A Model for 10kV Overhead Power Line Communication Channel

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Abstract—In order to achieve reliable and high-speed 10kV power line carrier communications, it is necessary to study the characteristics of channel. Based on the multi-conductor transmission line theory, the chain matrix channel model is established. A lumped parameter model of distribution transformer is proposed from impedance measurement in the frequency range 50-500kHz. The terminal voltages and currents of whole network are derived, which reveals the causes of frequency selective fading. The simulation results are compared and analyzed between different signal frequencies and propagation paths, based on a simplified model of distribution network.

Index Terms—power line communication, multi-conductor transmission line, chain matrix, transformer model

I. INTRODUCTION

The Medium Voltage (MV) distribution line can be used as a communication platform, which is formed by many components with different electric characteristics (e.g., overhead and cable lines). To overcome these problems, recent research efforts are focusing on the investigation of signal propagation and the channel characteristics of the MV network[1].

There are two basic approaches modeling the distribution line communication channel. The first is to assume that the line is so complicated that signal strength can not be accurately computed. Multi-path propagation approaches have been proposed by Philipps[2] and Zimmermann[3]. The parameters for the multi-path model are obtained from measurements of the channel transfer function. This method of statistical channel modeling can not be used to predict the signal propagation without preliminary measurement. The second approach is to assume the signal strength can be accurately computed from a transmission line model. In literate [4-5], the channel model is based on two conductor transmission line theory, where the whole network is regarded as a cascade of various two-port networks. So this frequency-domain model works with all the signals reflected from the discontinuities of the network. But this approach can not be applied to MV PLC because the signal propagation in MV is effected by all three conductors and ground.

The classical work in three phase lines model was done by Hardy[6]. The multi-conductor transmission line theory is used to analyze the signal strength on distribution lines. But his result is not applicable to complex distribution network, and the load in his measurement is artificial. The practical MV/LV transformer model for PLC applications is proposed in literate [7], three kinds of measurements are carried out to determinate the parameters of the model. It is obvious that the parameters are varied with the types and capability of the transformer. In order to study the transfer characteristic of the transformer, further measurements are needed.

This paper is organized as follows. First, the chain matrix channel of distribution network is presented in Section II. The propagation characteristic of the whole network is analyzed in Section III. Section IV reveals the transmission characteristics of distribution network based on a simplified model. The concluding remark is given in Section V.

II. THE MODEL OF DISTRIBUTION NETWORK

For the power line communication, the distribution line should be regard as multi-conductor transmission lines (MTL).

A. MV Overhead Power Line Model

From Fig.1, the 10kV overhead power line communication coupling modes can be divided into phase to phase coupling and phase to ground coupling. If phase to ground coupling is chosen, the signal propagation can also be effected by the other two lines.

![Diagram](https://example.com/diagram.png)

Fig.1.(a)Phase to ground coupling . (b) Phase to phase coupling

The propagation on the MTL is governed by the transmission line equation

\[
\frac{d^2}{dz^2} V(z) = Z Y V(z) \]
\[
\frac{d^2}{dz^2} I(z) = Y Z I(z) \]

Where \( V(z) = [v_1, v_2, v_3]^T \), \( I(z) = [i_1, i_2, i_3]^T \) are voltages and currents vectors respectively. The per-unit-length impedance matrix \( Z \) and admittance matrix \( Y \) are given by
The per-unit-length parameter matrices of resistance $R$, inductance $L$, capacitance $C$, and conductance $G$ can be determined from frequency, conductor and bundle characteristics, line geometry, etc. These line parameters are specified by $[3 \times 3]$ matrices calculated by the Matlab tools of power_lineparam.

In order to decouple the voltages and currents of different conductors, the transfer matrices $T_v$ and $T_i$ are introduced.

$$V(z) = T_v V_m(z)$$
$$I(z) = T_i I_m(z)$$

The $3 \times 3$ complex matrices $T_v$ and $T_i$ are said to be similarity transformations between the actual phase line voltages and currents, $V_m(z)$ and $I_m(z)$, which can be obtained from per-unit lines parameters. The proper $T_v$ and $T_i$ can be calculated, which make $T_v^{-1}ZYT_i$ and $T_i^{-1}YZT_i$ be the diagonal matrices. Then the uncoupled equations are derived as:

$$\frac{d^2}{dz^2} V_m(z) = T_v^{-1}ZYT_i V_m(z) = \gamma^2 V_m(z)$$
$$\frac{d^2}{dz^2} I_m(z) = T_i^{-1}YZT_i I_m(z) = \gamma^2 I_m(z)$$

Where $\gamma^2$ is the eigenvalue of matrix $ZY$ and $YZ$.

$$\gamma^2 = \begin{pmatrix} \gamma_1^2 & 0 & 0 \\ 0 & \gamma_2^2 & 0 \\ 0 & 0 & \gamma_3^2 \end{pmatrix}$$

The general solutions to these uncoupled equations are

$$I_m(z) = e^{-\gamma_1 z} I_m^+ - e^{\gamma_2 z} I_m^-$$
$$V_m(z) = e^{-\gamma_1 z} V_m^+ - e^{\gamma_2 z} V_m^-$$

The actual phase voltage and current can be obtained by similarity transformation

$$I(z) = T(e^{-\gamma_1 z} I_m^+ - e^{\gamma_2 z} I_m^-)$$
$$V(z) = Y^{-1}T_i e^{-\gamma_1 z} I_m^+ + e^{\gamma_2 z} I_m^-$$

The voltages and currents at the two ends of the line can be related with the chain parameter matrix as in (8)

$$\begin{bmatrix} V(l) \\ I(l) \end{bmatrix} = \begin{bmatrix} \phi_1(l) & \phi_2(l) \\ \phi_3(l) & \phi_4(l) \end{bmatrix} \begin{bmatrix} V(0) \\ I(0) \end{bmatrix}$$

The chain parameter matrix can be computed as

$$\phi_1(l) = \frac{1}{2} Y^{-1} T (e^{i\alpha} + e^{-i\alpha}) T^{-1} Y$$
$$\phi_2(l) = -\frac{1}{2} Y^{-1} T \gamma (e^{i\alpha} - e^{-i\alpha}) T^{-1}$$
$$\phi_3(l) = -\frac{1}{2} T (e^{i\alpha} - e^{-i\alpha}) \gamma^{-1} T^{-1} Y$$
$$\phi_4(l) = \frac{1}{2} T (e^{i\alpha} + e^{-i\alpha}) T^{-1}$$

Where $l$ is the length of power line.

B. Transformer Model

In literate [7][9][10] the equivalent circuit of transformer in high frequency is proposed. The model is based on the ideal transformer and a block of R, L and C circuit. Some measurements are carried out to determine parameters.

In addition of the ideal transformer, the follows are taken into account:
1) Winding leakage impedance of each phase.
2) Winding magnetizing impedance of each phase.
3) Winding capacitances including: capacitances between windings and ground, capacitances between windings.

Literate [7] gives the model of the leakage impedance, which is in series with the low voltage load.

The measurements of a 160kVA transformer show that the values are

$\text{R} = 2300 \text{ Ohm}$
$\text{L} = 0.176 \text{mH}$

So the magnitude of leakage impedance is beyond 50 Ohm in the range of frequency from 50kHz to 500kHz. The numerous experiments show the characteristics of input impedance of low voltage in China are not consistent with those in Europe and America. The measurements conducted by author show that the input impedance is usually lower than 10 Ohm in the frequency range 50-500kHz, which is in accordance with the result of literate[11]. So this input impedance is much lower than the leakage impedance. The MV primary impedance is not virtually depend on the secondary load, which makes the impedance of transformer with load easily determined by winding capacitances. So the simplified transformer model is shown as Fig.3. The nodes ABC correspond to the terminals at the medium voltage.
The admittance matrix of transformer is

$$\begin{pmatrix} jw(C \_B + C \_C + C \_A) & jw C \_B & jw C \_C \\ jw C \_B & jw(C \_A + C \_C + C \_B) & jw C \_B \\ jw C \_C & jw C \_B & jw(C \_C + C \_B + C \_A) \end{pmatrix}$$

C. Branch Line Model

The input impedance of branch line is related to the length of branch line $l$, the characteristic impedance $Z_c$, the propagation constant $\gamma$ and the equivalent impedance $Z_i$ of the transformer connected to the line terminal.

The reflection coefficients of the point $z$ can be expressed as:

$$\Gamma(z) = e^{j(z-L)}(Z_i + E)^{-1}(Z_i Y_0 - E)e^{j(z-L)}$$

Where the characteristic admittance matrix $Y_0$ is:

$$Y_0 = Z^{-1}$$

The reflection coefficients of the load are given by

$$\Gamma_L = (Z_i Y_0 + E)^{-1}(Z_i Y_0 - E)$$

The input impedance at point $z$ along the line can be obtained as

$$Z_I(z) = [E + e^{j(z-L)} \Gamma_L e^{j(z-L)}][E - e^{j(z-L)} \Gamma_L e^{j(z-L)}]^{-1} Y_0^{-1}$$

D. The Whole Model of Distribution Network

The entire power line channel are considered as two parts, with the uniform overhead line being the first, the intrinsic line parameter of which is different; and the equivalent input impedance of branch lines or transformers being the second. They both can be equivalent to the multi-port networks mentioned previously. So the entire distribution line are considered as the cascades of multi-port network.

If the chain matrix of each network is $[A_i]$, the whole matrix can be described as equation (17).

$$[A_n] = \prod_{i=1}^{n} [A_i]$$

III. Analysis of Power Line Propagation Characteristic

The 10kV power line carrier communication (PLC) is a technique for transmitting information via distribution line. The power line between the transmitter and receiver can be equivalent to a network in the studying of signal propagation characteristics at the two terminals. According to the practical PLC system, a channel model is illustrated in Fig.5.

The transmitter is equivalent to the thevenin circuit, which has voltage sources in series with resistances.

$$V_S = \begin{pmatrix} V_{s1} \\ V_{s2} \\ V_{s3} \end{pmatrix}$$

$$Z_S = \begin{pmatrix} Z_{s1} & 0 & 0 \\ 0 & Z_{s2} & 0 \\ 0 & 0 & Z_{s3} \end{pmatrix}$$

The vector $V_S$ is the independent voltage of source. $Z_S$ and $Z_I$ contain the effects of the impedances of the source and terminal network.

$$V(0) = V_S - Z_I I(0)$$

$$V(L) = Z_I \times I(L)$$
Incorporate the terminal conditions into the chain matrix characterization given in (20);

\[(\phi_2 - \phi_1)Z_4 - Z_5 \phi_2 + Z_6 \phi_2 Z_4) I(0) = (Z_4 \phi_2 - \phi_1) V_4,\]

\[I(L) = \phi_2 V_4 + (\phi_2 - \phi_5) Z_4) I(0) \quad (20)\]

Then voltage vector and current vector transfer function for the transmission line system can be obtained.

IV. SIMULATION ANALYSIS OF CHANNEL CHARACTERISTICS

A simplified model is presented to reveal the transmission characteristics of distribution network, which is shown in Fig. 6. A is the substation, G, H, D are the distribution transformers at the network terminals. The signal source is located at point B. The coupling mode is phase B to ground.

A. Model of Each Component

The models of common components in the distribution network are defined as follows: For the transformer, the capacitances between windings and ground are the same as capacitances between windings. The capacitance is 1000pF for distribution MV/LV transformer. The equivalent capacitance of step-down transformer of 10 kV side in the substation is 22600pF[12]. The power line is equivalent to 3-phases distributed parameters line. The R, L and C line parameters are specified by $[3 \times 3]$ matrices.

B. Overall Description of Channel Characteristics

The voltages of D, G on phase B are shown in Fig. 7.

From the graph we can see that the voltage shows frequency selective fading in the entire frequency band. And this fading is different at each sites. Meanwhile, there are a series of small frequency bands where the attenuation is acceptable for the power line carrier communication.

V. CONCLUSIONS

In this paper, the chain matrix channel model is presented, which includes the power line and distribution transformer. Base on the model, the propagation characteristics of 10kV overhead power line communication channel are analyzed, and the causes of frequency selective fading are discussed. The simulation results show the correctness of analysis. Based on the simulation, several proposals are put forward for the design of communication system.

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