The Factors Influencing Signal Propagations in the Underground Cable for Broadband Power-Line Communications (PLC) Systems

Justinian Anatory and Nelson Theethayi

***Abstract*—Recently power-line network has been proposed for broadband power-line communications. The network construction in most of the countries is the mixture of overhead and underground networks. The underground cable power transmission system is widely used in urban low voltage power distribution systems. In order to access the performance of such distribution systems as a low voltage broadband power line communication (BPLC) channel, this paper investigates the effects of load impedance, line length and branches on such systems, with special emphasis to the power line networks found in Tanzania. From the frequency response of the transfer function (ratio of the received and transmitted signals), it is seen that position of notches and peaks in the magnitude are largely affected (observed in the time domain responses too) by the above said network configuration and parameters. The observations presented in the paper could be helpful in suitable design of the PLC systems for a better data transfer and system performance.**

***Index Terms*-- load impedance, broadband power line, transfer function, multipath, branched network, interconnections, low voltage channel, underground cable.**

I. INTRODUCTION

RECENTLY power-line have been proposed as an infrastructure for Broadband Services, digital entertainment systems, and other services in most of the countries. However, the network is affected in terms of channel attenuation, variable position of notches, signal distortions, etc. In literature e.g. [1-7], the stochastic signals attenuations, notches, etc. are due to switching ON/OFF of equipments (sudden changes in loads), addition of new lines or customers, etc.

For this reason in the case of buried power transmission system working as a BPLC system, we shall study the influence of number of branches (N_{ob}), line lengths (d_L) from transmitter to the receiver and branched line length (X), terminal loads (infinite and low) impedances (Z_{inf} & Z_{Low}) on the signal response based on transmission line analysis.

The information presented in the paper could be helpful in BPLC system design that involves buried cables.

II. SYSTEM UNDER STUDY

In general the transmission line equations that are to be solved for voltage and currents on the line are given by (1). Assume that the line oriented in the x direction.

$$\left.\begin{aligned}\frac{dV(x,j\omega)}{dx}&=Z(j\omega)\cdot I(x,j\omega)\\ \frac{dI(x,j\omega)}{dx}&=Y(j\omega)\cdot V(x,j\omega)\end{aligned}\right\}\tag{1}$$

In (1) V and I are the voltage and current on the line and Z and Y are the total series impedance and shunt admittance of the line. The configuration of an underground cable power line beginning from a distribution transformer is shown in Fig. 1a and the corresponding transmission line representation for an adjacent conductor return is shown in Fig. 1b. Fig. 1c shows the cross section of a typical power cable that has four conductors. Thus for the case with adjacent conductor return the series impedance and shunt admittance of the line needed for solving (1) including the possible skin effect phenomena [8] of the conductor are shown below $Z(j\omega)=Z_i(j\omega)+j\omega\cdot L_e$ and $Y(j\omega)=G(j\omega)+j\omega\cdot C_e$.

$$Z_i(j\omega)\approx A+B\sqrt{j\omega}\tag{2a}$$

$$A=R_{DC}=\frac{1}{\pi.\sigma.r^2}\tag{2b}$$

$$B=\frac{1}{2\pi.r}.\sqrt{\frac{\mu}{\sigma}}\tag{2c}$$

$$G(j\omega)=2\pi.f.C_e.\tan(\delta)\tag{3a}$$

$$\delta=\frac{2}{\sqrt{\omega.\mu.\sigma}}\tag{3b}$$

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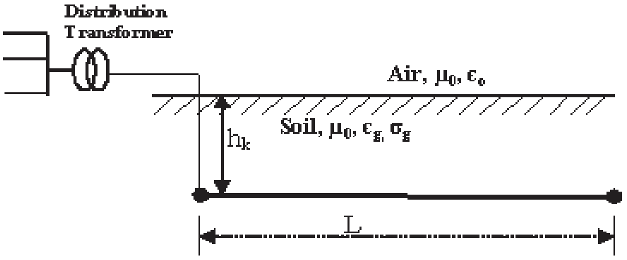

Fig. 1a: The underground cable with adjacent conductor as a return conductor

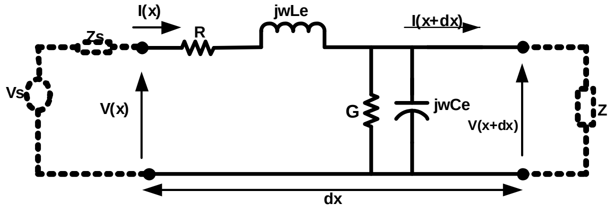

Fig. 1b: Per unit length equivalent underground circuit with adjacent conductor as a return

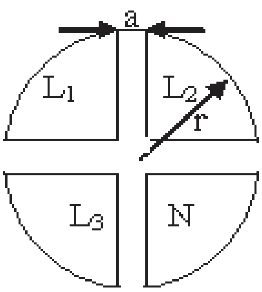

Fig. 1c: Cross section of a typical power line cable (4 conductors)

For the configuration corresponding to fig. 1a, h_k is the depth of the cable below the ground, with radius r and L is line length. The per unit length transmission line parameters are given by (4) for self inductance and capacitance of the line [6].

$$\left.\begin{aligned} L_e &= \mu_0 . \mu_r . \frac{a}{r} \\ C_e &= \varepsilon_0 . \varepsilon_r . \frac{r}{a} \end{aligned}\right\} \qquad (4)$$

III. POWER LINE CHANNEL MODEL

For a transmission line with distributed branches (e.g. fig. 2) the generalized transfer function can be represented by (5a) [9-16]. In (5a), N_T is the total number of branches connected at given node (e.g. see 'node 1' in fig. 2) and terminated in any arbitrary load. Let n, m, M, $H_{mn}(f)$ and T_{Lm}, represent, any branch number, any referenced (terminated) load, number of reflections (with total of L number of reflections), transfer function between a given source point (transmitter) to a referenced load termination m, transmission factor with reference to any load termination m, respectively. With these the signal contribution factor α_{mnd} at referred node'd' is given by (5b), where ρ_{nmd} is the reflection factor at node the referred node d between line $\mathbf{n}$ to the referenced load m, γ_{nd} is the propagation constant of line $\mathbf{n}$ at referred node 'd' that has line length ℓ_{nd}. All terminal reflection factors P_{Lnd} in general are given by (5c), except at source, where $\rho_{L1} = \rho_s$ is the source reflection factor [10]. Also Z_s is the source impedance, Z_n is the characteristic impedance of any terminal with source while V_s and Z_L are source voltage and load impedance respectively based on fig.2. M_T is the total number of distributed nodes (1, 2...d...M_T).

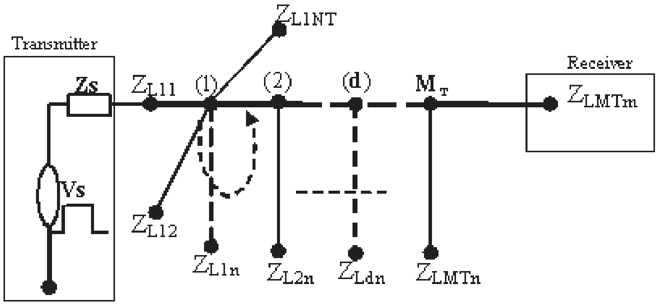

Fig. 2: Power line network with distributed branches

$$H_{mM_T}(f) = \prod_{d=1}^{M_T} \sum_{M=1}^{L} \sum_{n=1}^{N_T} \mathrm{T}_{Lmd} \alpha_{mnd} H_{mnd}(f) \qquad \mathbf{n} \neq \mathbf{m} \qquad (5a)$$

$$\alpha_{mnd} = P_{Lnd}^{M-1} \rho_{nmd}^{M-1} e^{-\gamma_{nd}(2(M-1)\ell_{nd})} \qquad (5b)$$

$$P_{Lnd} = \begin{cases} \rho_s & d = n = 1 (source) \\ \rho_{Lnd}, & otherwise \end{cases} \qquad (5c)$$

In (6) $h_{mMT}(t)$ is the impulse response obtained by inverse Fourier transform of (5a).

$$h_{mM_T}(t) = \prod_{d=1}^{M_T} \sum_{M=1}^{L} \sum_{n=1}^{N_T} \mathrm{T}_{Lmd} \alpha_{mnd} h_{mnd}(t) \qquad n \neq m \qquad (6)$$

IV. INFLUENCE OF LINE LENGTH

A. *Length from transmitter to the Receiver*

We consider the power line cables used in low voltage systems, whereby the line ABC (see fig. 3) is NAYY150SE with radius (r) per conductor equal to 6.9099mm, the insulation thickness (a=1.8mm), relative permittivity=4, using (4) the per unit length parameters are (L_1=0.32735µH/m, C_1=0. 27191pF/m). The branched cable BD is NAYY35RE with radius (r) per conductor equal to 5.9161mm, the insulation thickness (a=1.2mm), relative permittivity=4, using (4) the per unit length parameters are (L_2= 0.45179µH/m, C_2= 0.19702 pF/m) [5-7]. The characteristic impedance of the line was calculated as $Z = \sqrt{Z(j\omega)/Y(j\omega)}$ while the propagation constant as $\gamma = \sqrt{Z(j\omega)Y(j\omega)}$, whereby the parameters $Z(j\omega)$ and $Y(j\omega)$ is as described previously. The characteristic impedance of line AB is Z_1 while the characteristic impedance of BD is Z_2. In fig. 3, Z_L=Z_s=Z_1. For sensitivity, analysis the line length AC was varied as 1.2km, 600m, 300m and 150m, with point B always at mid point of AC. The branched line length (BD) was kept constant at 15m and terminated in 10kΩ. The transfer function was calculated by taking the voltage ratio of point C to that of A i.e. using (5). Fig.4 (a-d) shows the transfer function relating the voltages at the load and sending end for various lengths of AC with the same boundary conditions at line terminations. From fig.4, the peaks and notches in frequency response do not vary with either frequency or line length. The position of peaks and notches is independent of the line length from transmitter to receiver. However, the attenuation is increasing as line length and frequency increases. The effects of branch length are studied next.

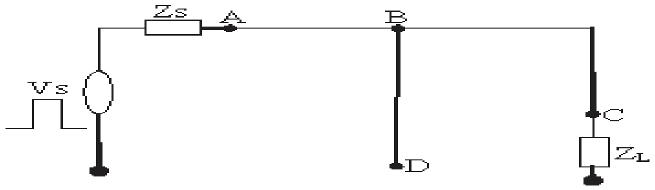

Fig. 3: Power line network with branch

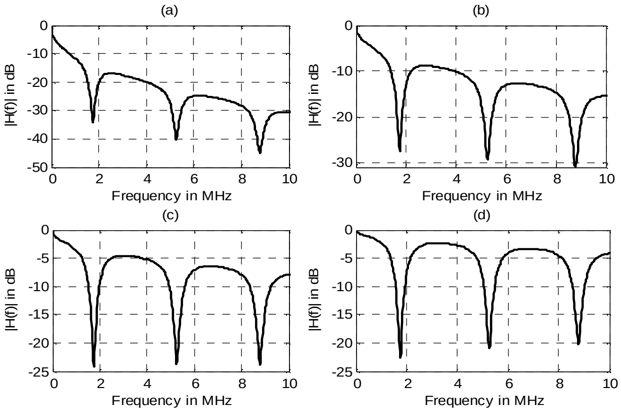

Fig. 4: Simulation Results for underground cable of a link with one branch (a) 1.2km (b) 600m (c) 300m (d) 150m.

B. Branched Length

The configuration is same as in fig. 3; but now the length AC is kept constant at 1.2km, while the length of BD was varied as 10m, 20m, 30m and 40m. Point D was terminated in 10kΩ. Similar investigations as done previously were carried out using (5). The transfer function for all cases relating the voltage at the load (Z_L) and launched voltage at point A is shown in fig. 5(a-d). It is observed that the position of notches and peaks are case dependant (dependant on branched line length). As the branched line length increases, number of notches increase. The attenuation in each case is increasing with the frequency. The generalized expression for frequency position (f_i in MHz) of an ith notch in terms of branched line length (X in m) is approximately given by (7). Next let us study the effect of number of interconnected branches.

$$f_i = \frac{26}{X}(1+2.i), \quad \forall i = 0,1,2... \tag{7}$$

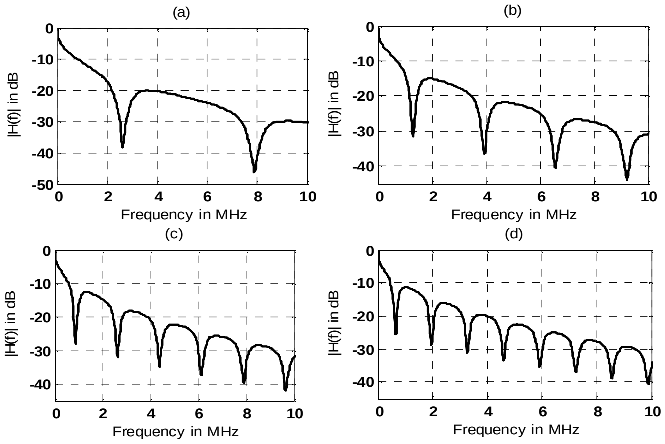

Fig. 5: Simulation Results for Low voltage channel of 1.2km with one branch of length (a) 10m (b) 20m (c) 30m (d) 40m.

V. INFLUENCE OF NUMBER OF BRANCHES

A. Multiple Branches at single node

Consider the configuration in fig. 6. The line length of AC is 1.2km with all branches 15m long concentrated at node B and terminated in 10kΩ. We vary the number of branches as 2, 4, 5 and 6 and fig. 7(a-d) shows the transfer functions for different number of branches. It is seen that the sharpness of notches are decreases with increase in number of branches at the same node, but with further increase in number of branches there is a tilt in the notch shape leading to a reduction in attenuation.

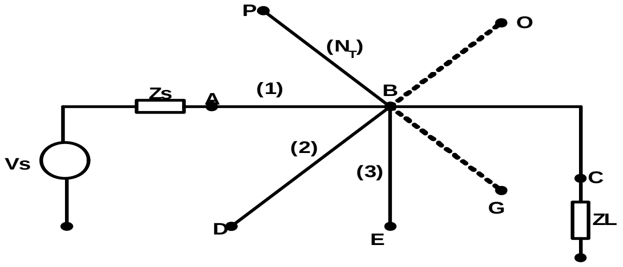

Fig. 6: Power line network with five multiple branches at a single node

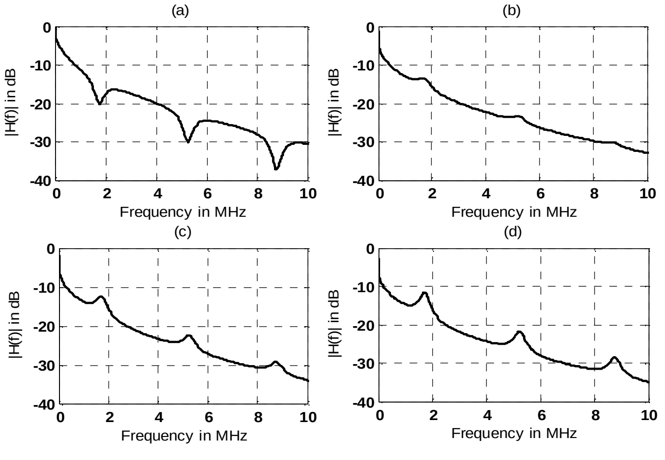

Fig. 7: Simulation results for medium voltage channel with multiple branches at single node (a) 2 branches (b) 4 branches (c) 5 branches (d) 6 branches

B. *Distributed Branches*

Now consider the underground cable with distributed branches as in fig 8. The number of branches was increased in the link between point A and J. The length AJ was 1.2km while all branches were 15m. The number of branches was increased as 2, 5, 10 and 15 such that in each case they were equally distributed between A and J. The terminations were each branch in any of the case was 10kΩ. Fig. 9(a-d) is the transfer function for different number of branches. It is seen that the positions of deep notches are not changed. As the number of branches increase the attenuations tends to increase.

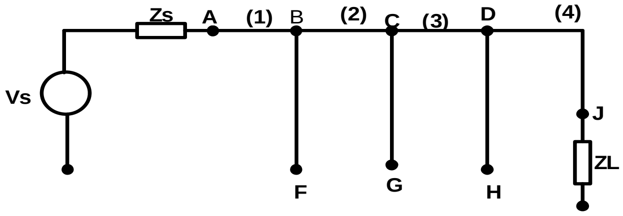

Fig. 8: Power line low voltage network with distributed branches

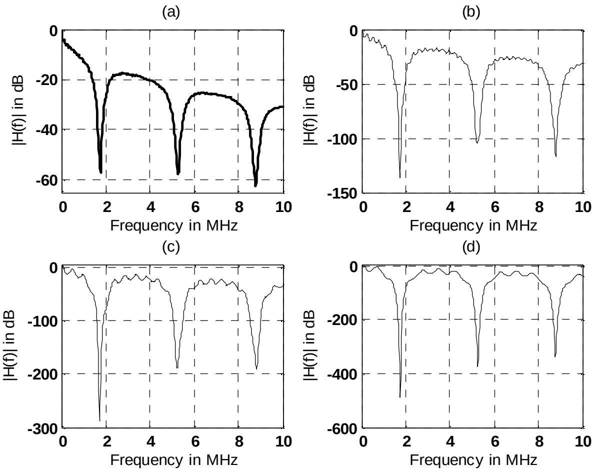

Fig. 9: Simulation results for low voltage channel with distributed branches (a) 2 branches (b) 5 branches (c) 10 branches (d) 15 branches

VI. INFLUENCE OF LOAD IMPEDANCE

A. *Low Resistive Load*

We now consider the effects of load impedances. The load impedances at point D in fig. 3 were varied as 5Ω, 10Ω, 20Ω and characteristic impedance. The length of AC is 1.2km and BD is 15m. Fig. 10(a-d) is a transfer function for all cases. It is seen that as the load impedance increases towards characteristic impedance the notches tend to improve.

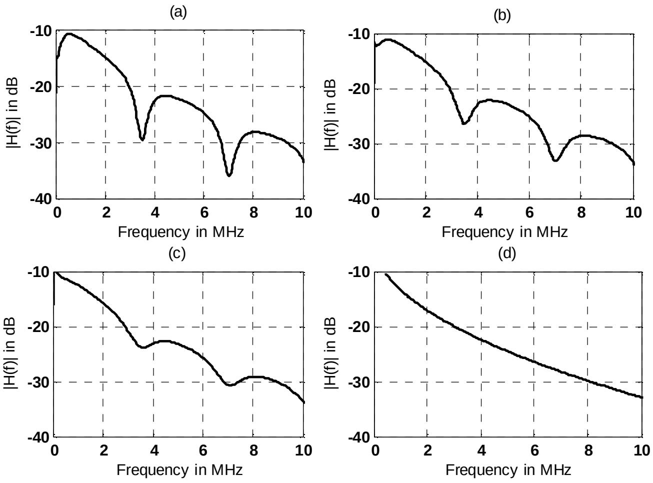

Fig. 10: Simulation results for low voltage channel with distributed branches (a) 5Ω (b) 10Ω (c) 20Ω (d) Zo

B. *High Resistive Load*

We consider the same case as in previous example but now with higher impedances for the load varied as50Ω, 100Ω, 1kΩ and 10kΩ. Fig. 11(a-d) is transfer function. It is seen that as the load impedance tends to be higher than channel characteristic impedance, the notches become tend to be more prominent.

The general expression for position of notches with open circuit load impedance is given by (8).

$$f_i = \frac{52}{X}(1+2i), \quad \forall i = 0,1,2... \qquad (8)$$

Next let us see the influence of load impedance, line length and branches on the channel capacity of the underground cable.

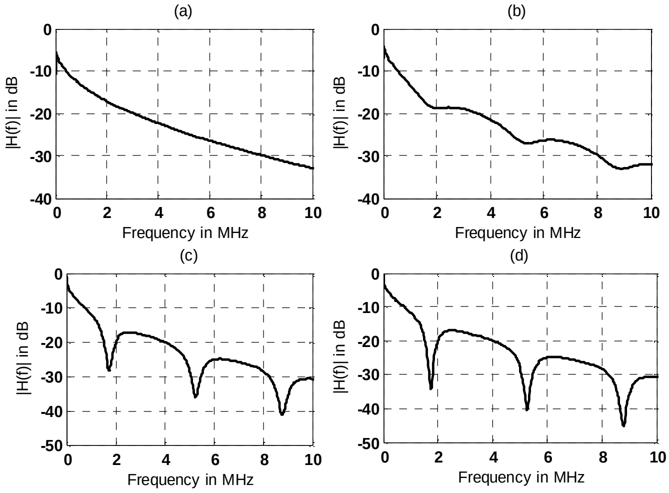

Fig. 11: Transfer function Response for low voltage channel with distributed branches (a)50Ω (b) 100Ω (c) 1kΩ (d) 10kΩ

VII. CONCLUSION

For underground low voltage cable channel the position of notches in frequency response do not vary with either transmitted source frequency or direct line or link length connecting the transmitting and receiving ends. However the signal attenuation increases as link length and frequency increases. Additionally the distortion increases in such a way that the signal tend to lose its original shape. The position of notches is case dependant, i.e. dependant on number of branches, branched line length and terminal impedances on those branches

As the branched line length increases, number of notches increase. The signal distortions also increase. The sharpness of notches are decreasing with increase in number of branches at the same node, but with further increase in number of branches there is a tilt in the notch shape leading to a reduction in attenuation. The increasing number of branches at the same node causes the received signals to be more attenuated and distorted. As the number of distributed branches in the link between the sending and receiving ends increase the attenuations tends to increase in such a manner that there could be a reduction in the available bandwidth. The reason could be due to the successive reflection from the distributed branches.

As the terminal impedances on the branches increase to line characteristic impedance, the notches tend to improve and both signal attenuation and distortions tend to reduce. As the load impedance is increased beyond corresponding line characteristic impedance, the notches tend to be more prominent and both signal attenuation and distortions improves further. It can be concluded that the adaptive means is appropriate to be able to communicate appropriately and equalizers is needed to overcome signal distortion. In addition for underground cables a number of repeaters are needed for feasible communication.

REFERENCES

[1] F. J. Canete, L. Diez, J. A. Cortes, J. T. Entrambasaguas, “Broadband Modeling of Indoor Power-Line Channels”, *IEEE Trans. On Consumer Electronics*, Vol. 48, No. 1, Feb. 2002.

[2] A. B. Gutierrez, A. Darmand, V. Watt, L. Ngalamou, “Design of an Analog Electronic Interface for a Power Line Based Telephony System”, *IEEE-ISPLC2006*, Florida, USA, March 2006, pp. 232-238.

[3] C. Papaleonidopoulos, C. G. Karagiannopoulos, D. P. Agoris, P. D. Bourkas, N. J. Theodorou. HF Signal Transmission over Power Lines and Transfer Function Measurement. *Proc. of the Sixth IASTED International Conference*. July 3-6, 2001, Rhodes, Greece. (502-505)

[4] N. Pavlidou, A.J. H. Vinck, J. Yazdani and B. Honary, “Power Line Communications: State of the Art and Future Trends”, *IEEE Communications Magazine*, April 2003. pp. 34-40

[5] M. Zimmermann and K. Dostert; “A Multipath Model for the Power line Channel”, *IEEE Trans. On Communications*, vol. 50, No. 4, April 2002. pp. 553-559

[6] M. Zimmermann and K. Dostert, “ A Multi-Path Signal Propagation Model for the Power Line Channel in the High Frequency Range Proc. of International Symposium on Power-line Communications and its Applications (ISPLC'99), pp. 45-51.

[7] M. Götz, M. Rapp and K. Dostert, “Power Line Channel Characteristics and their Effect on Communication System Design”, *IEEE Communications Magazine*, April 2004. pp. 78-86.

[8] S.N. Nahman and R. D. Holt., “Transient analysis of coaxial cables using the skin effect approximation,” *IEEE Transactions on Circuit Theory*, Vol. 19, No. 5, 1972, pp. 443-451.

[9] J. Anatory, N. Theethayi, R. Thottappillil, M.M. Kissaka and N.H. Mvungi, “The effects of Interconnections and Branched Network in the Broadband Power line Communications”, International Gathering of Radio Science, India, 23rd –29th October, 2005.

[10] J. Anatory, M.M. Kissaka and N.H. Mvungi, “Channel Model for Broadband Power line Communication”, *IEEE Trans. On Power Delivery,* January 2007 No. 1, pp. 135-141.

[11] Justinian Anatory, N. Theethayi, R. Thottappillil, M.M. Kissaka and N.H. Mvungi, The Effects of Load Impedance, Line Length and Branches in the BPLC- Transmission Lines Analysis: A Case of Indoor Voltage Channel, Accepted for publication *IEEE Transactions on Power Delivery*, 2007

[12] Justinian Anatory**,** N. Theethayi, R. Thottappillil, M.M. Kissaka and N.H. Mvungi, The Effects of Load Impedance, Line Length and Branches in the BPLC- Transmission Lines Analysis for Medium Voltage Channel, Accepted for publication IEEE Transactions on Power Delivery, 2006

[13] Justinian Anatory and Nelson Theethayi (2006), “On the Efficacy of Using Ground Return in the Broadband Power Line Communications–A Transmission Line Analysis”, Accepted for publication IEEE Transactions on Power Delivery

[14] Justinian Anatory, Nelson Theethayi, Rajeev Thottappillil, M.M. Kissaka and N.H. Mvungi (2006), “Broadband Power Line Communications: The Channel Capacity Analysis”, to appear IEEE Transactions on Power Delivery

[15] Justinian Anatory, Nelson Theethayi, Rajeev Thottappillil, M.M. Kissaka and N.H. Mvungi (2006), “Broadband Power line Communications: Factors Influencing the Signal propagations in the Medium Voltage Lines”, IEEE ISPLC2007, Pisa, Italy, 26-28, March 2007.

[16] J. Anatory, M.M. Kissaka and N.H. Mvungi, “Power line Communications: The effects of Branches on the network performance”, *IEEE-ISPLC2006*, Florida, USA, March 2006.

BIOGRAPHY

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