SIGNAL RADIATION LEAKAGE OF POWER LINE COMMUNICATION SYSTEMS

by

Francois Sekyere BSc. Electrical/Electronic Engineering (Hons.)

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DECLARATION

I hereby declare that this submission is my own work towards the MSc and that, to the best of my knowledge, it contains no material previously published by another person nor material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

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Supervisor(s) Name	**Signature**	**Date**

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ABSTRACT

The usage of power line communications, PLC over the low-voltage electrical power supply networks gives an alternative for the telecommunication access. Initially power lines were used for controlling appliances, however with the recent technology advancements the power lines are now able to compete successfully with other relatively stable home networking technologies like wireless and phone line. Despite the advantages that PLC can offer, it is associated with the major cause of harmful interference to other users of the wireless spectrum. PLC risks not living up to its full development and success unless proper standards and regulations are developed globally. The objective of this thesis is the analysis of problems related to electromagnetic compatibility of broadband power line communications. The study comprises both theoretical and experimental analysis. The experimental work was conducted in the form of field measurements, performed in real power line communication network. For the theoretical work, PLC networks were modeled and simulated with the Numerical Electromagnetics Code (NEC).

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GLOSSARY

ACSR	Aluminum Conductor Steel Reinforced
BPL	Broadband over Power line
CFS	Carrier Frequency System
CPE	Customer Premises Equipment
CVT	Coupling Capacitor
ECG	Electricity Company of Ghana
EFIE	Electric-Field Integral Equation
EMC	Electromagnetic Compatibility
FD	Frequency division
FORIG	Forestry Research Institute of Ghana
GRIDCo	Ghana Grid Company
HEU	Head End Unit
HG	Home Gateway
LF	Low Frequency
MF	Medium Frequency
MFIE	Magnetic-Field Integral Equation
MCD	Modular Coupling Devices
NEC	Numerical Electromagnetics Code
PLC	Power line communication
NR	Network Repeaters
TD	Time Division
VRA	Volta River Authority

1 INTRODUCTION

1.1 Background

In the present "information age" climate, the Internet is the technology mostly employed for dissemination of information. It is based on the use of computers, which employs speed in accessing information and have multi-tasking functionality to access several web sites as needed. Computers also provide access to a vast resource of educational materials. The internet therefore provides an effective means to disseminate information and creates an environment that accelerates the learning process. The added advantage of having global connectivity enable users to access developmental information from other nations thereby improving the knowledge base of Ghanaians, and hence the country's development. The government of Ghana has embarked upon extending the fiber optic backbone to cover all parts of the country. This will provide an information superhighway throughout the nation [3].

Telecommunications systems have increased rapidly over the last few decades. There is development of new telecommunication networks and transmission technologies because the communication flow of today is very high. Many applications are operating at high speed and a fixed connection is often preferred. Therefore, there are a large number of communications enterprises that are building up high-speed networks, ensuring the realization of various telecommunications services that can be used worldwide.

Investments in the telecommunication industries however, are mainly provided for transport networks that connect various communications nodes of different network providers, but do not reach the end customers. The direct connection of the subscribers is realized over the access networks. However, the costs for realization, installation and maintenance of the access networks are very high. It is usually calculated that about 50% of all network investments belongs to the access area [4]. On the other hand, a longer time is needed for paying back the invested capital because of the relatively high costs of the access networks, calculated per connected subscriber. Network providers therefore try to realize the access network with the possibility of saving costs. This problem is known as the "last mile problem" which has been an active area of research in recent years. After the deregulation of the telecommunications market in a large number of countries, the access networks are still the property of incumbent network providers (former monopolistic telephone companies). The situation is not different in Ghana as Ghana Telecom (now Vodafone) owns about 95% of the access networks. Because of this, the new network providers try to find a solution to offer their own access network.

An alternative solution for the realization of the access networks is offered by the Power Line Communication (PLC) technology using the power supply grids for communications. PLC is also known as Broadband over Power Line (BPL) and in this thesis the two names would be used interchangeably. The basic concept of PLC is to transmit information and electricity simultaneously along electricity lines as an alternative to constructing dedicated communications infrastructure. Thus, for the realization of the PLC networks, there is no need for the laying of new communications cables. Application of PLC in low voltage power networks seems to be a cost-effective solution for "last mile" communication networks, belonging to the access area.

For a developing nation like Ghana, a major factor in choosing an applicable technology is how expensive the technology will be to setup, as well as operational and maintenance costs. For this reason, if the technology can be overlaid or mapped onto an existing system, the cost of setting up an infrastructure to support the technology is eliminated, hence greatly reducing the overall cost. Another factor is how easily and efficiently the people will adapt to using the technology. If the technology is based on an existing system that the people are already used to and comfortable with in its application, the extra effort needed to become familiar with the new technology is not too great [3]. Therefore PLC access network is an ideal solution for the “last mile” communication networks here in Ghana.

Power networks however are not designed for communications and they do not present a favorable transmission medium. Thus, the PLC transmission channel is characterized by frequency-dependent attenuation, changing impedance and fading as well as unfavorable noise conditions. Various noise sources, acting from the supply network, due to different electric devices connected to the network, and from the network environment, can negatively influence a PLC system, causing disturbances in an error-free data transmission. In order to provide higher data rates, PLC networks have to operate in a frequency spectrum of up to 80MHz, which is also used by various radio services. Unfortunately, a PLC network operating at such high frequency act as an antenna producing electromagnetic radiation in its environment which disturb other services operating in the same frequency range.

Although a number of research have been done on Power line communication signal radiation leakage, they are mostly based on experiments and measurements conducted in the developed countries such as US and Europe. And since power distribution network and the environmental conditions in those countries are different from that of Ghana, implementing PLC technology based in these countries in the Ghanaian environment may have negative consequences on other wireless services. Currently there are no data on PLC deployment in Ghana, and without such data the National Communication Authority cannot set up a regulatory framework on PLC deployment which many companies have expressed interest in.

The objectives of this thesis are to identify the factors affecting PLC signal radiation leakage and then simulate these factors to calculate the radiation leakage level using the power networks configuration in Ghana as parameters. Also this thesis seeks to model and simulate the signal emission level of the Volta River Authority PLC system and verify the simulation with measured results.

1.2 Power Line Communication System

1.2.1 Introduction

Power line Communications, PLC is the usage of electrical power supply networks for communications purposes. In this case, electrical distribution grids are additionally used as a transmission medium for the transfer of various telecommunications services. The main idea behind PLC is the reduction of cost and expenditure in the realization of new telecommunications networks. High or medium voltage power supply networks could be used to bridge a longer distance to avoid building an extra communications network. Low-voltage supply networks are available worldwide in a very large number of households and can be used for the realization of PLC access networks to overcome the so-called telecommunications "last mile". Power line communications can also be applied within buildings or houses, where an internal electrical installation is used for the realization of in-home PLC networks.

The application of electrical supply networks in telecommunications has been known since the beginning of the twentieth century. The first Carrier Frequency Systems (CFS) had been operated in high-voltage electrical networks that were able to span distances over 500 km using 10-W signal transmission power [7]. Such systems have been used for internal communications of electrical utilities and realization of remote measuring and control tasks. Ripple Carrier Signaling (RCS) systems have also been applied to medium- and low-voltage networks for the realization of load management in electrical supply systems.

Internal electrical networks have been mostly used for realization of various automation services. Application of in-home PLC systems makes possible the management of numerous electrical devices within a building or a private house from a central control position without the installation of an extra communications network. Typical PLC-based building automation systems are used for security observance, supervision of heating devices, light control, and so on.

1.2.2 PLC network configuration

The PLC system can be broken down into 3 segments namely the Outdoor MV segment, Outdoor LV segment and Indoor LV segment as shown in Figure 2.6. The Outdoor MV segment extends from the connection to the backbone network (the Internet) to the MV/LV transformer at the substation. The Outdoor LV segment extends from the Head End Unit (HEU) located at the substation to the outdoor port of a Home Gateway (HG) located inside a building. HEU is a coupling unit which interfaces between the LV or MV power line network and the backbone. The HG is a time or frequency division repeater making the interface between the indoor and outdoor segments. The Indoor LV segment extends from the indoor port of a HG to the Customer Premises Equipment (CPE) inside a building [2].

The part of the power network from a MV/LV transformer to the customers fed by that transformer is known as a LV cell. The PLC connectivity within a LV cell is provided in a tree topology by a HEU which usually connects the LV cell to the MV network. CPE might be connected to the HEU either directly or through a series of Network Repeaters (NR). The repeaters increase the range of the PLC signal either by retransmitting the received signal at a different frequency (Frequency division FD) or in different time slots (Time Division TD) [2].

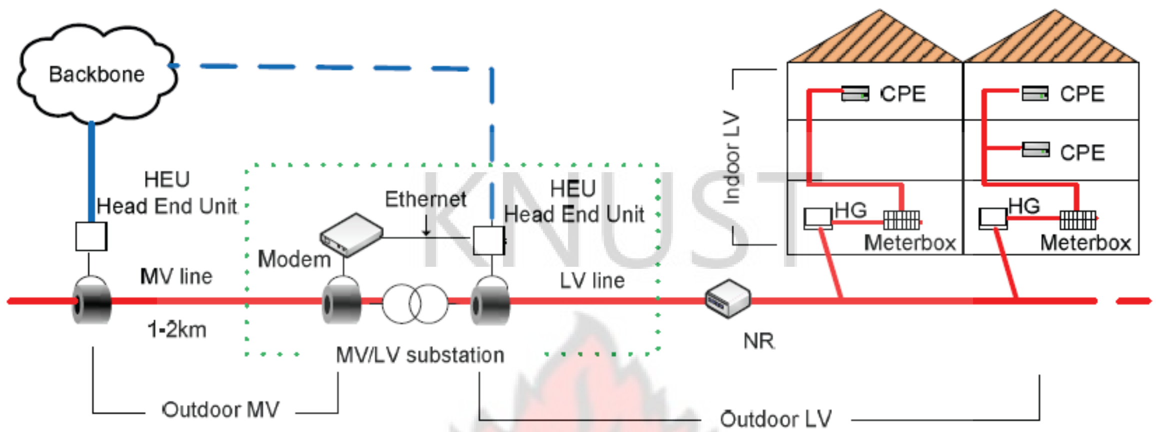

Figure 1-1 Reference topology showing the indoor and outdoor segments

1.2.3 PLC Network Elements

Basic PLC network elements are necessary for the realization of communication over electrical grids. The main task of the basic elements is signal preparation and conversion for its transmission over power lines as well as signal reception.

The PLC system components are:

- Modems, of which there exist three types, the central unit (head end or master device), repeaters (time division and frequency division) and customer premises equipment (slave or PLC modem).
- Signal couplers, which can be capacitive or inductive.

- Net conditioning components, such as RF-short circuits for the inductive coupling, bypass, etc.

1.2.4 Coupling Methods

Two coupling methods are used in PLC systems: capacitive and inductive coupling. When capacitive coupling is used, the modem is physically connected to the power line. In inductive coupling, ferrites are used to realize the coupling between the modem and the power line (see Figure 2.7).

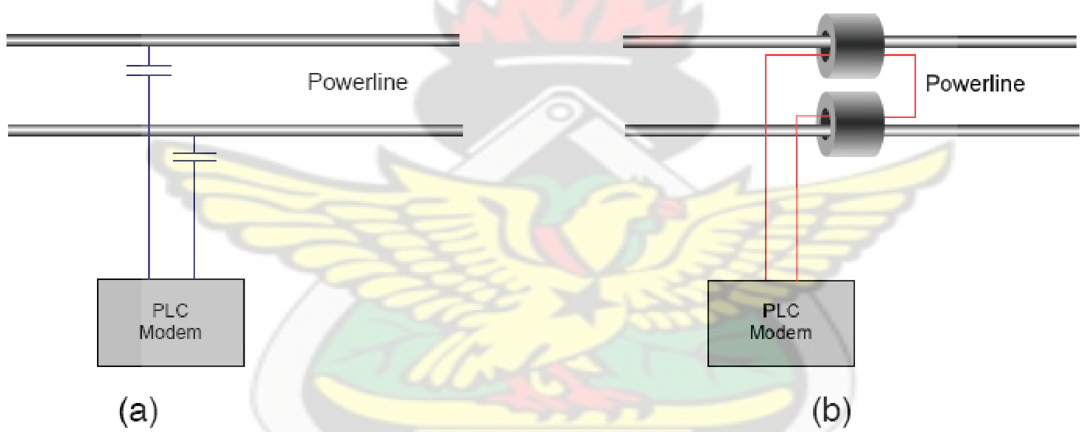

Figure 1-2 Connection in a case of (a) capacitive coupling and (b) inductive coupling [2]

Capacitive coupling introduces voltage onto the line and is the preferred method of coupling at the coupling points with relatively high impedance (>20Ω). Typically, these points are at the end of a power line (socket) and house access point with one incoming and only one outgoing cable. Capacitive coupling is also used when inductive coupling is not possible due to the geometry of the couplers (e.g., too small inner diameter of the ferrites), due to too high current ratings, etc. In the case of LV networks, capacitive coupling is always used since inductive couplers with suitable dimensions and saturation currents are not yet available [2].

Inductive coupling is used at coupling points with relatively low impedance (<20Ω), such as bus bars with many feeders or service lines and House Access Points (HAP) with more than two outgoing cables. Inductive coupling is also used wherever capacitive coupling is not possible due to safety reasons. The schematic of the connection and the equivalent circuits are given in Figure 2.8 for the case of the capacitive coupling and in Figure 2.9 for the case of inductive coupling.

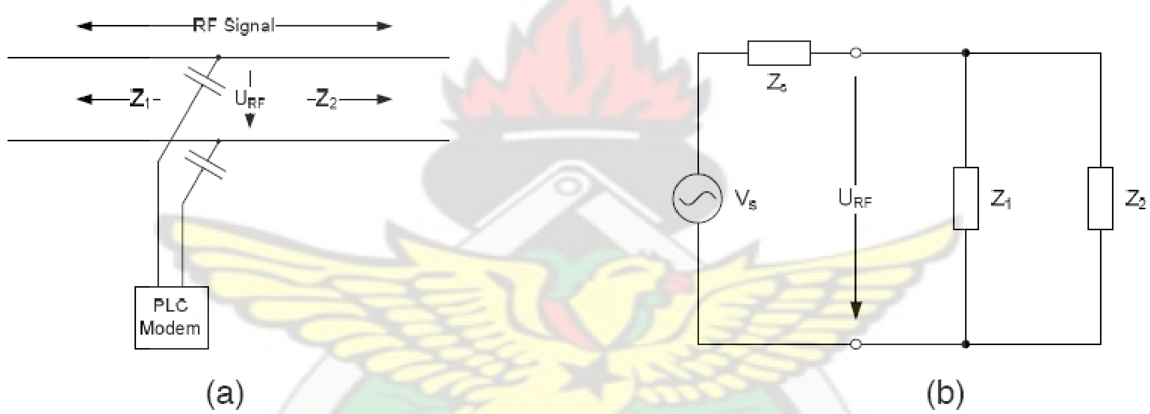

Figure 1-3 Capacitive coupling: (a) principle and (b) equivalent circuit [2]

In Figure 2.8 and Figure 2.9, the impedances are:

- Z_s , impedance of the coupler
- Z_1 and Z_2 , equivalent impedances the coupler sees at both sides

Since capacitive coupling requires direct connections to conductors, the electrical power is switched off whenever possible for installation. For the cases when the power cannot be switched off, the installation is dangerous. Unlike capacitive coupling, when inductive coupling is used there is no need to switch off the electrical power since no galvanic connection is involved. Inductive coupling is suitable for the coupling points with low impedance; the lower the impedance, the lower the coupling loss. It is also easy to realize multiple coupling points.

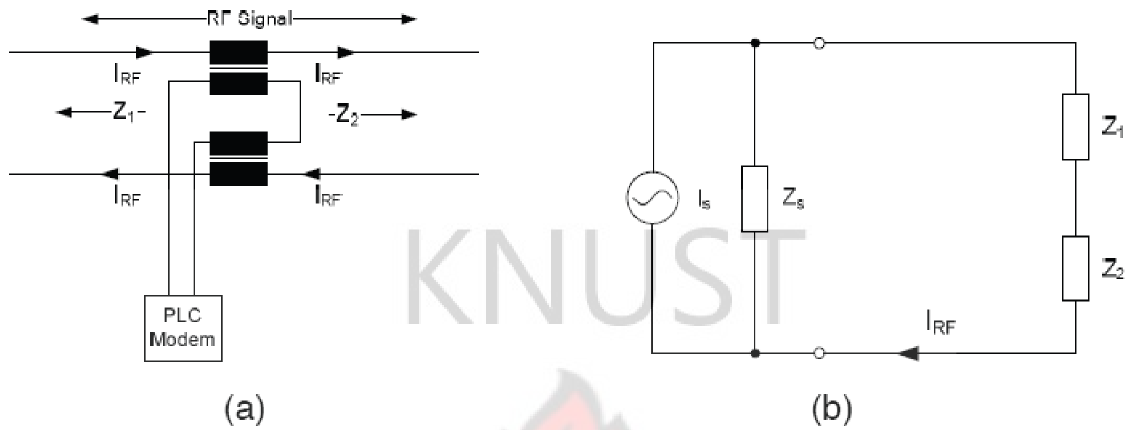

Figure 1-4 Inductive coupling: (a) principle and (b) equivalent circuit [2]

2 LITERATURE REVIEW

2.1 Power Systems in Ghana

In Ghana, Volta River Authority, VRA generate electricity and it is distributed throughout the country by Ghana Grid Company, GRIDCo via high voltage line at 161kV. As of December 2003, the existing transmission network system comprised 36 substations and approximately 4000 circuit km of 161 kV and 69 kV lines. This includes 129 km of double circuit 161kV interconnection to Togo and Benin. There is also a single circuit, 220 km of 225 kV inter-tie with La Côte d'Ivoire's network [9]. GRIDCo distributes power to Electricity Company of Ghana, ECG and mining companies via the 33kV medium voltage power lines. ECG then distributes electricity to low power consumers such as households, companies, factories and etc. At the ECG substations transformers are used to step down this 33kV medium voltage in to a much lower 11kV medium voltage which is then distributed to consumers in areas where power needs to be, see Figure 2-1. Before entering the customer's house as shown in Figure 2-2, another transformer is used to drop the voltage down from 11kV to more manageable levels of 240V.

2.2 PLC in Ghana

The only company that deploys PLC in Ghana is the VRA. Their PLC system is mainly used to reliably transmit power system protection signals, energy management and speech. The VRA PLC system consist of MCD 80 modular coupling device, coupling capacitor (or CVT) and PLC terminal (or PLC equipment). The MCD 80 modular coupling devices form the interface between the HV transmission line and the PLC equipment. It acts as a filter which accepts the carrier frequency signals and rejects the power system frequency. It also protects the PLC terminal from the power system voltage and transient over voltages caused by switching operations and atmospheric discharges. A complete coupling comprises a line trap to prevent the PLC signals from being short-circuited by the substation and a coupling filter formed by the coupling capacitor and the coupling device. The basic circuit diagram is shown in figure 2.14.

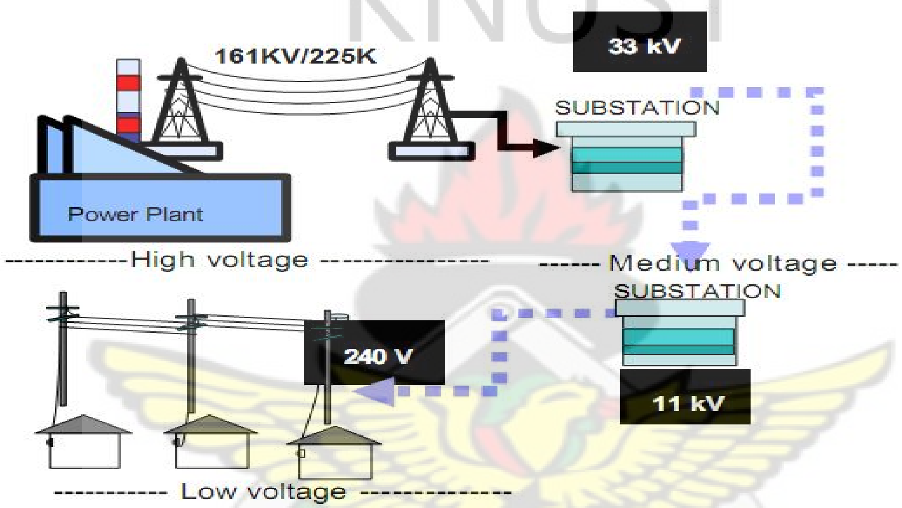

Figure 2-1 Power systems in Ghana [10].

At VRA, the PLC signals are coupled to two phases of the power system which is much more reliable than coupling to just one phase. A ground fault in this case will normally cause an additional attenuation of the PLC signal by about 6 dB [13]. A two-phase coupling scheme consists of two coupling units, one of which includes a hybrid module as shown in Figure 2-4. VRA uses Low Frequency (LF) and Medium Frequency (MF) for the operation of their PLC system. **Error! Reference source not found.** shows the list of PLC communication links and their frequencies at VRA substation in Kumasi to other substation around the country.

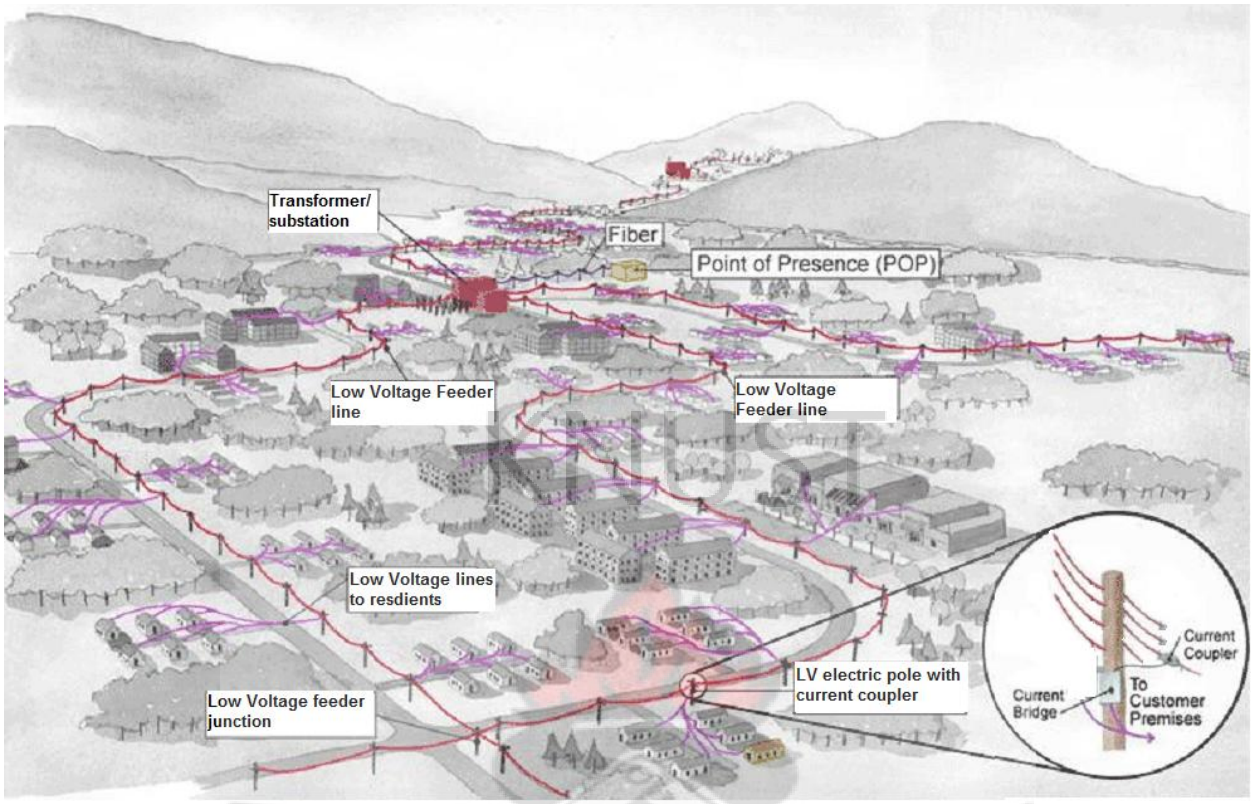

Figure 2-2 Electrical distribution system in a typical residential area in Kumasi [11]

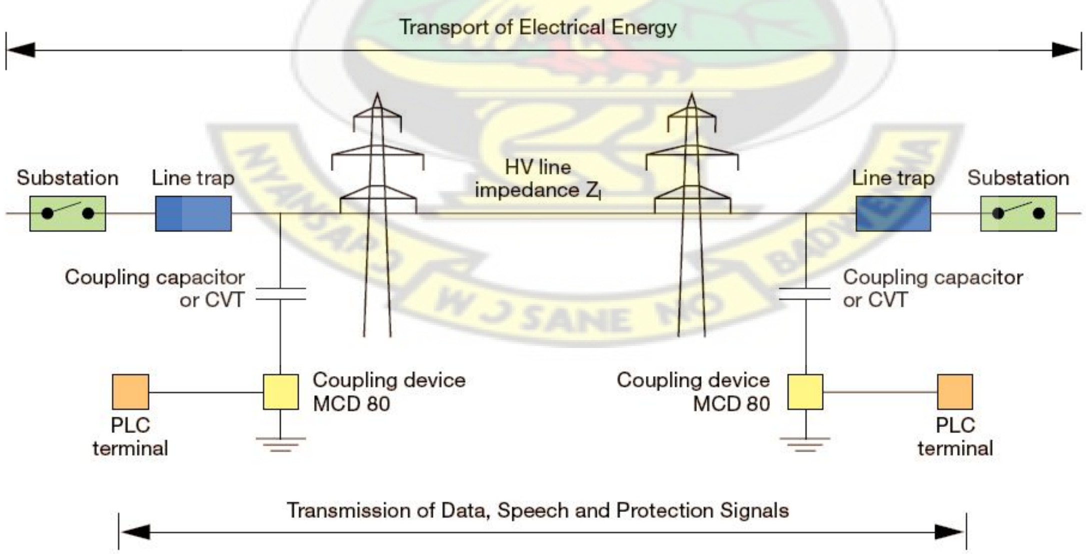

Figure 2-3 Schematic diagram of the PLC system deployed at VRA [12]

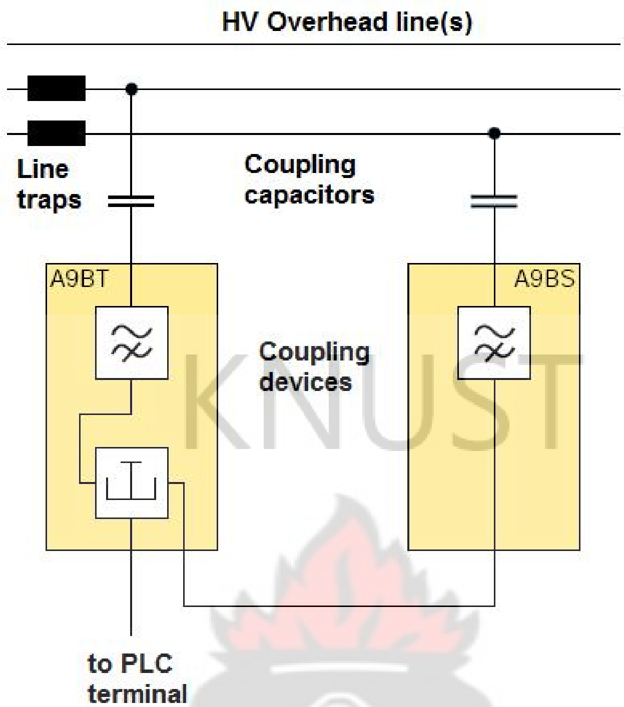

Figure 2-4 The two-phase coupling scheme deployed at VRA [12]

2.3 Electromagnetic Compatibility of PLC Systems

2.3.1 Introduction to relevant EMC aspects

PLC technology uses the power grid for the transmission of information signals. From the electromagnetic point of view, the injection of the electrical PLC signal in the power cables results in the radiation of an electromagnetic field in the environment, where the power cables begin acting like antennas. This field is seen as a disturbance for the environment and for this reason its level must not exceed a certain limit, in order to realize the electromagnetic compatibility. Electromagnetic compatibility refers to emissions and immunity of different systems that use the same frequency band. For any piece of equipment to be widely deployed, it is necessary to ensure that the emissions produced by it do not significantly disturb other services and systems using the same frequency band, and that it can function properly in the presence of a given measure of electromagnetic pollution. The levels of immunity and emissions are regulated by EMC standards. As shown in Figure 2-5, emissions and immunity can be either conducted or radiated.

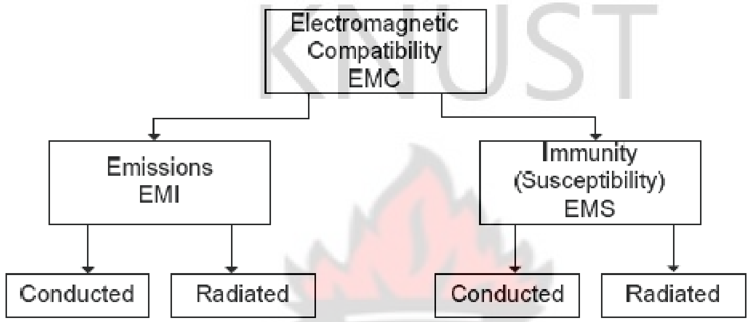

Figure 2-5 Different areas of Electromagnetic Compatibility. [2]

Several forms of electromagnetic coupling between a transmitter and a receiver are possible as illustrated in Figure 2-6 [8]. Depending on the frequency of the electromagnetic interference (EMI), various models describing the field coupling are used, ranging from low-frequency capacitive and inductive coupling to the higher frequency radiative coupling.

2.3.2 Field coupling

Field coupling (also known as Radiated coupling) between transmitter and receiver takes place by the transfer of electromagnetic energy through a radiation path, usually the air. Very often there is an element that behaves as an undesired transmitter or receiver antenna. At low frequencies, radiated coupling can be classified in terms of:

- Capacitive coupling, due to parasitic capacitances between nearby conductors. Its origin is the existence of an electric field.
- Inductive coupling, due to currents induced by time-varying magnetic field. All conductors generate a magnetic field and its variations can have an effect on nearby conductors.

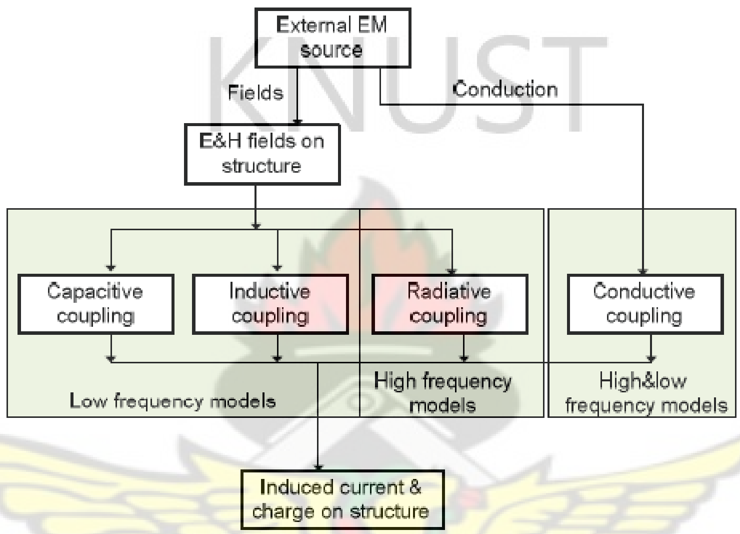

Figure 2-6 EM coupling process [2]

2.3.3 Conducted coupling

Conducted coupling between a source and a victim takes place via a direct path between transmitter and receiver, this path being different from the air. This coupling can take place because of the existence of direct conduction or common impedance:

- Direct conduction takes place when there is a physical connection between transmitter and receiver through the power supply cables, signal cables or control cables. The interference propagates among the different devices via these connections.

- Common impedance exists when there is a common wire among the various devices, typically power supply and ground wires. The interference propagates over these common lines to all and among all devices.

2.4 Numerical Electromagnetic Code (NEC)

The Numerical Electromagnetics Code, NEC is a user-oriented computer code for the analysis of the electromagnetic response of antennas and other metal structures. It is built around the numerical solution of integral equations for the currents induced on the structure by sources or incident fields. This approach avoids many of the simplifying assumptions required by other solution methods and provides a highly accurate and versatile tool for electromagnetic analysis.

The code combines an integral equation for smooth surfaces with one specialized to wires to provide for convenient and accurate modeling of a wide range of structures. A model may include non-radiating networks and transmission lines connecting parts of the structure, perfect or imperfect conductors, and lumped-element loading. A structure may also be modeled over a ground plane that may be either a perfect or imperfect conductor. The excitation may be either voltage sources on the structure or an incident plane wave of linear or elliptic polarization. The output may include induced currents and charges, near electric or magnetic fields, and radiated fields. Hence, the program is suited to either antenna analysis or scattering studies. NEC has been used successfully to model a wide range of antennas including complex environments such as ships.

The integral-equation approach is best suited to structures with dimensions up to several wavelengths. Although there is no theoretical size limit, the numerical solution requires a matrix equation of increasing order as the structure size is increased relative to wavelength. Hence, modeling very large structures may require more computer time and file storage than is practical on a particular machine. In such cases standard high-frequency approximations such as geometrical or physical optics or geometric theory of diffraction may be more suitable than the integral equation approach used in NEC.

The NEC program uses both an electric-field integral equation, EFIE and a magnetic-field integral equation, MFIE to model the electromagnetic response of general structures. Each equation has advantages for particular structure types. The EFIE is well suited for thin-wire structures of small or vanishing conductor volume while the MFIE, which fails for the thin-wire case, is more attractive for voluminous structures, especially those having large smooth surfaces [14]. The EFIE can also be used to model surfaces and is preferred for thin structures where there is little separation between a front and back surface. Although the EFIE is specialized to thin wires in this program, it has been used to represent surfaces by wire grids with reasonable success for far-field quantities but with variable accuracy for surface fields. For a structure containing both wires and surfaces the EFIE and MFIE are coupled. This form of simulation breaks the structure of interest down into *moments* or line segments (for solid structures, a wire mesh is used). The current in each segment is calculated and the resulting electromagnetic fields are derived. The equations and their derivation are outlined in the following sections.

2.4.1 Surface integral equations

To solve radiation and scattering problems, it is often useful to formulate the problem in terms of an equivalent one that may be easier or more convenient to solve in the region of interest. These equivalents are often written in terms of surface currents that mathematically modify or eliminate the presence of obstacles present in the original problem. Scattering problems can be considered as radiation problems where the locally radiating currents are generated by other currents or fields [15]. Antenna analysis is consequently a scattering problem, where antenna currents are excited via an externally applied voltage source. The Electric Field Integral Equation, EFIE describes a radiated field **E** given a set of sources **J**, and as such it is the fundamental equation used in antenna analysis and design. It is a very general relationship that can be used to compute the radiated field of any sort of antenna once the current distribution on it is known. The most important aspect of the EFIE is that it allows us to solve the radiation/scattering problem in an unbounded region, or one whose boundary is located at infinity. For closed surfaces it is possible to use the Magnetic Field Integral Equation, MFIE or the Combined Field Integral Equation, both of which result in a set of equations with improved condition number compared to the EFIE [15].

2.4.2 Derivation of Electric Field Integral Equation

We consider all quantities in the frequency domain, and so assume a time-dependency e^{-jwt} that is suppressed throughout. Given a homogeneous medium with permeability and permittivity ϵ and μ, respectively the electric and magnetic fields must satisfy the frequency-domain Maxwell equations:

$$\nabla \times \mathbf{E} = -j\omega\mu\mathbf{H} \qquad \mathbf{2.1}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + j\omega\epsilon\mathbf{E} \qquad \mathbf{2.2}$$

$$\nabla \cdot \mathbf{D} = \rho_v \qquad \mathbf{2.3}$$

$$\nabla \cdot \mathbf{B} = q_m \qquad \mathbf{2.4}$$

Where **D** = ϵ**E**, **B** = μ**H**,

To start from first principles and derive an integral equation of radiation, we take the curl of (2.1) and combine it with (2.2) to get

$$\nabla \times \nabla \times \mathbf{E} = -j\omega\mu\nabla \times \mathbf{H} = \omega^2\mu\epsilon\mathbf{E} - j\omega\mu\mathbf{J} \qquad \textbf{2.5}$$

$$\nabla \times \nabla \times \mathbf{E} - \omega^2\mu\epsilon\mathbf{E} = -j\omega\mu\mathbf{J} \qquad \textbf{2.6}$$

Using the vector identity

$$\nabla \times \nabla \times \mathbf{E} = \nabla(\nabla \cdot \mathbf{E}) - \nabla^2\mathbf{E} \qquad \textbf{2.7}$$

We write this as

$$\nabla(\nabla \cdot \mathbf{E}) - \nabla^2\mathbf{E} - k^2\mathbf{E} = -j\omega\mu\mathbf{J} \qquad \textbf{2.8}$$

Where k is the wave number, $k = \omega\sqrt{\mu\epsilon} = 2\pi/\lambda$. Substituting (2.3) into the above we get

$$\nabla^2\mathbf{E} + k^2\mathbf{E} = j\omega\mu\mathbf{J} + \frac{\nabla\rho_v}{\epsilon} \qquad 2.9$$

Employing the equation of continuity

$$\nabla \cdot \mathbf{J} = -j\omega\rho_v \qquad \textbf{2.10}$$

Allows us to obtain

$$\nabla^2\mathbf{E} + \mathrm{k}^2\mathbf{E} = \mathrm{j}\omega\mu\mathbf{J} - \frac{1}{\mathrm{j}\omega\epsilon}\nabla(\nabla \cdot \mathbf{J}) \qquad \textbf{2.11}$$

Since Maxwell's Equations are linear, we can consider **J** to be a superposition of point sources distributed over some volume. Therefore, if we know the response of a point source, we can solve the original problem by integrating this response over the volume. We now make use of this idea to convert (**3.21**) into an integral equation.

Since (**3.21**) comprises three separate scalar equations, let us consider just the **x** component, which is

$$\nabla^2 E_x + k^2 E_x = j\omega\mu\left(J_x + \frac{1}{k^2}\frac{\partial}{\partial x}\nabla \cdot J\right) \qquad \textbf{2.12}$$

Introducing the Green's function $G(\mathbf{r},\mathbf{r'})$, which satisfies the scalar Helmholtz equation,

$$\nabla^2 G(\mathbf{r},\mathbf{r}') + k^2 G(\mathbf{r},\mathbf{r}') = -\delta(\mathbf{r},\mathbf{r}') \qquad \textbf{2.13}$$

Where

$$G(r,r') = \frac{e^{-jk|\mathbf{r}-\mathbf{r}'|}}{4\pi|\mathbf{r}-\mathbf{r}'|}$$

which is the electrodynamic Green's function in three dimensions.

We can obtain E_x via

$$E_x(\mathbf{r}) = -j\omega\mu \iiint_V G(\mathbf{r},\mathbf{r}')\left[J_x(\mathbf{r}') + \frac{1}{k^2}\frac{\partial}{\partial x}\nabla' \cdot \mathbf{J}(\mathbf{r}')\right] d\mathbf{r}' \qquad \textbf{2.14}$$

Generalizing to the full vector form, we write

$$\mathbf{E}(\mathbf{r}) = -j\omega\mu \iiint_V G(\mathbf{r},\mathbf{r}')\left[\mathbf{J}(\mathbf{r}') + \frac{1}{k^2}\nabla'\nabla' \cdot \mathbf{J}(\mathbf{r}')\right] d\mathbf{r}' \qquad \textbf{2.15}$$

where the integral is performed over the support of **J.**

By a similar derivation, the radiated magnetic field due to magnetic current **M** is

$$\mathbf{H}(\mathbf{r}) = -j\omega\epsilon \iiint_V G(\mathbf{r},\mathbf{r}')\left[\mathbf{M}(\mathbf{r}') + \frac{1}{k^2}\nabla'\nabla'\cdot\mathbf{M}(\mathbf{r}')\right] d\mathbf{r}' \qquad \mathbf{2.16}$$

In scattering problems, the currents of (2.5) and 2.6) are unknown quantities. Therefore, solving a scattering problem involves solving an integral equation for unknown local currents **J** or **M** created by an external but known incident field $\mathbf{E}^i$ or $\mathbf{H}^i$ and integrating the induced currents **J** or **M** to obtain the scattered fields $\mathbf{E}^s$ and $\mathbf{H}^s$. The radiated electric field is obtained from the induced surface current via

$$\mathbf{E}^s(\mathbf{r}) = -j\omega\mu \iint_S G(\mathbf{r},\mathbf{r}')\left[\mathbf{J}(r') + \frac{1}{k^2}\nabla'\nabla'\cdot\mathbf{J}(\mathbf{r}')\right] d\mathbf{r}' \qquad \mathbf{2.17}$$

We can eliminate the dependence on $\mathbf{E}^s(\mathbf{r})$ in (2.7) by enforcing the boundary conditions on the tangential electric field:

$$\hat{\mathbf{n}}(\mathbf{r}) \times \mathbf{E}^s(\mathbf{r}) = -\hat{\mathbf{n}}(\mathbf{r}) \times \mathbf{E}^i(\mathbf{r}) \qquad \mathbf{2.18}$$

where $\hat{\mathbf{n}}(\mathbf{r})$ is the surface normal. This allows us to write the above in terms of the known incident electric field $\mathbf{E}_i(\mathbf{r})$ as

$$-\frac{j}{\omega\mu}\hat{\mathbf{n}}(\mathbf{r}) \times \mathbf{E}^i(\mathbf{r}) = \hat{\mathbf{n}}(r) \times \iint_S G(\mathbf{r},\mathbf{r}')\left[\mathbf{J}(\mathbf{r}') + \frac{1}{k^2}\nabla'\nabla'\cdot\mathbf{J}(\mathbf{r}')\right] d\mathbf{r}' \qquad \mathbf{2.19}$$

Equation (2.9) is known as the electric field integral equation (EFIE) for perfectly conducting surface. A similar equation can also be derived by enforcing the boundary conditions on the magnetic field on the surface of a conducting object.

$$\hat{\mathbf{n}}(\mathbf{r}) \times \mathbf{H}^i(\mathbf{r}) = \left[1 - \frac{\Omega_0(\mathbf{r})}{4\pi}\right]\mathbf{J}(\mathbf{r}) - \hat{\mathbf{n}}(\mathbf{r}) \times \iint_{S-\delta S}\mathbf{J}(\mathbf{r}') \times \nabla' G(\mathbf{r},\mathbf{r}')d\mathbf{r}' \qquad \mathbf{2.20}$$

3 METHODOLOGY

3.1 Overview

This research was conducted in order to determine potential signal leakage of a BPL system deployed in a typical Ghanaian residential neighborhood. BPL has a target spectrum from 1MHz (just above the AM broadcast band) to 80MHz (just below the FM broadcast band) for delivery of wideband data signals to residential neighborhoods using overhead power line as radio frequency transmission line. Unfortunately, overhead power distribution lines can act rather as efficient antennas at high frequencies which can disturb other services operating in the same frequency range. In order to answer this research goal, the researcher opted to use the Numerical Electromagnetics Code (NEC) to model the signal radiation leakage levels of transmission lines representing simplified versions of the power line in various geometries. The following factors and their effects on BPL signal radiation were simulated using NEC.

- Power lines' wire spacing and BPL signal frequency.
- The method of BPL signals injection on power lines
- BPL signal radiation effect on other HF communication systems
- Mismatch between the characteristics impedance of the power line and the load impedance.

The NEC was also used to model and simulate the Volta River Authority, VRA PLC system to compare with measured results conducted around their system. And finally, to examine the potential interference of PLC in a residential area, a case study was undertaken by using NEC to model a PLC system installation in a typical residential neighborhood in Kumasi.

3.2 Modelling of power lines using NEC

The NEC software program was used to create a number of power line models to gain a greater understanding of the effects various physical power line topologies might have on the BPL signal leakage. In Ghana, a typical arrangement of medium voltage, MV power line consist of three horizontal parallel Aluminum Conductor Steel Reinforced (or ACSR) wires which are about 12mm in diameter and 10m above the ground. The conductors have a minimum line spacing of about 400mm. And that of a three phase low voltage, LV power line consist of four vertical parallel ACSR wires which are about 10 mm in diameter and 7 m above the ground. Figure 3.1 depicts the orientation of power line conductors topologies found in Ghana.

Several ways can be imagined to configure the overhead power lines for conducting radio frequency signals. These include driving a single live wire against an adjacent grounded wire or driving two live wires against each other in a balanced mode. In the NEC models, two-wire transmission lines representing simplified versions of the power line were used.

All models assumed the power lines were configured for balanced two-wire operation to achieve the maximum amount of radiation suppression possible. The NEC model used for the simulation is a two-wire transmission line 200m long in free space composed of 12.7-mm diameter conductors as shown in Figure 3.2. The transmission lines were vertically parallel just like the LV power lines here in Ghana. The resistance of the conductors is assumed to be zero and the spacing between them is 1m. A power source is connected at one end of the line and a terminating load of 500 Ω is connected at the other end. The values of the electric field radiation are obtained as a function of frequency and load impedance using NEC.

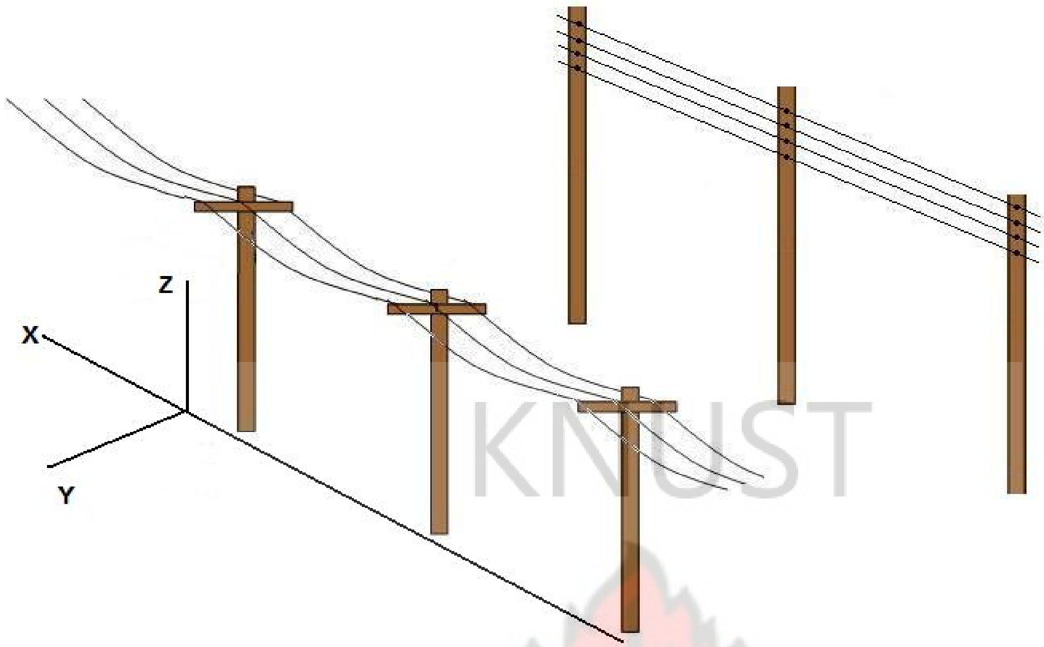

Figure 3-1 Common Power line topologies in Ghana (medium voltage and low voltage) and the coordinates used in NEC

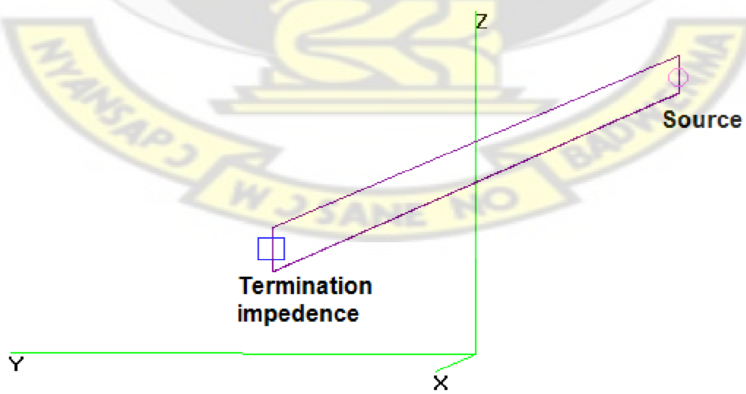

Figure 3-2 NEC Model of a two-wire transmission line

3.2.1 Case 1: Effect of powerline's wire spacing on PLC signal radiation leakage

To examine the effect of increasing power line wire spacing on radiation leakage, the NEC model described above was used. The resistance of the conductors is assumed to be zero. This researcher considered only the balanced mode configuration described above, as this is the only mode recognized as being capable of significant external field cancellation. The values of the source and load powers are obtained as a function of frequency and load impedance using NEC [16]. Because the line is located in free space and has no resistance, the only loss mechanism for the line is through radiation. That is, the difference between the source power P_{src} and the load power P_{load} must be completely due to radiation. Therefore, the percentage power radiated by the line P_{rad} is calculated using

$$P_{rad} = 100\left(1 - \frac{P_{load}}{P_{src}}\right) \qquad 3.1$$

3.2.2 Case 2: Effect of signal injection method on PLC signal radiation leakage

A PLC access network produces electromagnetic emission by acting as an antenna which disturbs other communications services operating in the same frequency range. A number of possible means for the prevention and reduction of PLC interference to other services have been proposed. The researcher looked at PLC signal injection mode as a means of prevention and reduction of PLC interference to other services. The method of feeding overhead electrical power distribution lines with PLC signals and the relationship between these methods and the PLC signal radiation were studied.

Three different ways of feeding PLC signal onto power lines were modeled. They are

- Differential feed (also known as balanced feed) between two phases for vertical and horizontal power lines as shown in Figure 3-3 and Figure 3-4 respectively.
- Differential feed between one phase and the neutral line for the vertical power lines as shown in Figure 3-5 and
- Feeding PLC signal onto only one phase (unbalanced or common mode feed) similar to the way a dipole antenna is fed as shown in Figure 3-6.

The power-line radiator antenna model was configured with two 12.7mm aluminum conductors, 300m in length. One line was placed 7m and other line was 7.3m above ground except for the horizontal line were both conductors were placed 10m above the ground. The ground was modeled with average conductivity and dielectric constant. The two conductors were parallel, spaced 300m for LV power line and 500mm for the MV power line. For the differential feed between a phase wire and the neutral wire of the vertical power line, the neutral wire was grounded to simulate typical imbalance in the line. The ground connection consists of four 10-meter radials, 5cm above ground. This is a relatively poor RF ground, to simulate the typically poor RF characteristics of power-line grounds. This also allows NEC-2 calculation engine, which cannot handle direct ground connection, to simulate the model correctly. The simulations use the "average" ground characteristics with a conductance of 0.005 S/m and a dielectric constant of 13 to model the ground under the power lines.

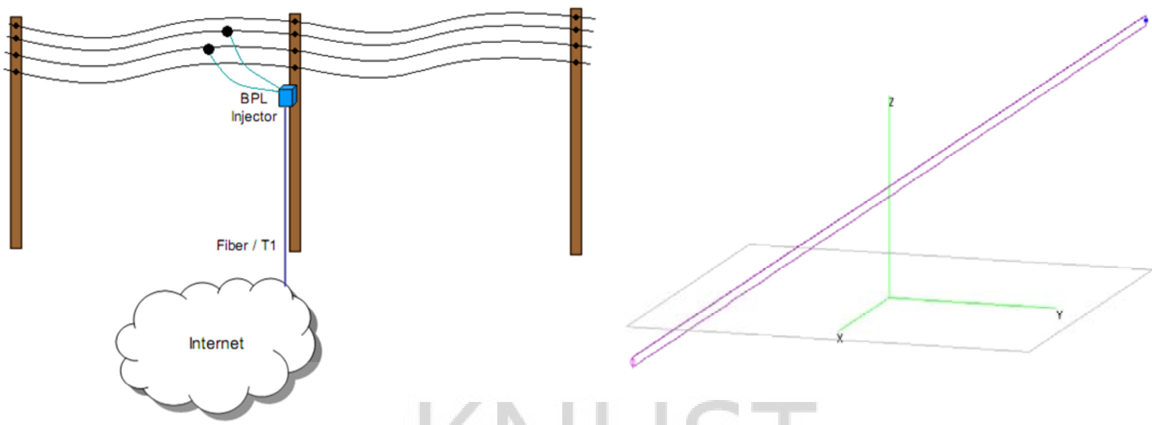

Figure 3-3 Pictorial view of differential feed between two phases on a vertical power line and its model used in NEC

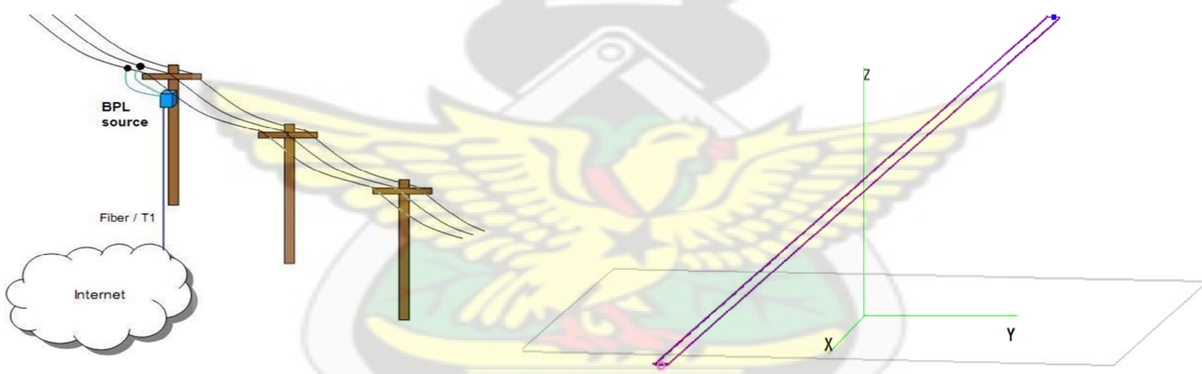

Figure 3-4 Pictorial view of differential feed between two phases on a horizontal power line and its model used in NEC

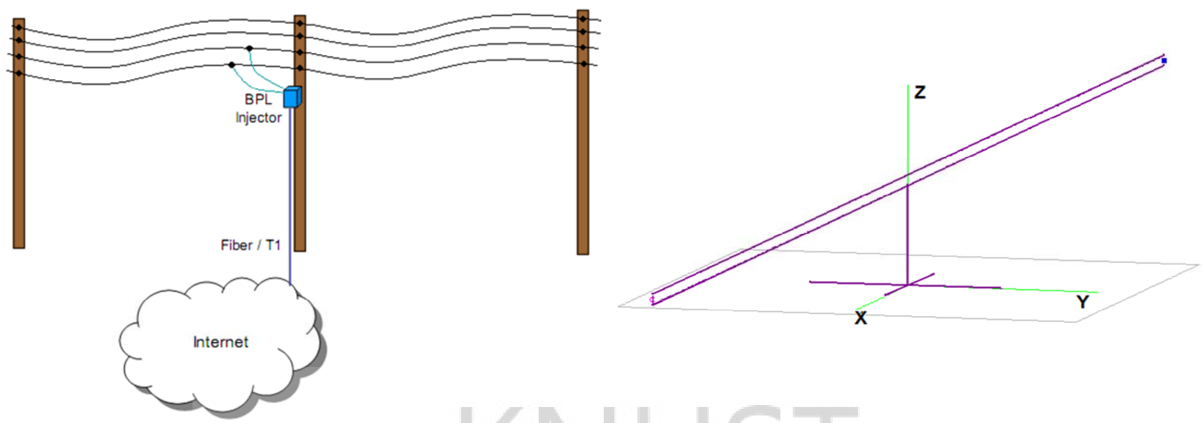

Figure 3-5 Pictorial view of differential feed between one phase and the neutral line and its model used in NEC

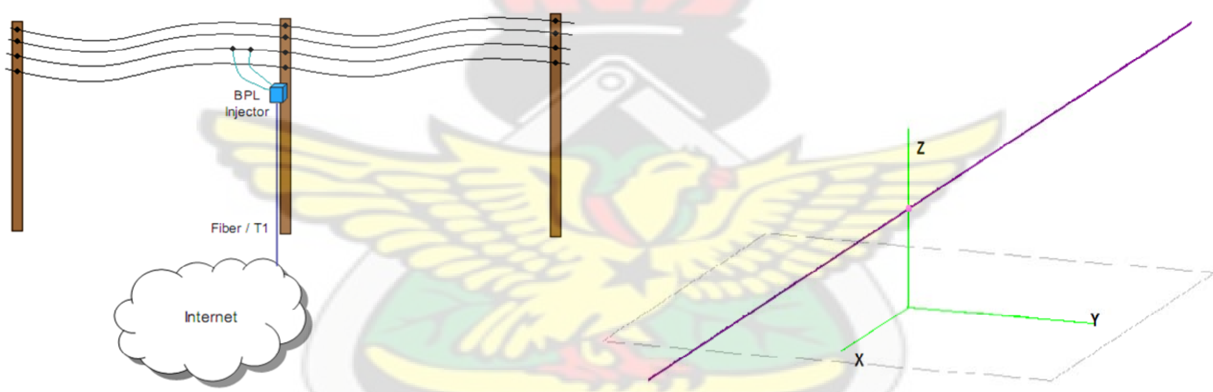

Figure 3-6 Pictorial view of feeding one phase (unbalanced or common mode feed), similar to the way dipoles are fed and its model used in NEC

The field strength (dBμV/m), in the near field was plotted in a plane 2m above the ground at frequency 20 MHz. With source impedance of 150Ω and load impedance of 500Ω, each method of feeding PLC signal to power line was modeled in the Near-field at a distance of 0 – 60 m perpendicular to the PLC source. The source power used was 1W.

3.2.3 Case 3: The effect of PLC signal radiation leakage on other HF communication systems

Commonly used High Frequency (HF) antennas were modeled to determine the approximate radiation signal level that will be coupled onto a typical HF station due to the PLC system. Although its gain is relatively small, the half-wave dipole is probably the most common antenna used at HF and it is oriented here in two different ways: Antenna 1 is a half-wave dipole located 10 meters above ground, at the height of the power line, representing tree-mounted antennas use by hobbyist radio operators. This antenna is at a distance of 30m from the line. Antenna 2 is a half-wave dipole located 30 meters above ground and 30 meters away from the line. The height of this antenna is representative of taller tower installations. This spacing is representative of what might be encountered in a typical residential neighborhood. Each of these antennas has a 50-j0 ohm load in the center and NEC is used to calculate the power that reaches each load by radiation. The simulations were run for three different frequencies 7 MHz, 20 MHz and 50MHz. The power level of the PLC source used for this simulation was 1W and the PLC load impedance at a distance of 300m was 500 Ω.

3.2.4 Case 4: The effect of impedance mismatch on PLC signal radiation leakage

The impedance of power lines are typically in the ranges of 250 to 450 Ω [12]. In order to reduce PLC signal radiation leakage, the source and load impedances representing the PLC provider and subscriber should match characteristic impedance of the power line. To show the effect of impedance mismatch on PLC signal leakage, a two-wire transmission line 200m long in free space composing of 12.7mm diameter conductors were modeled with NEC. The resistance of the conductors was assumed to be zero and the spacing between them was 1m. The impedance of the power line was set to 500Ω. A power source of 10W was connected at one end of the line and a terminating load of 50, 500 and 5000Ω were connected at the other end. The values of the source and load powers were obtained as a function of frequency and load impedance using NEC. Using equation 3-21, the percentage of radiated signal is shown in Table 4-3.

3.2.5 Case 5: Simulation of PLC Deployment in a Residential Area

To examine the potential interference of PLC in a residential area, a case study was undertaken. The study modeled a residential neighborhood with PLC devices installed on over head power line. The NEC model was constructed based on the physical layout of the LV power distribution at Forestry Research Institute of Ghana (FORIG) residential area in Fumesua near Ejusu. This model was designed using power line maps as well as actual observation. The model, which is shown in Figure 3-7, consists of three phase and neutral wiring but the BPL signals were injected on a single-phase. A single-phase power line has been used for this simulation because of the fact that many residential customers are served by single-phase lines in their neighborhood. The topology of the power line wiring in the simulation is vertical, which is just the same as found in LV power line distribution in Ghana. As closely as possible and within program constraints, this model was designed to conform to the actual features of the power grid, including the use of wires, correct placement of loads, wire height and wire junctions. The overall extent of the model was approximately 900 meters in the x-axis direction, and 800 meters in the y-axis direction. The modeled power line height was 10 meters. All wires were 12.6 millimeters in diameter and given the conductivity of copper (5.8×10^{7} S/m). The ground plane for the model (a flat earth structure beneath the wires) had characteristics typical of “good” ground (dielectric constant of 15.0, conductivity of 0.005 S/m).

The field strength (dBμV/m) in the near field was plotted in a plane 2m above the ground at frequencies 20MHz, 40MHz and 60MHz. The source power and impedance was 1W and 150Ω respectively. The results are shown in Figure 4-4 and Figure 4-5. Figure 4-4 shows the electric field radiation at 30m away from the wire and along the PLC power line with the injection point at the middle at different frequencies.

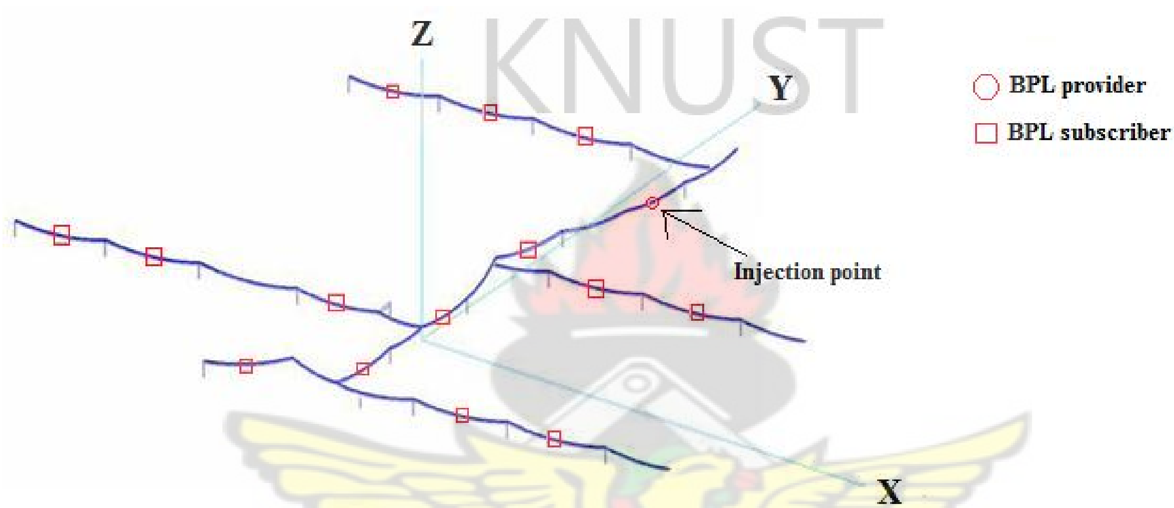

Figure 3-7 NEC model simulation of the residential neighborhood power lines carrying BPL signals

3.3 Signal radiation leakage level of the VRA PLC system

This section looks at the VRA PLC systems currently been deployed for control and protection of the high voltage power lines. NEC was used to simulate and calculate the electric field radiation level from the PLC setup. The modeled power lines consisted of three horizontal parallel aluminum wires. Two of the wires were 25m above ground (they represent the two phases the PLC signal was coupled on) while the remaining one was at a height of 29m (had no PLC signal on it). Each wire had a diameter of 24mm and the wires were separated in the horizontal plane by 6m. The equivalent of a BPL coupler was placed at the end of the two horizontal parallel wires and was modeled as a voltage source of 1V in series with a resistor that represented the source impedance. The transmitting power of the source was set to 200W.

3.3.1 Field Measurement

Measurements were performed with a goal of quantifying key aspects of PLC signals. The measurements were conducted at the VRA substation in Kumasi where PLC system is currently deployed for line protection and voice communication. The following measurements were conducted.

- PLC signal power at locations along and near an energized line
- PLC signal power at various distances away from an energized line.

These measurements were made using an RF spectrum analyzer positioned 2 meters above the ground on the *Kumasi-Techiman* line operating at the frequencies 444 kHz and 482 kHz. The measurement results for PLC signal radiation along and away from the power line are given in Table 3-1.

These measurements indicate that, in general the PLC electric field along and near the power line decay with distance from the device. But in at least one case, the electric field actually increased with increasing distance from the PLC device as shown in Figure 4-6. This is thought to be due to PLC signal reflection by one or more impedance discontinuities and the generation of standing waves. In general, the location variability in the field strength is thought to be due to the presence to standing waves in the current distribution along the power line [19]. The measurement results of PLC signal power at the distance away from the PLC device are also shown in Table 3-1. The results indicate that there is a decrease in received power with an increase in distance from the PLC device and power line.

Table 3-1 Measured PLC signal radiation at some distance along the power line and at some distance away from VRA PLC power line at the frequencies 444 kHz and 484 kHz.

(A) distance along the PLC powerline			**(B) distance away from PLC powerline**		
distance (m)	Field Strength (dBuV/m)		distance (m)	Field Strength (dBuV/m)	
	444 kHz	**482 kHz**		**444 kHz**	**482 kHz**
0	46.5	47	0	46.5	47
200	40	38	150	39	35
400	33.5	32	300	32	34
600	28.5	28	450	30	30
800	26	26	600	31	27
1000	24	29	750	26	22
1200	19	22	900	Area not accessible	Area not accessible
1400	11	19	1050	Area not accessible	Area not accessible
1600	12	17	1200	Area not accessible	Area not accessible

4 RESULTS AND DISCUSSION

4.1 RESULTS

4.1.1 Case 1: Effect of power line wire spacing on PLC signal radiation leakage

Table 4-1 shows how the radiated power, P_{rad} varies from 2 to 80 MHz on a line spacing of 0.5m, 1m, 1.5m and 2m. The radiated power increases significantly with increasing frequency because the spacing between the line conductors is larger relative to the wavelength as the frequency and line spacing increase. The maximum value shown is almost 70% of input power for the case of 80 MHz on 2m spacing line. This is not too surprising considering that 2m is 53.3% of a wavelength at 80 MHz. Things do not improve very quickly as frequency lowers and the line spacing is halved. A 1m spacing line at 20 MHz still radiates about 2% of the input power.

Table 4-1 Simulation results of radiated power leakage of power lines with wire spacing 0.5 m, 1 m, 1.5 m and 2 m.

Frequency MHz	Percentage of radiated power			
	0.5 m	**1 m**	**1.5 m**	**2 m**
2	0.05	0.06	0.07	0.1
10	0.23	0.51	0.98	1.61
20	0.63	1.86	3.81	6.43
30	1.25	3.88	7.86	13.03
40	2.11	6.88	14.35	23.82
50	3.22	10.59	21.04	32.71
60	4.45	14.43	29.08	46.4
70	6.04	20.08	38.39	54.38
80	7.75	24.61	45.98	66.95

4.1.2 Case 2: Effect of signal injection method on PLC signal radiation leakage

The result is shown in Figure 4-1. In the balanced feed, the PLC signals traveling side by side down the wire generate fields that tend to cancel one another. The electric field near and along the PLC tends to decay with distance from the power line. The “horizontal balance” decay rapidly with distance compared to the “vertical balance”. This could be due to the difference in height of the conductors, in the “vertical balance”, which affect the electric field near the PLC power line.

The differential feed between a phase and a neutral (vertical with ground) is implemented by feeding PLC signal on a phase and the neutral line that typically runs at the lower boundary of the “power space” on the utility poles. The near fields at 20 MHz associated with this configuration are shown as “vertical with ground” in Figure 4-1. The field suppression compared to the unbalanced case “single wire feed or common mode injection” is apparent, but not as good as with the (vertical and horizontal) balanced configurations. The effectiveness of the “vertical with ground” configuration may be seriously compromised by the grounding wires that are typically connected to the neutral wire. These grounds unbalance the system and degrade the cancellation associated with differential drive.

For the “vertical with ground” configuration in Figure 4-1, the electric field radiation does not measurably decay with distance from the device (along the power line). At point x=45 in Figure 4-1, the electric field actually increased with increasing distance from the PLC devices. This is thought to be due to PLC signal reflection by one or more impedance discontinuities and the generation of standing waves. In general the location variability in the field is thought to be due to the presence of standing waves in the current distribution along the power line.

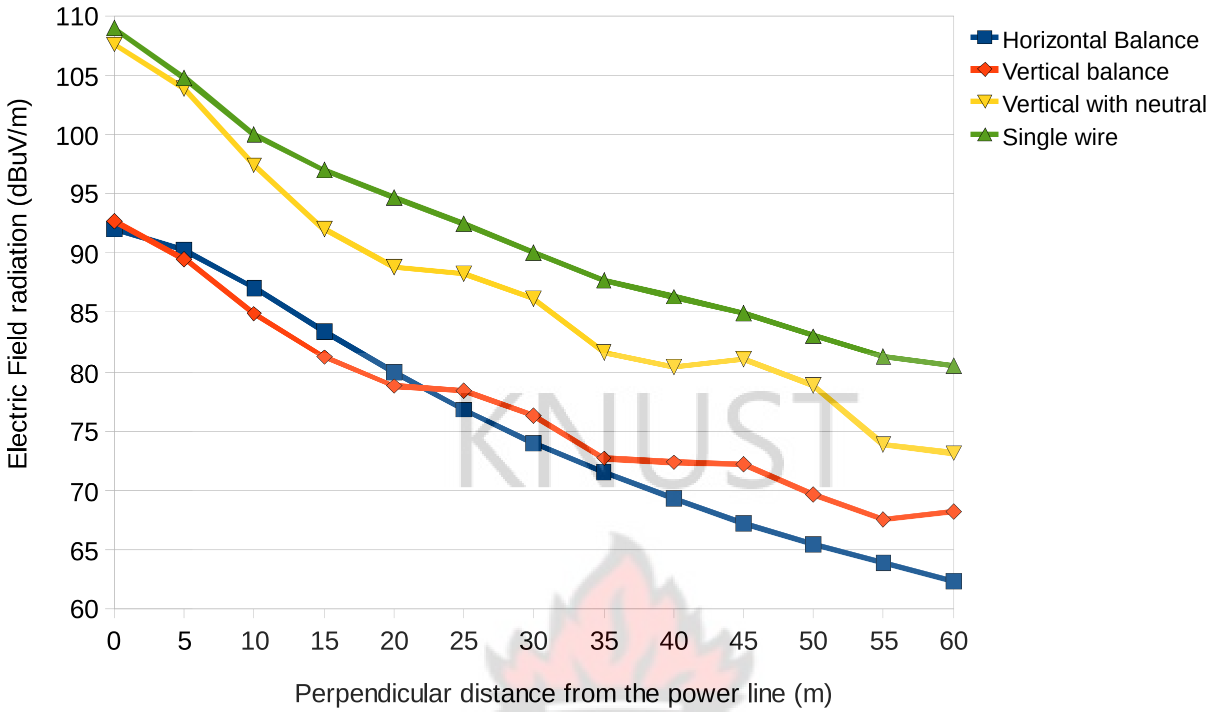

Figure 4-1 simulation results of electric field radiations of power lines with various methods of feeding PLC signals on them at 20MHz. the various methods are Horizontal feed, Vertical feed, Vertical with ground feed and single wire feed.

4.1.3 Case 3: The effect of PLC signal radiation leakage on other HF communication systems

The table below shows the signal levels coupled to the two modeled dipole antennas at different frequencies. From Table 4-2, it can be seen that feeding PLC signal on two phases or feeding it on a phase and a neutral differentially results in less signal being radiated than feeding it on a single wire. Feeding PLC signal on a single power line wire is the worst choice which results in a higher power-line antenna gain and generally more coupling to the two simulated amateur antennas.

Table 4-2 Simulation results of PLC signal radiated to Antenna1 at 10m above the ground and Antenna2 at 30m above the ground at 7MHz, 20MHz and 50MHz using Phase to phase feed, Phase to neutral feed and Single wire feed.

Method of feeding PLC signals on power line	**7MHz**		**20MHz**		**50MHz**	
	Signal level (dBμV/m)		Signal level (dBμV/m)		Signal level (dBμV/m)	
	Antenna 1	Antenna 2	Antenna 1	Antenna 2	Antenna 1	Antenna 2
Phase to Phase feeding	69.33	63.69	74.57	69.81	83.35	77.71
Phase to neutral feeding	83.52	85.11	87.6	89.54	86.44	86.44
Single wire feed	94.96	97.62	103.77	100.51	101.29	98.38

The difference between the total applied power and the power absorbed in the load impedances is the amount of power radiated from the line.

Figure 4-2 shows the PLC signal radiated from the power line for three different PLC feeding configurations. As expected, phase to phase differential feed has the lowest PLC signal radiation. At 80 MHz, only 27 % of the source PLC signal is radiated while the single wire feed radiates about 86% of its source signal. From 2 MHz to 20 MHz the single wire acts as just like an antenna, radiating about 96-99 percent of its source power.

The near-field coupling tends to be much greater, particularly at or near points of maximum coupling, when the power line is grounded rather than ungrounded. Since neutrals are grounded, PLC providers might consider inserting RF chokes so that their lines are effectively ungrounded at high frequencies. However, in some cases when the receiving antenna is positioned at or near a point of minimum coupling, the signal level is actually greater for the ungrounded line than the grounded one. Of the various scenarios studied, even the one having the absolute minimum degree of coupling could cause harmful interference to the communication system.

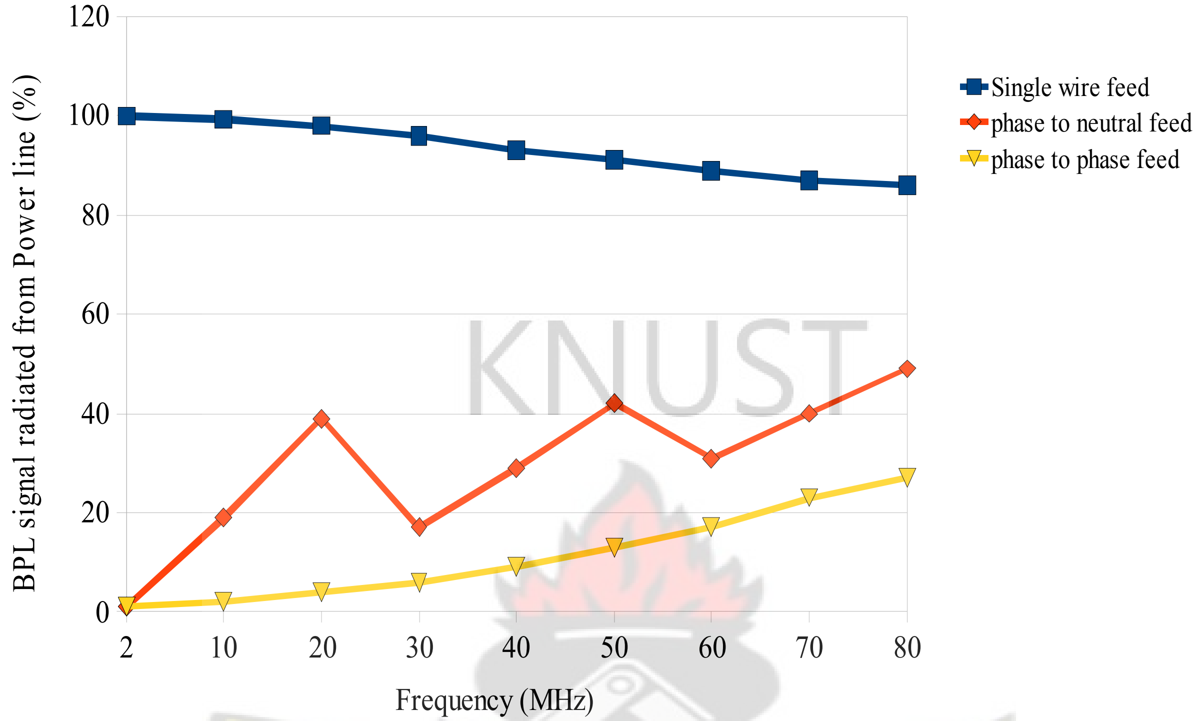

Figure 4-2 Simulation results showing the percentage of radiated PLC signal verses frequency for three different methods of feeding PLC signal onto power lines.

4.1.4 Case 4: The effect of impedance mismatch on PLC signal radiation leakage

Table 4-3 shows that, when the terminating impedance is too low or too high from the impedance of the power line, the radiating power tends to increase. For a specific frequency, the load impedance plays a significant role, the closer the line is terminated in its characteristic impedance, the lower the radiation. Mismatched lines have larger standing waves and radiate more than matched lines, all other factors being equal.

Table 4-3 Results of radiating powers at different frequencies of a power line with terminating loads of 50 Ω, 500 Ω and 5000 Ω.

Frequency MHz	Percentage of radiated power		
	50Ω	500Ω	5000Ω
2	0.1	0.02	0.07
10	2.31	0.43	1.7
20	9.06	1.73	5.85
30	15.84	3.69	13.42
40	26.86	6.62	20.3
50	38.19	10.34	26.78
60	41.12	14.25	40.91
70	52.05	17.81	42.36
80	55.18	23.55	52.05

The current distribution along the power line for the three different load impedances were also simulated with NEC. Figure 4-3a, Figure 4-3b and Figure 4-3c depict calculated current distribution along the line with terminating load impedance of 50Ω, 500Ω and 5000Ω respectively. Under Matched conditions the standing-wave ratio, SWR is low, i.e. there are few reflections from either end and the current distribution along the line is fairly uniform, as depicted in the calculated current distribution in Figure 4-3b, which has a terminating load impedance of 500Ω.

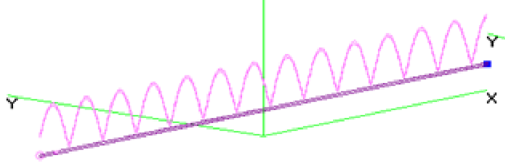

Figure 4-3a

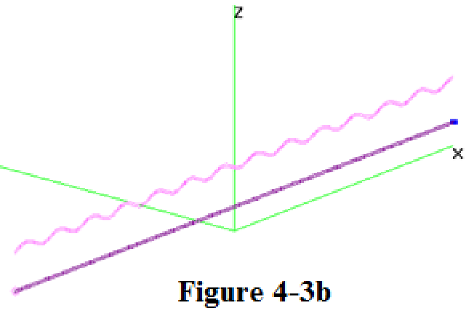

Figure 4-3b

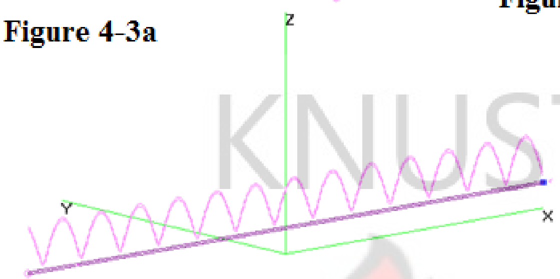

Figure 4-3c

Figure 4-3: Figures 4-3a, 4-3b and 4-3c show the simulation results of current distribution along a power line with different terminating loads impedance of 50Ω, 500Ω and 5000Ω respectively.

4.1.5 Case 5: Simulation of PLC Deployment in a Residential Area

It can be seen from Figure 4-4 that, at the PLC injection point x = 0, the electric field radiation is very high at all frequencies. Moving away from the injection point along the power line, the electric field radiation decreases. The radiation also tends to increase with frequency. Figure 4-5 also shows the electric field strength at the perpendicular distance of 500m away from the power line. Again the field strength around the PLC injection point is very high but moving away from the injection point there is a steep decrease in the field strength.

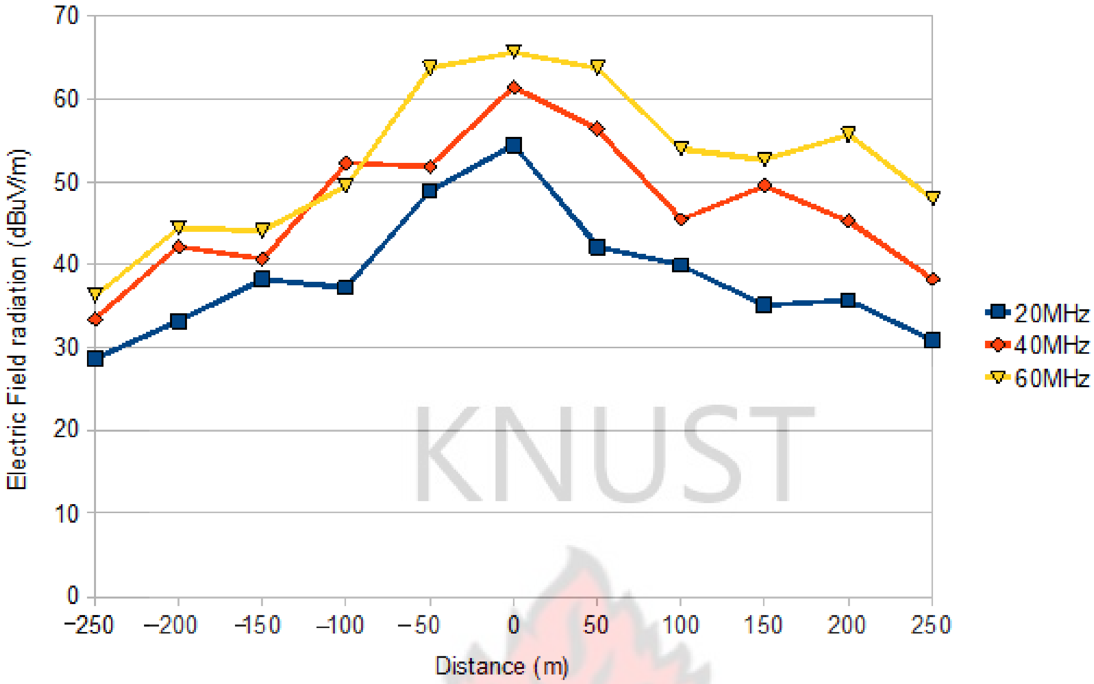

Figure 4-4 results of electric field radiation along PLC power line at different frequencies. The injection point is at the middle of the power line at x=0.

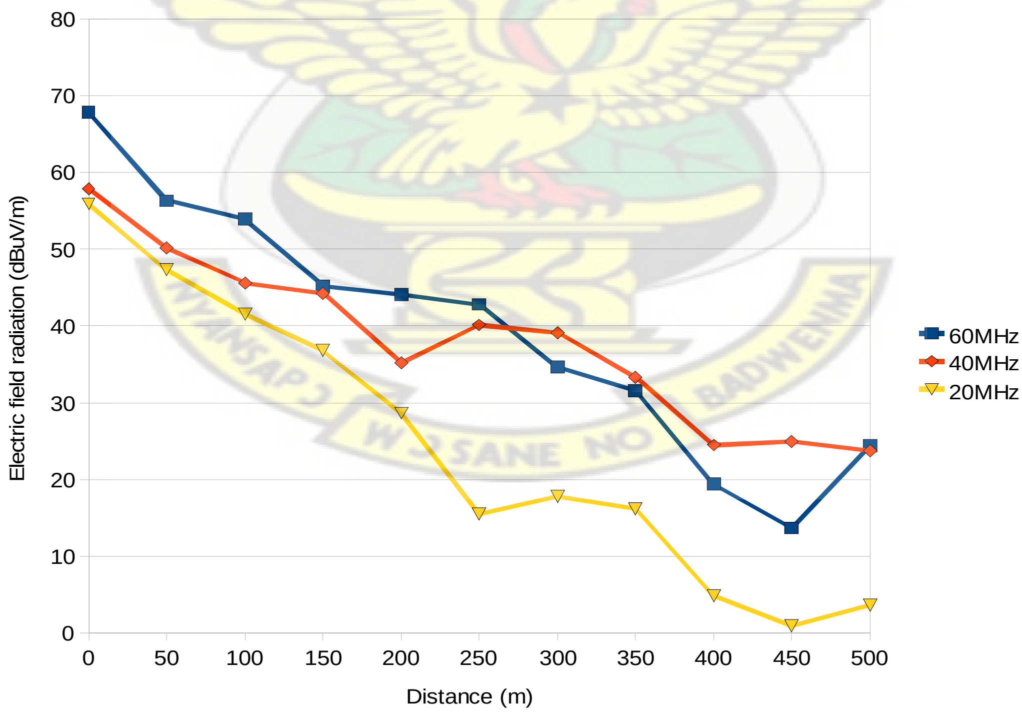

Figure 4-5 simulation results of electric field (dBµV/m) radiation at some distance away from the PLC power line at different frequencies.

4.1.6 Signal radiation leakage level of the VRA PLC system

The simulated results from VRA PLC system simulation are shown in Table 4-4 and Table 4-5

Table 4-4 Simulation of PLC signal radiation at some distance along the VRA PLC power line at the frequencies 444 kHz and 482 kHz.

PLC signal along the power line		
Distance (m)	Radiated electric field (dBuV/m)	
	482kHz	**444kHz**
0	65.12676	63.71958
200	37.04405	38.57302
400	31.28193	27.12316
600	29.78796	26.01327
800	27.79302	23.9183
1000	26.31578	22.37277
1200	25.14536	21.17107
1400	24.15311	20.16365
1600	23.28029	19.28338

Figure 4-6 and Figure 4-7 show the comparison of measured and simulated electric field radiations along the power line at frequencies 444 kHz and 482 kHz respectively. Figure 4-8 and Figure 4-9 also show the electric field radiation leakage away from the power lines at frequencies 444 kHz and 482 kHz respectively. From Figure 4-6 and Figure 4-7, it can be seen that as you move along the power line and away from the PLC device, the electric field radiation decays.

Table 4-5 Simulation of PLC signal radiation at some distance away the VRA PLC power line at the frequencies 444 kHz and 482 kHz.

PLC signal away from the power line		
Distance (m)	Radiated electric field (dBuV/m)	
	482kHz	**444kHz**
0	65.12676	63.71958
150	44.38219	43.95657
300	41.8159	41.21014
450	39.09924	38.30802
600	37.05005	36.0429
750	35.37953	34.34918
900	34.04589	32.95437
1050	32.92539	31.79843

It is clear that the correlation between measurement and simulation in Figure 4-6 is very good. That of Figure 4-7 is ok but not perfect. At least one explanation for not getting a perfect correlation is that, the supplied antenna of the RF analyser is optimized for the UHF band, so it was not possible to receive some desired signals at MF band in which the VRA PLC operate. At least, more than 60% of the measured values agreed very closely with the simulated values, therefore validating the simulation.

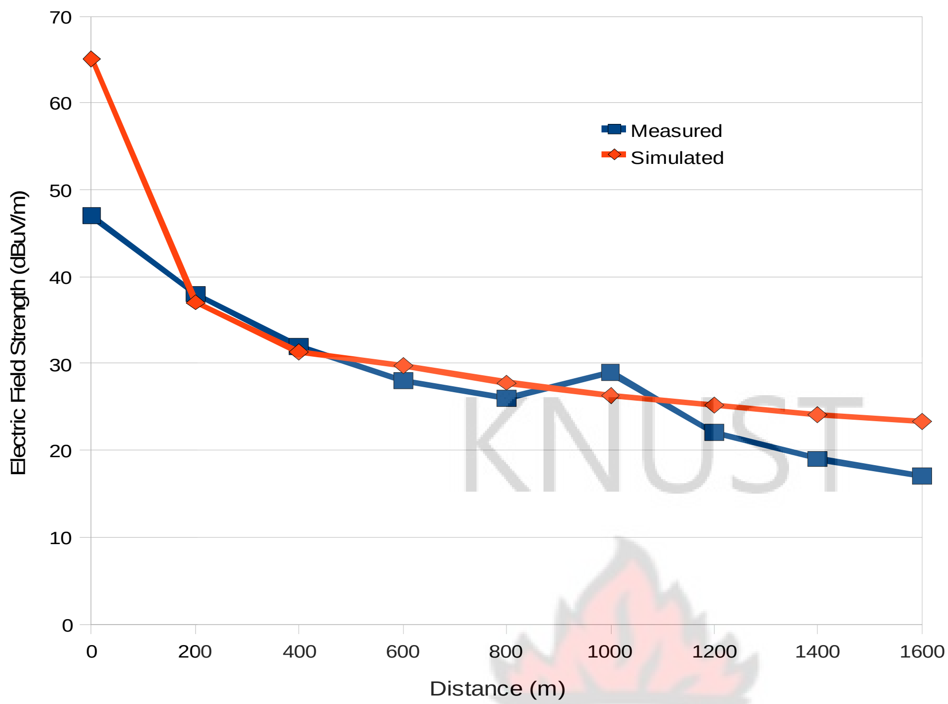

Figure 4-6 Comparison of simulated (Table 4-4) and measured (Table 3-1A) electric field radiations along the power line at 482 kHz

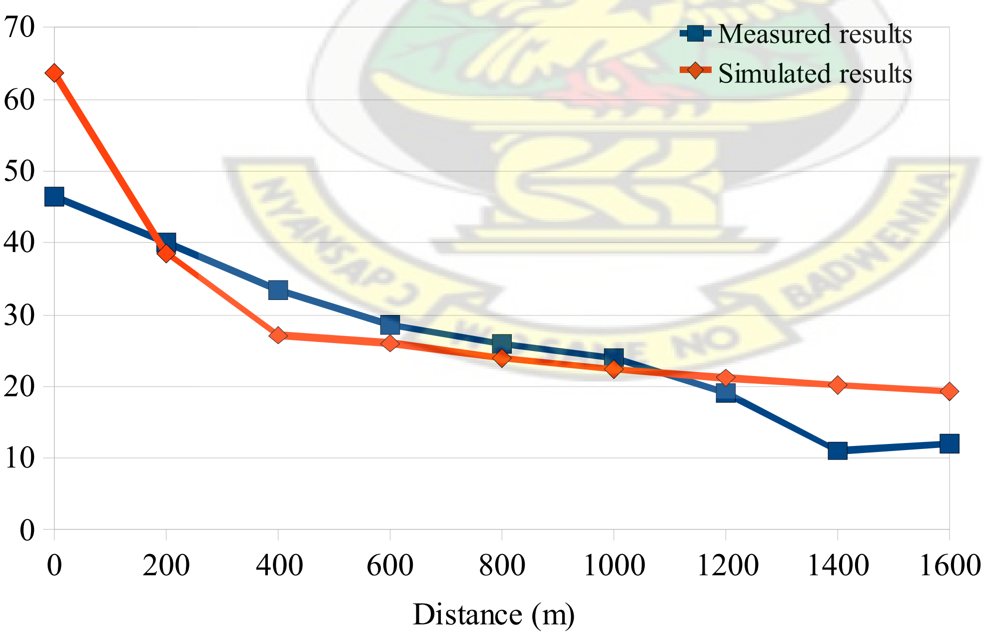

Figure 4-7 Comparison of simulated (Table 4-4) and measured (Table 3-1A) electric field radiations along the power line at 444 kHz

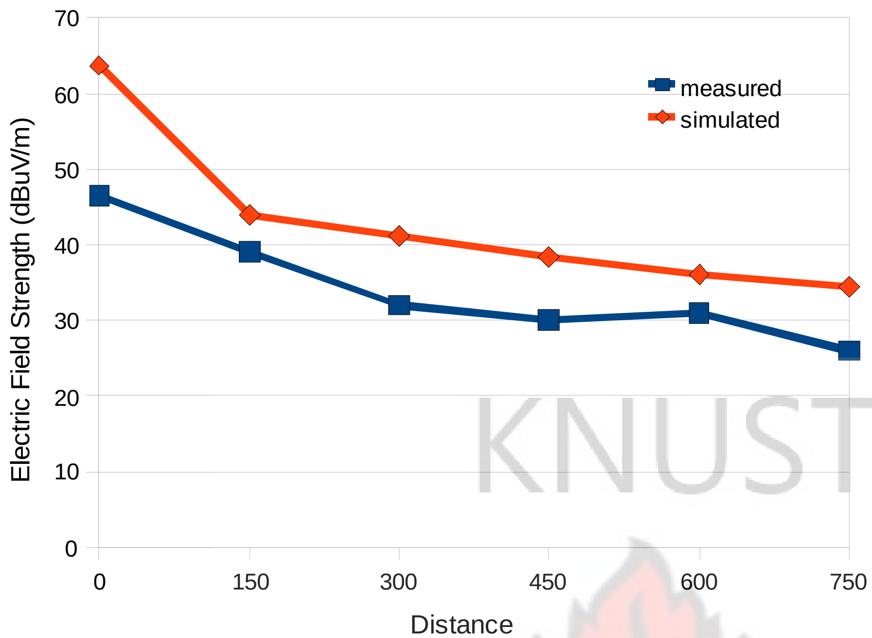

Figure 4-8 Comparison of simulated (Table 4-5) and measured (Table 3-1B) electric field radiations away from the power line at 444 kHz

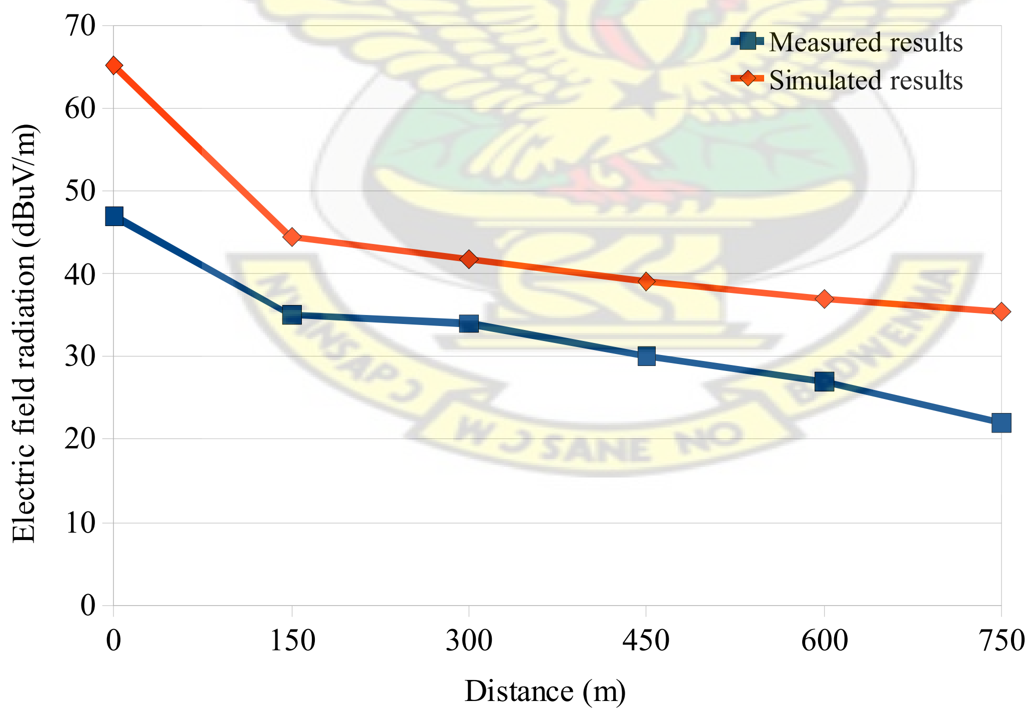

Figure 4-9 Comparison of simulated (Table 4-5) and measured (Table 3-1B) electric field radiations away from the power line at 482 kHz

4.2 DISCUSSIONS

The spacing between the wires on the power lines has effect on the radiation leakage. As wire spacing increases and external cancellation degrades, radiation escapes similar to those of long wire antennas. External cancellation of equal and opposite fields relies on the signals on the two wires being of opposite sign, equal in amplitude, and physically close together in terms of wavelength. High levels of radiation suppression can be achieved only if the wires are very close together in terms of wavelength and carry carefully balanced signals. As a guide to what kind of line spacing is suitable for transmission line use, consider the open wire lines in common use in the radio and TV industries. Open wire line normally used at HF frequencies (less than 30 MHz) is typically 450-ohm "ladder line" with 2 cm spacing. The open wire line used at VHF (300 ohm TV "twin lead") has about 6.5 mm spacing. At worst case, the line spacing is less than 1% of a wavelength [17]. To minimize line radiation, the distance between the conductors should be a very small fraction of a wavelength [8]. For the usual conductor spacing used in overhead distribution lines, this requirement is clearly not satisfied at PLC frequencies.

In Ghana, several residence are served from a single phase low-voltage (LV) cable operating at 220–240 V. Key challenges at the physical layer include dealing with the high losses of the cable (several tens of decibels in a few hundred meters) and multiple, possibly time-varying, reflections associated with taps to individual residences. Neglecting all these factors, radiated interference from LV cables is relatively very low compared to medium-voltage (MV) and high-voltage (HV) cables. This is because the conductors in the LV cable are closely spaced, so their radiation fields decay rapidly with distance from the cable [18].

In differential mode injection, reverse and forward paths are two currents flowing with the same amplitude in opposite directions. These currents travel in two parallel identical conductors with relatively small separation distance. Due to their opposite direction and small separation distance, their radiated electric fields tend to cancel out one another. On the other hand, in common mode injection, forward path is a current flow in one phase conductor and the return path is ground surface, which is a dielectric with losses [20]. Also, in common mode injection, forward current travels in a near-perfectly conducting material, whereas return current has to go through a material with loss. Because of all these facts, it is expected that the cancellation of electric fields, emitted from forward and return paths, in common mode injection, is much less than those in differential mode injection.

Transmission lines do not extend to infinity, but have a definite length. They are connected to, or terminated in a load. If the load is a pure resistance whose value equals the characteristic impedance of the line, the line is said to be matched. For current traveling along the line, such a load at the end of the line acts as though there were still more transmission line of the same characteristic impedance. In a matched transmission line, signal travels outward along the line from the source until it reaches the load, where it is completely absorbed. When the impedance of the load is not equal to the characteristic impedance of the transmission line, the line is mismatched. RF energy reaching the end of a mismatched line will not be fully absorbed by the load impedance. Instead, part of the energy will be reflected back toward the source. The amount of reflected versus absorbed energy depends on the degree of mismatch between the characteristic impedance of the line and the load impedance connected to its end [21].

Coupling PLC signal to the power lines with low impedance is advantageous from a standpoint of noise immunity and the ability to deliver signal to a load when there are other loads on the line (e.g., additional subscribers, stray capacitances associated with transformers, etc.) [16], however, as shown in Figure 4-3a and Figure 4-3c, which have load impedance of 50Ω and 5000Ω respectively, this dramatically increases the SWR on the line. With mismatched source and load impedances, large standing waves are formed and radiation increases.

Reducing the SWR on the line to avoid the increased radiation can only be accomplished by properly terminating the line over the entire frequency band and on all parts of the line. Because the power line dimensions remain constant over length, the characteristic impedance of the line remains constant. If multiple sources and loads are placed along the line, maintaining impedance match will be impossible because of cumulative loading. The effects of incidental loads presented by power line hardware are hard to predict but will surely increase SWR and line radiation.

In Ghana, PLC emission limits have not yet been set by the National Communication Authority, but for reference purposes, the PLC emission levels in the simulation have been compared with the existing American FCC emission limit [13]. From the simulation the PLC emission leakage calculated at 30m from the power line injection point was peaked 54dBµV/m at 20MHz and even higher to 65dBµV/m at 60MHz. The level exceeds the American FCC emission limit by up to 24dB. The most likely reason for this is due to method of PLC injection on the power line. In the previous section, it was seen that the neutral wire had effect on PLC power line radiation. The neutral lines tend to increase the overall gain of the power line radiation. The electric field radiation tends to be much greater, particularly at or near injection point. Since neutrals are commonly grounded, utilities might consider inserting RF chokes so that their lines are effectively ungrounded at high frequencies.

Although the PLC emission levels calculated in the simulation above are higher than the American FCC BPL emission limits, they are limited to the vicinity of the power line injection point. It would be difficult to achieve the American FCC BPL emission limits here in Ghana because the power line network configuration deployed here is different from that in the US. But by employing techniques such as minimizing power level and avoidance of locally used frequencies, the potential interference to other communication systems can be minimized.

5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The principal objective of this thesis is to identify and analysis the factors related to electromagnetic compatibility of powerline communication systems. The study comprises both theoretical analysis and experimental characterization. The experimental work was conducted in the form of field measurements, performed in a real powerline communication network at the VRA substation. For the theoretical work, simulations were performed based on the Method of Moments by using the Numerical Electromagnetics Code (NEC).

From the simulation work and measurements carried out, the following findings were made:

- As wire spacing of powerlines increases, the external field cancellation degrades resulting in higher radiation leakages.

- Horizontal power lines such as the medium voltage power network radiates less PLC signals compared to the low voltage vertical power lines. The vertical powerlines configuration may be seriously compromised by the grounding wires that are typically connected to the neutral wire. These grounds unbalance the system and degrade the cancellation associated with differential drive.

- Differential mode PLC signal injection onto powerlines significantly reduces radiation leakage than Common mode PLC signal injection. In differential mode injection, radiation leakage from currents flowing opposite directions with the same amplitude tends to cancel out one another. On the other hand, in common mode injection, current flow in one phase conductor and the return path is ground surface, which is a dielectric with losses.

- When the terminating impedance is too low or too high from the impedance of the power line, the radiating power tends to increase. The load impedance plays a significant role, the closer the line is terminated in its characteristic impedance, the lower the radiation. Mismatched lines have larger standing waves and radiate more than matched lines, all other factors being equal.

- Deploying powerline communication system in a typical residential neighborhood in Ghana would emit signals higher than the American emission standard limit. This could interfere with other communication systems operating in the high frequency band. But by employing techniques such as minimizing power level and avoidance of locally used frequencies, the potential interference to other communication systems can be minimized.

- Signal radiation leakage at the vicinity of the VRA PLC system was around 50µdBV/m which is high enough to interfere with other communication systems. But the radiation leakage decays along the power lines up to 10µdBV/m. The simulation results were verified with the measured results from the VRA substation.

5.2 Recommendations

The results of the experimental and theoretical work which were geared towards a better understanding of EMC phenomena in power line systems should be adapted by the National Communication Authority to obtain approximate and analytical data applicable in practical cases as EMC guidelines to avoid interference and guarantee the coexistence with broadcast radio services.

To reduce the interference risks or facilitate mitigation of interference problems a number of techniques and other potential means can be employed [22]. These mitigations include

- **Minimize Power Level**: The single most effective method for reducing the potential for interference may be to reduce PLC device output power. PLC system operators are encouraged to use the least power needed to carry out power line communications. The use of adaptive transmitter power control could be used to ensure that the farthest subscriber in the line has an adequate but not excessive conducted signal level.
- **Avoidance of Locally Used Frequencies**: A second method that can minimize the potential of PLC interference on other RF systems is to avoid certain frequencies and frequency bands used by other local RF systems. The NCA should issue a list of excluded frequencies that cannot be used by PLC. PLC systems can use modulation techniques that avoid excluded frequencies as well as filtering to minimize the potential of harmonics from causing interference.
- **Differential-mode Signal Injection**: Use of differential-mode injection of the PLC signal onto power lines could potentially reduce radiated PLC emissions leakage The generally unbalanced nature of power line pairs will limit the effectiveness of this technique.

- **Filters and Signal Terminations**: The use of filters on the power lines that would absorb, rather than reflect, RF signals at impedance discontinuities or termination points beyond the last subscriber on the line could reduce unnecessary RF emissions from PLC energized power lines. Further, the use of absorbing filters on LV lines to prevent RF signals from entering the premises of non-subscribers may mitigate certain interference problems.

5.3 Future Research

With respect to future research, exact and large scale real-time analysis of line characteristics and response is needed on certain potential areas with the availability of full resources (including the testing, measurement, performance analyzers, etc.) to establish verified and authentic results.

Also this work should be continued to improve further our understanding and for verification of models such as the linear two-source model in which the common mode anywhere can be determined from the amount of common mode and differential mode injected.

Additional work planned by the author includes investigating the effect of PLC signal radiation leakage on the power lines themselves. Since the power lines can act as antenna, they can pick up the leakage signals, that can caused data transfer in the PLC system to cease. Other future research includes

- The appropriate measurement antenna height and need for a height-adjustment factor should be determined with a goal of identifying the minimum set of measurements that will ensure identification of peak PLC emissions in important directions of radiation.

Measurement distance extrapolation factors reflecting the realistic decay of PLC field strength with increasing distance should be determined.

- Aggregation of emissions from PLC systems via ionospheric propagation and the associated PLC deployment models require study. This is of concern in the long term insofar as skyward emissions from many hundreds of PLC systems deployed over a large region might produce significant composite interfering signal levels at a very distant receiver.
- The local interference risk reductions obtained from the proposed compliance measurement guidelines should be determined to ensure that PLC systems will neither be unnecessarily constrained or pose unacceptably high interference risks.

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