km)
0.8	300.18	0.589	49.04	4.956	1103.43	0.194	0.19
1.004	300.18	0.588	48.96	5.52	985.742	0.217	0.213
2.804	300.18	0.586	48.78	12.27	590.995	0.362	0.356
8	300.18	0.587	49	23.87	349.102	0.611	0.605
20	300.18	0.589	49.01	43.86	220.764	0.965	0.958
40	300.18	0.589	49.02	70.99	156.085	1.363	1.356
80	299.59	526.96	49.04	114.98	127.366	1.297	2.859
196	296.05	620.77	49.01	355.72	114.798	0.987	6.858

Table 2. Transmission line parameters experimental results

Frequency (KHz)	R (Ω/Km)	L (μH/Km)	C (nF/Km)	G (μS/Km)	Z_0 (Ω)	α (nep/Km)	β (rad/Km)
0.8	300.18	0.65	54.03	3.66	1051.3	0.203	0.2
1.004	300.18	0.66	54.85	3.09	931.384	0.229	0.227
2.804	300.18	0.56	47.16	76.46	599.81	0.37	0.34
8	300.18	0.58	48.16	44.5	350.465	0.6111	0.6
20	300.18	0.58	48.42	133.59	222.088	0.966	0.945
40	300.18	0.59	49.04	427.33	156	1.383	1.34
80	299.6	527.129	48.46	4068.3	127.259	1.523	2.75
196	295.08	600.55	48.69	16656.3	113.113	2.138	6.52

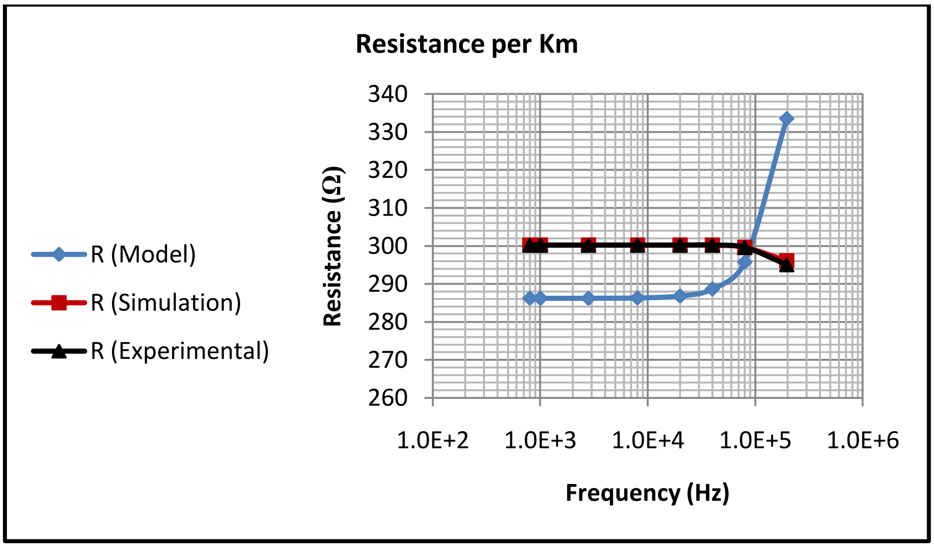

Fig 3: Resistance per Km

Figure 3 shows that the experimental results of R have acceptable accuracy frequency band. At the frequency 196 KHz, the measured value has a large error compared to the RLCG model. The error can be reduced if the known resistance value is chosen to be 1 KΩ. The accuracy of measurements using the three voltmeter method improves when the value of both the known and unknown impedances are nearly equal.

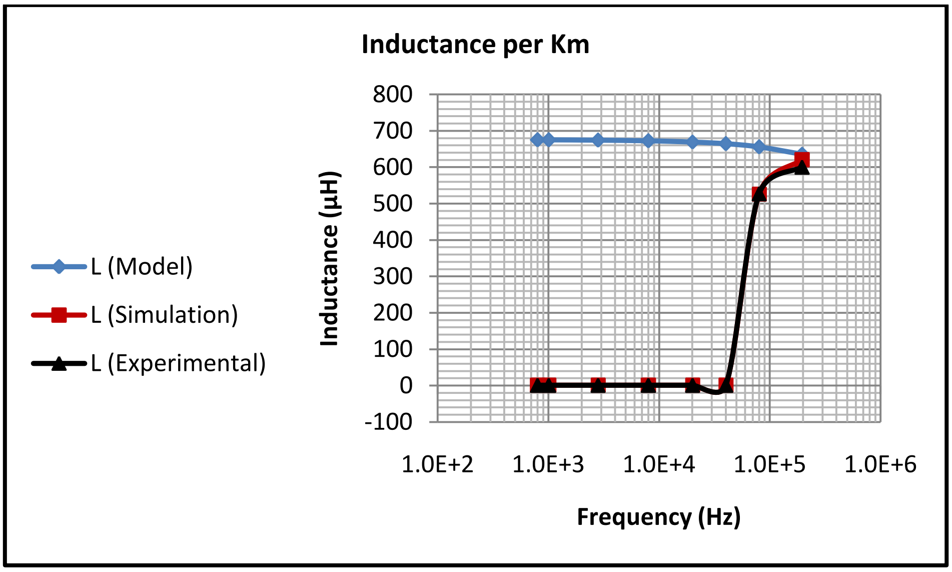

Fig 4: Inductance per Km

Figure 4 illustrates that the simulation and experimental results of L have large error value compared to the RLCG model for most of the frequency band. The accuracy improves at 196 KHz frequency. The transmission line equations implies that

$$Z = R + j\omega L \qquad (16)$$

Where Z represents impedance per unit length. At low frequency band, L is very small as

$$\omega L \ll R \qquad (17)$$

This means that the value of R is dominant at low frequencies. The phase is very small in this case so L cannot be measured with acceptable accuracy.

The value of L can be measured with good accuracy at high frequencies in addition to decreasing the known resistance value. Using a DAQ card of higher resolution; 16-bit, can give more accurate results.

The amplifier used is LM318 which is commercially available. Also, using precision amplifier in the peak detector circuit and measuring circuit can allow us to get more accurate results.

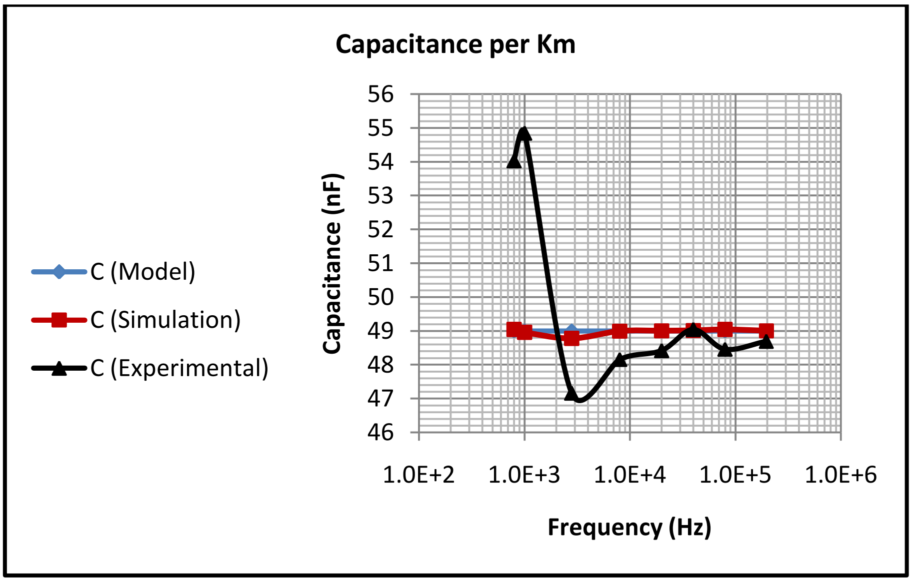

Fig 5: Capacitance per Km

Figure 5 shows that the simulation and experimental results of *C* have acceptable accuracy compared to the RLCG model. The RLCG model shows that the capacitance has a constant value of 49 nF/Km at all frequencies.

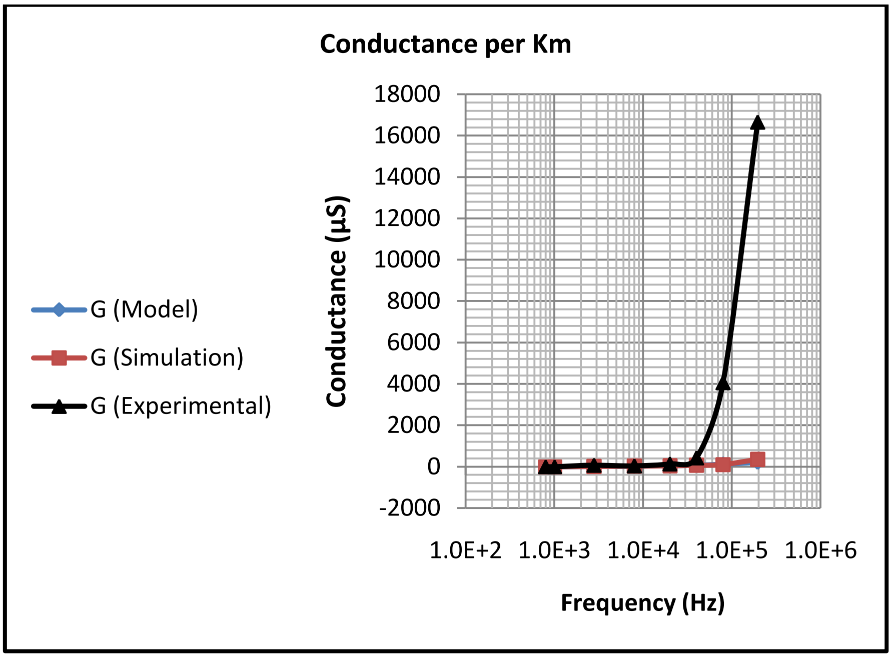

Fig 6: Conductance per Km

Figure 6 shows that the simulation and experimental results of *G* have acceptable accuracy compared to the RLCG model at low frequencies while have large error value at high frequencies. The transmission line equations implies that

$$Y = G + j\omega C \qquad (18)$$

Where *Y* represents admittance per unit length. At low frequencies, *G* is dominant as it has greater value than $|\omega C|$ so it can be measured with good accuracy. However, *G* is very small with respect to $|\omega C|$ at high frequencies so the measured value error is high. The value of *G* can be measured with good accuracy at low frequencies in addition to increasing the known resistance value. Using higher resolution DAQ card and precision amplifiers can give more accurate results.

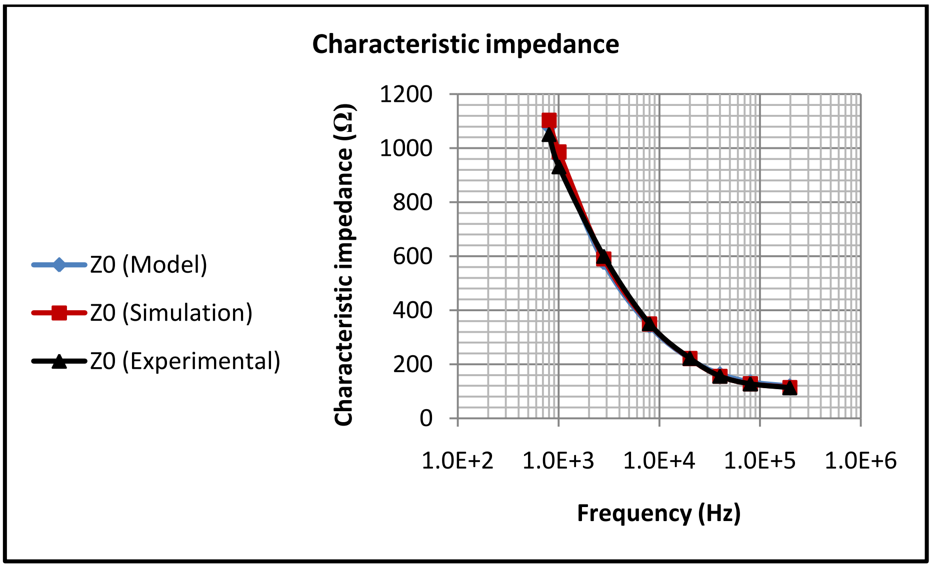

Fig 7: Characteristic impedance

Figure 7 shows that the simulation and experimental results of Z_0 have acceptable accuracy compared to the RLCG model at all frequencies. It is noticed that the characteristic impedance value decreases as the frequency increases.

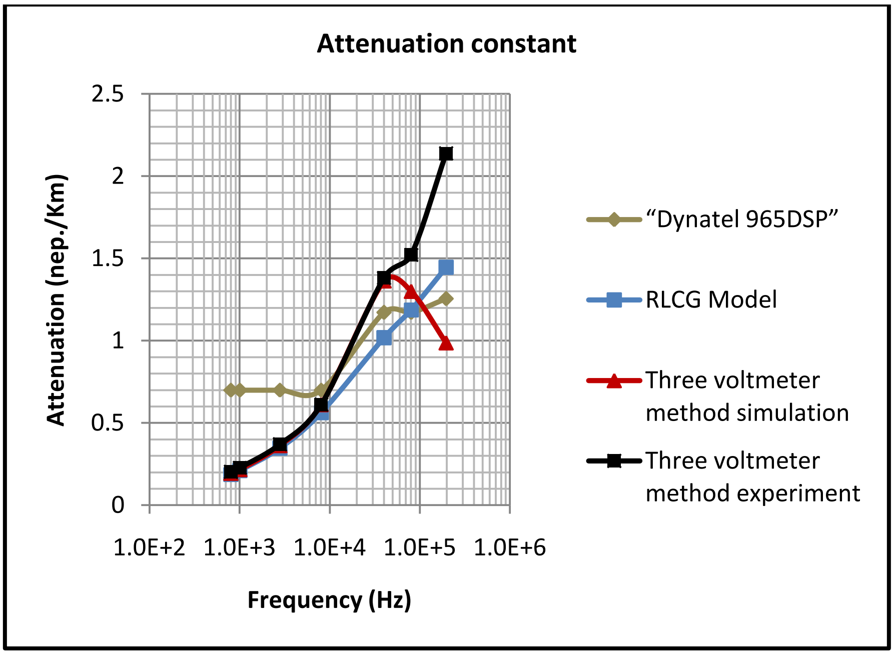

Fig 8: Attenuation constant per Km

Figure 8 shows that the simulation and experimental results of the attenuation constant have acceptable accuracy compared to RLCG model at low frequencies. The attenuation constant is calculated mathematically according to the equation

$$\alpha = \Re\left(\sqrt{(R + j\omega L)(G + j\omega C)}\right) \quad (19)$$

Equation (19) shows that there is a relation between the attenuation constant and the transmission line parameters so the obtained error is due to all errors in the transmission line parameters. The improvement of the measured values as discussed above yields to decreasing the error. Figure 8 also shows that the "Dynatel 965DSP" results have large error values at low frequencies and acceptable accuracy values at high frequencies.

Figure 9 shows that the simulation and experimental results of the phase constant have acceptable accuracy compared to RLCG model at low frequencies. The phase constant is calculated mathematically according to the equation

$$\beta = \Im\left(\sqrt{(R + j\omega L)(G + j\omega C)}\right) \quad (20)$$

Equation (20) shows that there is a relation between the phase constant and the transmission line parameters so the obtained error is due to all errors in the transmission line parameters. The improvement of the measured values as discussed above yields to decreasing the error.

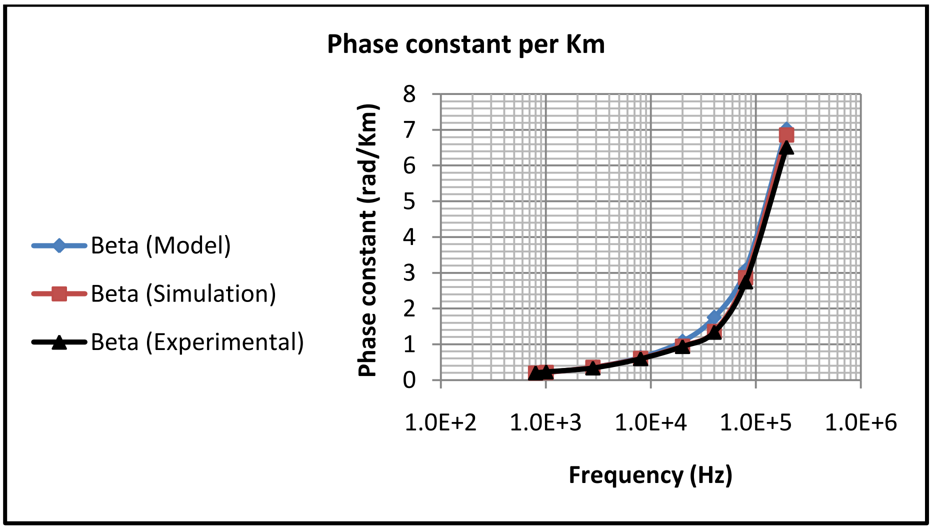

Fig 9: Phase constant per Km

5. CONCLUSIONS

From the simulation and experimental results of the three voltmeter method and the comparison with the RLCG model and the measured values obtained by "Dynatel 965DSP" instrument, the accuracy of *R* does not exceed 4.89% error for frequency range 0.8 KHz to 80 KHz, while it suffers from large error value at 196 KHz. The accuracy of *C* is less than 3.75% for the frequency range 2.804 KHz to 196 KHz, while it exceeds the accepted value error (10%) by a small amount for both frequencies 0.8 KHz and 1.004 KHz. the accuracy of Z_0 does not exceed 5.2% error for frequency range of interest. The accuracy of α does not exceed 8.54% for the frequencies less than or equal 8 KHz while suffers from large error value for frequencies higher than this frequency. The accuracy of β does not exceed 8.1% for the frequencies less than or equal 8 KHz while suffers from large error value for frequencies higher than this frequency. The attenuation constant result obtained by the three voltmeter method is more accurate than the result obtained by "Dynatel 965DSP" at l.004 KHz; the standard frequency in TE measurements. *L* and *G* suffer from large error values. The three voltmeter method has many advantages. First, the three voltmeter circuit is simple and cheap. Second, most of the measured parameters have acceptable accuracies. Third, the program is simple to be used by engineers and technicians. Finally, the parameters are calculated easily. Also, the "Dynatel 965DSP" does not measure all the transmission line parameters as the three voltmeter method.

The main disadvantage of the three voltmeter method is that its accuracy depends on the accuracy of the measured voltages and the used DAQ card.

As a future work, measuring the telephone line parameters using the three voltmeter method can be used in Resistance Fault Location (RFL) of the telephone cables. The accurate determination of the fault location depends on the accuracy of the telephone line parameters; especially the resistance *R*. Using the three voltmeter method in RFL enhances the accuracy of fault location determination to be better than the accuracy obtained by "Dynatel 965DSP" in addition to the advantages of the three voltmeter method.

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