DATA COMMUNICATION THROUGH DISTRIBUTION NETWORK FOR SMART GRID APPLICATIONS

By:

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Abstract

This work investigates a novel solution for overcoming excessive signal attenuation in distribution transformers for power line communication (PLC) applications in smart grids. The proposed solution avoids classical hardware bypassing and does not require sophisticated modulation schemes like Orthogonal Frequency Division Multiplexing (OFDM). It explores the resonance that occurs in transformer windings at the kHz range to transmit the communication signal. The transformer is modeled as a network of resistors, inductors and capacitors. This results in several resonance frequencies in the kHz and MHz ranges that can be used to pass the communication signal. Several methods can be used to obtain the frequency response of distribution transformers. In this work, the Frequency Response Analysis (FRA) technique is implemented. This technique measures the amplitude and phase response due to the application of a swept sinusoid at one terminal of the transformer winding. FRA measurement of a 20kVA (220/20kV) transformer indicated that there is a resonance at 490 kHz with a gain of 2 V/V and a bandwidth of 40 kHz. The captured frequency response is then modelled as a communication channel. Then digital modulated Binary Phase Shift Keying (BPSK) signals (at resonance and non-resonance frequencies) are transmitted through the modeled transformer. Sending data at 490 kHz within the 40 kHz bandwidth resulted in Bit Error Rate (BER) values that *appear* better than the Additive White Gaussian Noise (AWGN) channel because of the associated gain in the transformer. In addition, the simulation verified that sending data at non-resonance frequencies or outside the resonance bandwidth resulted in poor BER. The final issue investigated in this work is the effect of distribution cables from the utility substation up to the customers' distribution transformers. The simulation confirmed that the cable at high frequency acts as an attenuator with a value of attenuation that depends on the cable length. The BER was calculated for variable cable lengths cascaded with the transformer. By sending a BPSK signal at resonance with a bandwidth of 20 kHz, the BER was zero for cases where the attenuation was less than 40 dB. The research results showed that sending data at resonance frequencies has the potential to be an effective method for improving data communication using PLC for smart grid applications.

Search Terms: PLC, resonance frequency, distribution transformer, distribution cables, BER.

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Abbreviations

AM: Amplitude Modulation

AMI: Advanced Metering Infrastructure

AWGN: Additive White Gaussian Noise

BB-PLC: Broad Band-Power Line Communication

BER: Bit Error rate

BPSK: Binary Phase Shift Keying

CL: Convergence Layer

DSL: Digital subscriber line

EMI: Electro Magnetic Interferences

EPRI: Electrical Power Research Institution

FEC: Forward Error Correction

FM: Frequency Modulation

FRA: Frequency Response Analysis

GPRS: General Packet Radio Service

GSM: Global System for Mobile

LVI- FRA: Low Voltage Impulse- Frequency Response Analysis

MAC: Medium Access Control

NB- PLC: Narrow Band – Power Line Communication

OFDM: Orthogonal Frequency Division Multiplexing

PLC: Power Line Communication

PM: Phase Modulation

PRIME: Powerline Intelligent Metering Evolution

SFRA: Sweep Frequency Response Analysis

UNB-PLC: Ultra Narrow Band – Power Line Communication

Chapter 1: Introduction

1.1 Smart Grid Preface, Definition and Need:

Electric grids deliver electrical energy from utility generation units to customers' loads. This has been the case since the starting of the electric grid. Nevertheless, the current electric grid suffers from several drawbacks. For example, carbon emissions and environmental pollution produced from the generation units are increasing. Meeting the continuous growing demand of electricity is another issue with new generation plants built. New plants are costly and require several years of work. Customers tend to consume more electricity during the peak hours which creates a burden on electrical utilities, forcing the electrical authorities to either build further generation plants without critical need or to apply electrical shedding due to supply shortages. Furthermore, customers in the current grid are considered to be "passive" because they cannot generate or sell electricity and they cannot even communicate with the utilities [1],[2].

All these drawbacks and others can be overcome by the use of the Smart Grid. European Technology Platform Smart Grid (ETPSG) defines the Smart Grid to be "an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies" [1]. In other words, developing the traditional electrical grid into Smart Grids is becoming an attractive possibility because it will integrate renewable energy sources into the grid and it will help the customers ration their power consumption. Therefore, the total carbon emissions and the cost on the utility as well as on the customers will be reduced [2],[3].

Converting the traditional grid into a Smart Grid requires an established two-way communication system between the utilities and the customers. For Smart Grids, several communications techniques have been proposed such as Global System for Mobile Communications (GSM), Power Line Communication (PLC), and Digital Subscriber Line (DSL). PLC technology appears as one of the preferred solutions by utilities since the infrastructure is already available and it is independent from third parties. Moreover, it is considered to be a secure medium to carry information as it is dangerous to hack live electrical cables [4],[5].

As mentioned, traditional grids suffer from different issues that could be overcome by smart grids. The main drawback of the traditional grid is its inability to

match the increase in the load demand growth. If the load demand increases, the utility has to build a new generation plant that would take at least 5-10 years; hence, this solution is not the optimum one. For example, a general study in Scotland, conducted by the Scottish Power Company [6], expects the growth in load demand in Scotland to grow up to 30 TWh by 2020. Furthermore, the UAE Minister of Energy stated that the energy demand in the UAE will be 40 TW by 2020 [7]. These studies show how the demand growth can increase dramatically over a short period of time and hence the need for fast and economic solutions is a must. Another issue of traditional grids is the power outage issue due to limited power generation. The Energy Information Administration (EIA) stated that in the US there were more than 200 outages of 100 MW between 2001 to 2005 and that increased to 236 outages from 2006 to 2010 which affected more than 50,000 customers [8]. By the implementation of smart grids, customers can generate power on his/her side in an independent manner from the utility. This feature will reduce the burden and pressure on the utility company and enable the current generation plants to stand for several coming years. In addition, the customer will be able to sell power back to the utility [9]. According to the Electrical Power Research Institution (EPRI), it is estimated that implementing smart grids will save around five to ten percent of the current generated energy [3], [10].

Another drawback of the traditional grid is carbon emissions. According to a study conducted in Copenhagen, Denmark [11], a traditional grid generates around 41% percent of the total carbon emissions all over the world and this percentage is expected to increase up to 50% during the period between 2007 and 2030. The Climate Group stated that implementing smart grids will reduce carbon emissions by 2.03 Giga-ton annually which is equivalent to removing the carbon emission generated by all the cars in North America [11].

Furthermore, a case study approximates that if a single customer is able to generate a 16 kW using renewable sources, then the customer will be able to reduce his/her carbon emissions by 36000 pounds which is equivalent to planting 90 trees annually [12].

In the traditional grid, the utility generates the power and the clients consume it; in other words, the power flows in one direction: from utility to customer. Also, the utility cannot observe if there is breakdown at a specific individual load (like a single apartment in a building) unless the client complains [13]. Another advantage of smart

grids is the bi-directional flow of information to/from the customer. The utility will be able to perform remote billing and will have a remote outage detection feature. The customers will be able to see the electric behavior curve of their consumption and change their habits accordingly to match the lowest price offered by the utility, allowing them to reduce their electricity bills [3], [14].

Smart Grid benefits include an overall growth in the Gross Domestic Product (GDP). For instance, an investment of one billion dollars in smart grids will result in a growth of one hundred billion dollars in the GDP. In addition, an investment of two billion in the smart grid will create more than four hundred thousand jobs in different fields, as smart grids are considered a multidisciplinary area that involves several professions [15].

1.2 Smart Grid Challenges:

Smart Grid faces several challenges that are holding it back from being implemented all over the world. Challenges include factors that are related to integrating renewable sources, and customer consumption behavior. Major challenges include but are not limited to [16]:

- Safety regulations and issues of integrating renewable sources to the current grid supplied by the utility.
- Allowing the customers to supply energy from their sides using renewable sources.
- Controlling the storage elements that should supply power during the absence of the renewable energy supply.
- Effect of hybrid electric vehicles as they may increase or decrease the load at various nodes in the grid.

Nowadays, the transmission level part of the electric grid is monitored and controlled remotely using a Supervisory Control and Data Acquisition (SCADA) system which is one of the features of the Smart Grid [16]. However, at the distribution level, such monitoring is not available. So, designing a viable communication channel between the utility and the customers will help to implement the Smart Grid at the distribution level and overcome some of its challenges [14], [17].

1.3 Communication in the Smart Grid:

In a smart grid, data must flow in two directions between the utility and the customers. Data flow is classified into two main categories [18]:

1. Data flow between home area network and the utility:

Home data such as the "billing, required maintenance, peak hours and peak rate price" are exchanged between the utility and the consumers.

2. Data flow between distribution automation system and the utility:

Typically, the data will report faults and the condition of the apparatus in the grid.

Several technologies are available to provide communication links such as WiFi, GSM, satellite and PLC. Table 1 summarizes the main differences between these different technologies [19].

Power Line Communication (PLC) is one of the communication means that has been addressed for smart grids by which the transmission and distribution of electrical power lines are used to carry information from master to slave nodes and vice versa. Up till now, no standardized communication technology for Smart Grid applications has been developed. Nevertheless, PLC technology is the most preferred technology among other alternatives such as GSM, DSL, and satellites. The main advantage of PLC is its independence from third parties because the utilities can completely control and organize the communication between their side and the customers' side and this will reduce the running cost as well. Furthermore, PLC uses the electrical grid so the infrastructure is already available and hence there is no need to install additional equipment or cables. PLC compared with other solutions like DSL provides complete coverage to the customers as it is based on the existing electrical wiring. For example, only 20% of customers in Australia have a subscription to DSL service which reveals a poor coverage if DSL is used to be the communication channel between the utility and customers [20]. PLC technology is considered a secured communication channel because it is difficult and dangerous to hack the electrical cable and the grid apparatus. On the other hand, other communication channels like DSL will require the development of new technology to improve the security level [8]. Further, PLC provides additional protection over utility information because "utility applications most likely require redundancy in protection and control applications, and the need for redundancy should also be extended to the availability of the redundant communication channels" [16].

Table 1: General Comparison of Alternative Communication Technologies for Smart Grids [19]

Technique	Advantages	Disadvantages
GSM/GPRS	• Easy to handle • Low modem costs • Mature technology	• Dependency on third party • Severe limitations when meters are installed in cellars • Limited bandwidth • No influence in case of problems/failures • High overload risk • Large problem in cities
High Speed Narrow Band (NB) PLC	• Available infrastructure • Secured medium • Independence from third party	• Performance depending strongly on channel • Changing channel characteristics • Only medium coverage • Lack of standards • Shared channel
Broad Band (BB) PLC	• High throughput • Available infrastructure • Independence from third party	• Electromagnetic disturbance • Short coverage • Lack of standards
DSL	• High bit rate • No shared medium	• No full coverage • Dependency on third party
Satellite	• Quick deployment • 100% coverage	• High latency • Dependency on third party • Cost

1.3.1 Historical View of PLC Technology:

Using power cables as a communication means is a relatively old technology as it was invented in the early twentieth century. PLC has been used on high voltage lines to carry audio signals for telecommunication purposes since 1920. Moreover, it has been used for control actions since 1930 to connect/disconnect remote heavy loads from the grid. Recently, the technology has improved and can achieve high data rates, as the transmitted signal frequency can range from 3-500 kHz [16], [21].

1.3.2 PLC Technologies:

In power line communication there are three main modules: Ultra Narrow Band (UNB), Narrowband (NB), and Broadband (BB). Table 2 summarizes the main features and operation regions for each mode [16].

Table 2: Classes of PLC Technology [16]

Module		Data Rate	Operating Frequency
Ultra Narrow Band		~100bps	0.3 -3 kHz
Narrowband	**Low Data rate**	Few kbps	3-500 kHz
	High Data Rate	~500kbps	3-500 kHz
Broadband		~100 Mbps	1.8-250 MHz

Ultra Narrowband and Narrowband PLC:

First application of PLC was achieved using Ultra Narrowband and Narrowband technologies. Initially the technology allowed only one-way communication, but in 2002 the communication model was updated and a two-way communication was implemented. To organize and control the bandwidth of the power lines, the Comité Européen de Normalisation Électrotechnique (European Committee For Electrotechnical Standardization, CENELEC), standardized the spectrum in 1992 allowing communication to be performed over the low voltage of the grid, and it allocated the bandwidth from 3-148.5 kHz for that purpose. The range then was classified into four sections summarized in Table 3 [16]:

Table 3: CENELEC Frequency and Application Divisions [16]

Range/ Section Name	Frequency Range (kHz)	Application
CENELEC A	3-95	Reserved for Utility
CENELEC B	95-125	Any Application
CENELEC C	125-140	in-Home networking
CENELEC D	140-148.5	Alarm and Security

On the other hand, the CENELEC standard is not followed in the US as the Federal Communications Commission (FCC) has assigned the spectrum of NB technology up to 500 kHz without specifying sub-divisions in the bandwidth.

Broadband (BB) PLC:

The main objective of BB PLC is to carry data for Internet access applications and successively for HAN and A/V applications. In 1997, the initial data rate was about 1Mbps but the technology was not improved due to the high cost and severe electromagnetic interferences. By the beginning of the twenty first century, BB PLC was adopted for in-home PLC. Several associations appeared within that field application such as: HomePlug, Universal Powerline Association (UPA), and High Definition Powerline Communication (HD-PLC) and they were able to achieve data rates up to 200Mbps [16].

1.3.3 PLC Applications within Smart Grid [16]*:*

An electrical grid is classified into three main sections according to voltage level: High, Medium and Low Voltage. PLC could be implemented for applications over all three sections and in this work we will narrow the scope to the low voltage sector. Applications of PLC over the low voltage network include:

- Automatic Metering, Billing and Two-Way Communication:

Using Advanced Metering Infrastructure (AMI) will establish the two communication means between the utility and the customers. Customers can receive information about the electrical pricing for their consumption and the utility can know the consumption of the customer remotely.

- Consumer Load Management:

Rationing consumers' electrical consumption is an objective that can be achieved through PLC technology. Customers can alter their behavior and daily activities especially at peak times, hence making the demand curve smoother with less peak value at peak times. The direct incentive for consumers to alter their behaviors is applying a layer billing system depending on the time. Also, customers can supply electricity if they have extra electrical power due to installing distributed generators at their premises. The best PLC scheme is the NB PLC, as with a BB PLC, signals over the low voltage side will suffer from high attenuation, and the UNB PLC provides slow and limited data rates.

1.4 Challenges of PLC Implementation:

Like any technology, PLC suffers from impairments. PLC technology uses the available power cables to carry information between the two recipients: utilities and customers. Within the cable connections between the transmitter and the receiver of the message, distribution transformers usually exist. The main issue of having transformers in the link between the transceivers is its nature to act as a low-pass filter with a cut off frequency around 300 Hz. Typical communication signals are modulated at higher frequencies like the MHz range; hence, the communication signal will be filtered out by entering the transformer. The transformer filter action occurs because its core gets saturated. The transformer core is made out of iron divided into small internal regions called "domains". Each domain includes iron atoms and they get aligned in the direction of the applied magnetic field. Thus, each domain will point to the direction of the applied magnetic field [22]. As the frequency of the applied signal increases, the rate of change of the direction of the induced magnetic field in the core will increase as well. Changing the direction of the magnetic field rapidly will not allow the "domain" sections in the core to re-align; therefore, the core will be saturated. As the core enters the saturation region, the core is no longer able to carry and deliver the change in the magnetic flux from the primary winding to the secondary winding; therefore, the communication signal will not be able to pass the transformer. This phenomenon addresses the main challenge that affects PLC technology within the scope of the transformer element.

Power cables form another challenge. Cables have resistive, inductive and capacitive natures; consequently, the cables will act as a filter which will cause a

significant degradation and attenuation to the communication signal. Cables are designed for a 50/60 Hz signal; therefore, high frequency signals will be filtered out due to the nature of the cables. Moreover, the skin effect is an important parameter for high frequency signals. In [16], the path loss per kilometer over the PLC cables was estimated as shown in Table 4 given that the signal travels at 100 kHz and 10 MHz. Table 4 indicates that as the frequency increases, the loss will increase per unit length. In addition, Table 4 states that the signal will encounter higher attenuation if the cables are underground with respect to overhead line cables. The main reason for this issue is the high stray capacitance values for underground cables compared with overhead lines.

Table 4: Typical path loss values in dB/km for PLC application

Voltage Level	At Frequency (100 kHz) Attenuation dB/km	At Frequency (10 MHz) Attenuation dB/km
Low Voltage	1.5-3	160-200
Medium Voltage (OH)	0.5-1	30-50
Medium Voltage (UG)	1-2	50-80
High Voltage (OH)	0.01-0.09	2-4

1.5 Overcoming PLC Challenges:

1.5.1 Bypassing Transformer by External Circuits:

In order to overcome the transformer signal attenuation issue at high frequencies, it has been suggested to bypass the transformer using an external circuit. However, this solution is impractical as it requires installing the bypass circuit at each transformer in the grid. Hence, the installation cost will be high as well as the running cost because of the circuit's regular maintenance. Furthermore, the external circuit could reduce and affect the data rate, which is not desirable in communication [23] [24]. A new bypass circuit model has been designed to have low cost, low insertion loss in the communication band, and high rejection capabilities for the power signal (50 Hz) [20]. It has been found that the signal loss is less than 15 dB and hence the signal will be able to serve millions of customers. The bypass circuit is based on using

capacitive couplers and it was designed to have low cost with low data loss. However, the circuit suffers from several drawbacks. One of the main drawbacks is the requirement of having fuses and protection circuits before and after the bypass circuit. Another drawback is the requirement of matching the circuit impedance with the transceiver modem because having mismatched impedances will result in significant ripples in the frequency response of the system. In order to ensure the system is reliable, the bypass circuit must be coupled to the three phases of the distribution transformer; hence, an RF transformer should be installed at the low voltage side along with a capacitive coupler [20]. In [25] a bypass circuit that is based on the coupler technique is used. The research simulated and tested signal propagation through a distribution transformer (from MV to LV and vice versa) and MV transmission cables of 1 km length. The results validated the feasibility of using a bypassing circuit to avoid the attenuation issue of the transformers. However, the main downside of using a bypassing circuit is the initial and the running cost.

1.5.2 Bypassing Transformer by Sophisticated Modulation Schemes (OFDM):

In order to overcome the problems of using a bypass circuit, a study in [26], [27] suggested a sophisticated modulation scheme such as Orthogonal Frequency Division Multiplexing (OFDM)to transmit the information without bypassing the transformer using an external circuit. The major drawback of the suggested solution is the complexity of both the transmitter and the receiver. A general description of the physical layer of G3-PLC, where an OFDM modulation scheme was used to transmit data in the frequency range of 35 kHz to 90.6 kHz, was presented. It has been stated that PLC channel characteristics and features depend on the signal frequency, location, time and the type of equipment connected to the channel. Furthermore, it has been found that the signal frequency has severe influence on the attenuation level; for example, if the transmitted signal is at high frequency (> 1 MHz), then the signal will suffer from significant multipath frequency selective fading and will get attenuated if it travels a distance more than 100 ft. On the other hand, if the signal frequency is low (20 kHz ~ 500 kHz), then the signal will be prone to impulsive noise. A G3-PLC system was tested practically on the electrical grid and the transmitter and the receiver were located in four orientations: Low Voltage-Low Voltage (LV-LV), Mega Voltage-Mega Voltage (MV-MV), and Mega/Low Voltage – Low/Mega Voltage (MV-LV or LV-MV). For the LV-LV case, both source and

destination points lie on the same potential level with 200 meters of space between the two nodes. An attenuation of 30 dB over the transmitted signal between the nodes due to differences in the cable material along the signal path was observed. For the MV-MV scenario, transmitting and receiving the signal is performed by a capacitive coupler. It was proven that this scenario is prone to inference signals like ship telecommunication signals and radio station waves. For the MV-LV or LV-MV case one of the nodes was before an MV/LV transformer and two nodes were after it. The transformer caused 40 dB attenuation over the transmitted signal. Because a single transformer feeds several loads, routing the signal to the desired node is an issue. By using G3-PLC technology it is required to use one concentrator to route the signal to its required destination instead of three concentrators. Also, it was noted that data flow in the case of the MV-LV is better and higher compared to the LV-MV case because the transformer model was a Delta-Wye connection and moving from the Wye to the Delta side provides high isolation compared to the flow in the opposite direction. The main reason behind this is due to the neutral point in the Wye connection, as that point increases the isolation [27].

1.5.3 Overcoming Transformer Filtering Issue Using Transformer Resonance Frequencies:

It has been reported that the transformer filtering phenomenon can be overcome at certain frequency bands since the transformer acts as a "window" allowing the communication signal to pass with minimum loss and attenuation at these bands [23]. The effect of sending data modulated in a MHz band and transmitted at a low rate (1-2 kbps) through commercial and residential transformers has been studied [23]. One of the main challenges the study encountered was the interference signals from adjacent bands. In order to mitigate the effect of this problem, communication techniques were used.

This study opens the door for further investigations in the PLC field. The study examined the effect of transmitting data in MHz bands at certain frequencies. By analyzing the features of theses frequencies, it was found that they are the resonance frequencies of the transformer. At resonance the impedance is the lowest; hence, the transformer acts as a window that allows the signal to pass.

Transformers have resonance frequencies in both the kHz and MHz ranges. Sending data at resonance frequency will allow the signal to pass with minimum

attenuation. Furthermore, the effect of the interferences can be reduced by sending data in the kHz band. Identifying the resonance frequency can be done by investigating the frequency response of the transformer. Moreover, the effect of cable attenuation can be minimized by the same method if the communication signal is transmitted at the resonance frequency of the cable.

1.6 Problem Definition, Scope and Assumptions:

The investigation in the thesis includes a power grid from the secondary side of the distribution substation (typical value is 33/11 kV) to the meters of the customers where PLC technology is adopted. Figure 1 represents the scope of the work.

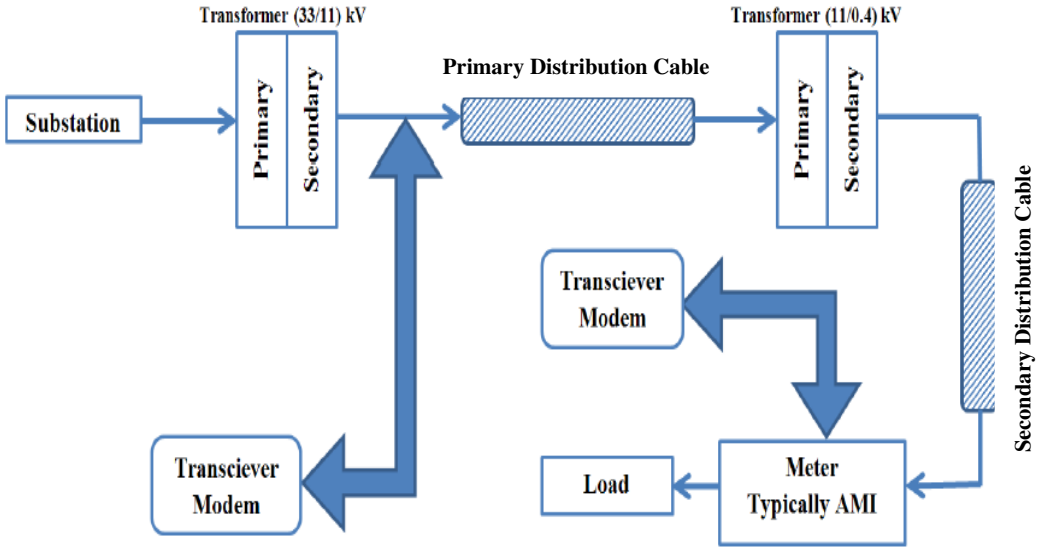


Figure 1: Scope of the thesis

It is assumed that there is one customer meter connected to the second transformer (typical voltage ratio in the UAE is 11/0.4 kV) and the investigation is carried out for this scenario. This assumption simplifies the issue and reduces the sources of error in the modeling process.

The scope of this thesis involves two important elements: cables and distribution transformer. The cable connecting the customer's transformer with the meter is not simulated as its length is short and its effect is not vital. On the other hand, the cable connecting the substation with customer's transformer is simulated as it is long; hence, it will have a vital effect on the transmitted message. Furthermore, the study is implemented using a single phase transformer due to its availability in the lab. As discussed in aforementioned subsections, a distribution transformer acts as a low-pass

filter while the cables act as attenuators. Adopting PLC technology for smart grid applications requires a technique that helps overcome the challenges of distribution transformers and power cables. The main thrust in this thesis focuses on the potential to successfully transmit valid communication signals for Smart Grid applications at the resonance frequency of the distribution transformer.

1.7 Thesis Organization

Chapter 1 of this thesis presents a general introduction of PLC technology, the problem definition and work scope. In Chapter 2, the frequency band of the operation is defined. Furthermore, the method of modeling the transformer and distribution cables is discussed. Chapter 3 presents the experimental setup that has been used in the thesis. In Chapter 4, the experimental results are discussed and compared to the simulation. Finally, the conclusion and recommendations are presented in Chapter 5.

Chapter 2: Modeling of Distribution Network's Elements:

2.1 Methods to Model a Power Transformer at High Frequency:

The frequency response of a transformer can be found either using a pre-determined model or by a direct measurement using Frequency Response Analysis (FRA). All frequency dependent models are extracted from physical measurements and the complexity of the model is dependent on the frequency of the operation. In the literature, there are two main models that are used to characterize transformers at high frequencies [28], [29]:

- Lumped Model
- Transmission Line Model

2.1.1 Transformer Models at High Frequency:

- **Lumped Model:**

Typically, this model is used to characterize the transformer up to 20 kHz. This model requires knowledge of the capacitance between each transformer winding turn, the capacitance between each layer of winding turns, and the inductance in each turn. Modeling a complete transformer results in a dense mesh of LC elements as shown in Figure 2. The main drawbacks of this model are the frequency limitations, neglecting the resistance and the need to access the transformer internally to measure the capacitances and inductances.

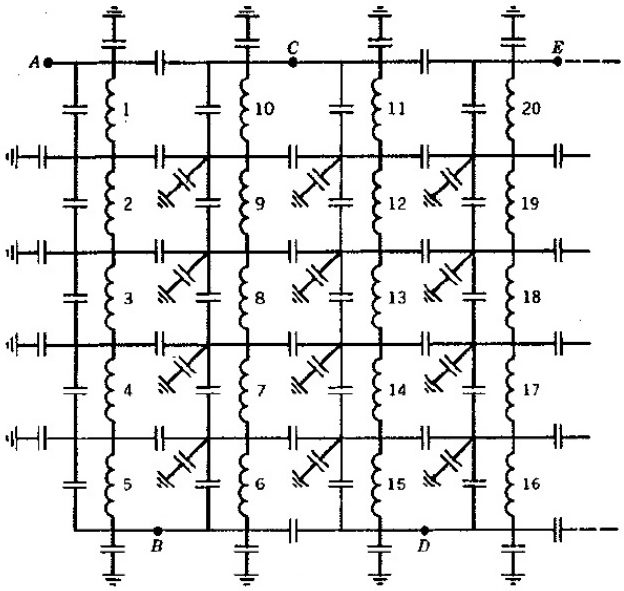


Figure 2: LC network of transformer in Lumped Model **[29]**

- **Transmission Line Model:**

To overcome the frequency limitations of the lumped model, a transmission line model can be used. The basic theory of this model is based on taking a small segment of the windings' turns and measuring the capacitances, the resistances and the inductances. After that, the measurements are performed for another small segment of the windings until the whole transformer is covered. This method represents the transformer as a transmission line system with multiphase in-network format layers as represented in Figure 3 [29].

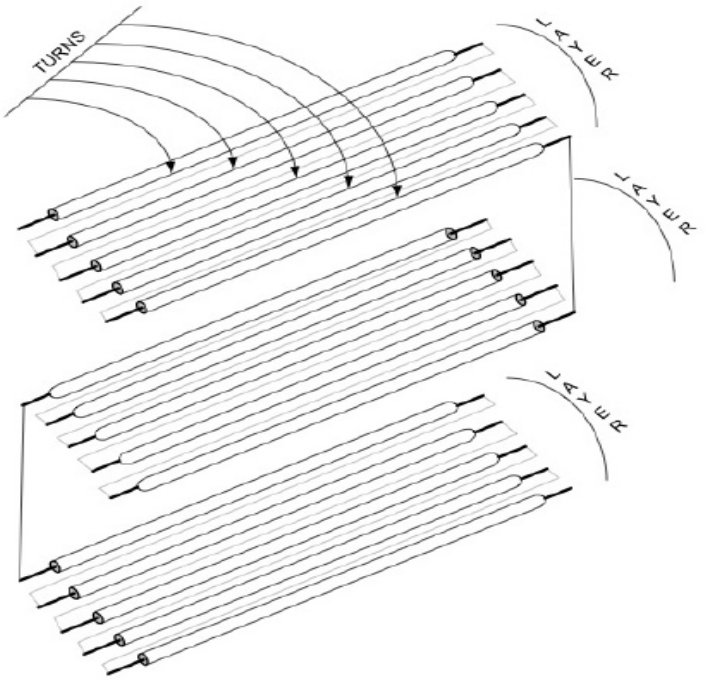


Figure 3: Multiphase transmission line representation of transformer **[29]**

The main advantage of this model is the inclusion of the capacitance, inductances and the losses as distributed parameters and it can be used for signals in MHz bands. Nevertheless, the measurements require internal access to the transformer windings like the lumped model. Hence, there is a need to find a better approach to find the transformer frequency response.

2.1.2 FRA Analysis:

Unlike the previous models, the frequency response of the transformer can be obtained without measuring the internal impedances and admittances using Frequency Response Analysis (FRA). It can be performed by applying either Sweep Frequency Response Analysis (SFRA) or Low Voltage Impulse Frequency Response Analysis (LVI-FRA).

- **SFRA Test:**

The SFRA method uses a sweep generator to apply sinusoidal voltages at different frequencies to one terminal of a transformer winding. Both the amplitude and phase of the measured signals from selected terminals of the transformers are plotted directly as a function of frequency [30]. So, the obtained frequency response represents the transformer's internal resistances, capacitances and the inductances.

The gain and the phase response are found using Equations (1) and (2) respectively:

$$Magnitude\ Response\ = \frac{V_{out}}{V_{in}} \tag{1}$$

$$\begin{aligned} Phase\ (radian) =\ & Phase(V_{out}) - Phase(V_{in}) \\ & = \Delta t * Signal\ Frequency * 2\pi \end{aligned} \tag{2}$$

Where (Δt) is the time difference between the transmitted and the received signal.

- **Low Voltage Impulse:**

This test is performed by injecting a low voltage pulse at one side while capturing the output signal at the other side. After that Fourier transform analysis is applied to the transmitted and received signals. Fourier transform provides the signal phasors which can be used to calculate the amplitude (gain) response, phase response and, if required, the impedance and admittance response.

Compared to LVI test, SFRA test has more advantages than LVI. The main advantages of SFRA are the simplicity of the test and the better performance at high frequencies. Furthermore, the SFRA test requires fewer devices to perform the test. However, the SFRA test requires a long period of time measurements. Table 5 highlights the main advantages and the drawbacks of each test.

Table 5: Comparison between SFRA and LVI tests

SFRA Advantages	LVI Disadvantages
High signal-to-noise ratio	Signal to noise ratio decreases with frequency as higher frequency components have less energy
Wide frequency range	Frequency resolution is fixed and poor at low frequencies
Adaptable frequency increments (better resolution at low frequencies)	Several pieces of equipment needed (function generator, rogowski coil, digital oscilloscope)
Can be implemented by only one piece of measuring equipment needed (Network analyzer)	Difficult to filter out broad band noise
SFRA Disadvantages	**LVI Advantages**
Measurement is relatively long (several minutes)	Measurement is short (typically less than one minute)

In this thesis, the SFRA test will be used to obtain the frequency response of the distribution transformer due to its advantages over LVI and the transmission line model.

2.2 Resonance Phenomenon in Transformer:

A transformer resonates at medium frequencies such as kHz and MHz bands. This work uses the resonance phenomenon that occurs in the transformer as channels to allow signals to pass through with minimum attenuation and on some occasions with amplification gain. The transformer can be modeled as a network of resistive, capacitive and inductive elements. As the frequency increases, stray capacitors start to significantly influence the transformer's transfer function, consequently increasing the complexity of the overall network. Figure 4 shows an illustrative circuit diagram of the RLC network model of a transformer at high frequency showing a complex net of parasitic capacitors.

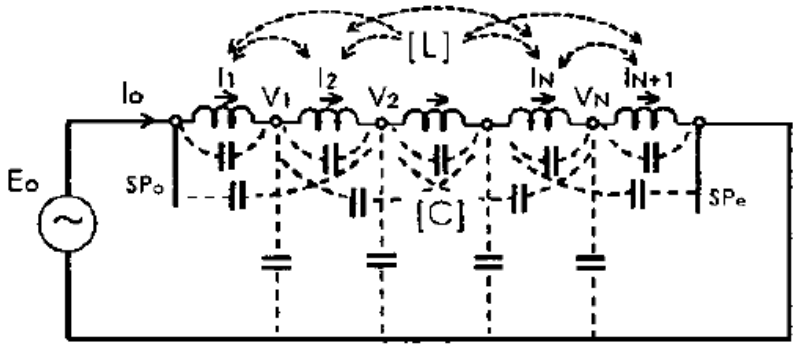


Figure 4: RLC network elements of transformer at high frequencies **[31]**

In general, a network of RLC elements results in several resonance frequencies because of different interaction behaviors between the magnetizing inductance, air-cored inductance of the windings and the shunt and series capacitors. Primarily, the resonance that occurs at low frequency is due to the interaction between the shunt capacitance and the self-inductance of the windings. This type of resonance varies from one transformer to another as it depends on the residual magnetization state of the core and the core joints. Minor differences in core joints between two transformers may result in different resonance frequencies. Beyond the low frequency range, resonance happens because of an interaction between the mutual inductances between winding turns and the series and the shunt capacitors of the windings. Resonance frequency values vary from one transformer to another as the capacitances and the inductance values are functions of winding geometry, transformer tap position, internal lead shape and the presence of oil [32] [33].

2.3 Transformer Frequency Spectrum of Operation:

The first step of this research is to determine the working band of resonance frequencies. Resonance occurs at different frequency ranges and it was decided to select resonances that happen at the kHz range up to 1 MHz. for several reasons. The selection of this frequency band is due to the global availability of this band for PLC applications. Furthermore, operating at this frequency range would reduce the Electromagnetic Interferences (EMI) from wireless applications (HF, VHF, UHF, GSM, RFID, etc.) that operate at Mega and Giga-Hertz ranges. Reducing the EMIs reduces the noise in the system and leads to an overall improvement in the system operation.

The next step, after defining the band of operation, is to determine the resonance frequency. Resonance frequency differs from one transformer to another; consequently, defining a fixed and standardized single resonance frequency is not

possible. Resonance frequency values of a transformer can be obtained by finding the frequency response. Several methods can be used to obtain the frequency response and in this work SFRA is implemented.

Having a communication signal that operates at resonance frequency will help to overcome the filtering obstacle of the transformer. The signal at resonance will propagate with reduced attenuation as the system is purely resistive. Moreover, the resonance nature may enhance the system's overall performance with some amplifying gain from the least impedance and LC elements of the transformer [34].

2.4 Methods to Model Power Cables at High Frequency:

The PLC network method is based on using power cables to carry the communication signal from the destination to the source node. Hence, power cables are vital elements that should be modeled, and their behavior over the signals should be evaluated.

In theory, there are two main models to characterize power cables: the statistical model and the deterministic model.

- **Statistical Model:**

A statistical model is logarithmic and has a normal distribution. It is driven mainly by the multipath effect that the signal encounters when traveling from one node to another. The multipath nature of the channel arises from the presence of several branches and impedance mismatches that cause multiple reflections [35]. In this model, the captured distortion is due to the low pass behavior of the cable as well as the reception of multiple versions of the original signal caused by reflections in the cable due to any mismatch in the impedance that occurs over the line [16].

A statistical model can be used to represent the channel as a transfer function as defined in Equation (3):

$$H(f) = \sum_{i=0}^{Npath-1} g_i(f) e^{-\alpha(f) v_p \Theta_i} e^{-2j2\pi f \Theta_i} \quad (3)$$

Where: $g_i(f)$ is a complex number, generally frequency-dependent that depends on the topology of the link; $\alpha(f)$ is the attenuation coefficient which takes into account both the skin effect and dielectric loss; θ_i is the delay associated with the i^{th} path; v_p is the velocity of propagation along the power line cable; and N_{paths} is the number of non-negligible paths [16].

A statistical model is based on the reflections of the transmitted signal in the cables and it requires precise and accurate selection of parameters that represent the

signal propagation properties as well as the multipath effect. Those determined parameters are estimated after measuring the transfer characteristics of the channel to be used [36]. Hence, some constants such as propagation and reflection constants must be determined by transmission line theory. To have an accurate model representing the cables, the model will require determining the number of paths, the power delay profile, and the cable loss properties such that the path distribution, path delay, path magnitude and phase are determined and evaluated [36].

Moreover, signal reflections will increase severely if cable joints are used in the connections because they create mismatched impedance between the two connected cables. Another parameter that may affect the reflection in the cable is the cable strands. Power cables are not single core; nevertheless, they are stranded cables and between the strands there are extremely small voids that would increase the reflection across the cables. Practically, there are infinite paths that the transmitted signal can follow which can be categorized into propagation and reflection paths [36].

- **Deterministic Model:**

Initially, this model was mostly empirical and the defining and critical variables were not related to the physical characteristics of the channel such as channel length, cable cross sectional area, and attenuation versus frequency. Basically, the channel was represented by a multipath through which the signal travels. All the parameters such as delay and attenuation were added to the model after physical measurement of the cables. As that model is not precise and concise, a need to derive another model is required [16].

Using transmission line theory of electromagnetics, it is possible to model electric cables based on their physical parameters. Hence, transmission and distribution cables can be represented by transmission matrices only. Therefore, the channel (cable) can be represented as two-port network as shown in Equation (4) [35].

$$\begin{bmatrix} V_1 \\ I \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \qquad (4)$$

Where $A = D = cosh(\gamma l)$, $B = Zo\, sinh(\gamma l)$, $C = \frac{1}{Zo}\, sinh(\gamma l)$,

"l" is cable length and "γ" is propagation constant [m^{-1}] = $\sqrt{z.y}$ and z = R + jωL [Ω/m] and y= G +jωC [s/m],

Hence:

$$\gamma = \sqrt{(R + j\,\omega\, L).(G + j\,\omega\, C)} \quad [m^{-1}]$$

If the cable is divided into sections, then each section is represented as a two-port network; consequently, the overall model from point X to point Y is a cascaded form of the transmission matrix as shown in Equation (5).

$$T_{XY} = T^{(1)}.\ T^{(2)}.\ \ldots\ldots T^{(N)} = \prod_{i=1}^{N} \begin{bmatrix} A^i & B^i \\ C^i & D^i \end{bmatrix} \quad (5)$$

In case of having ground cable along with the transmission lines, the same concept is applicable but the only difference is the arrangement of the transmission matrices.

Further, this model allows us to calculate the transfer function of the channel in the form of a ratio between the voltage at the receiver side and the source voltage in terms of the impedances and transmission matrix coefficients, as shown in Equation (6) [35]:

$$H(f) = \frac{V_2}{V_1} = \frac{Z_L}{AZ_L + B + CZ_S Z_L + DZ_S} \quad (6)$$

The main drawback of this theory is that the complexity of building a complete model increases with the amount of branching to different customers. Therefore, this model is not recommended to model indoor cables and lines. However, the scope of this research involves one path from the distribution substation to the customer transformer. Consequently, a deterministic model is used in this work to characterize the power cables representing the segment from the substation up to the customer node in the described system. On the other hand, the cables connecting the 220 V transformer side to the customer distribution board (DB) are not considered as they are short; therefore, their effect will not be vital. In addition, the deterministic model has additional advantages in implementation and simulation compared to the challenges of the statistical model. The major advantage of the deterministic model is that it can be used to model power cables' transfer function easily compared to the statistical model. This is because it only requires specifying the resistance, inductance, capacitance and trans-conductance of the cable segment as indicated in Equation (4).

In this thesis, the distribution cable is modeled using Equation (6) and the resistance, inductance and capacitance parameters of a commercially available 24kV concentric distribution cable are shown in Table 6.

Table 6: Parameters of simulated distribution cable

Parameter	Value – Unit	Unit
DC Resistance	0.727	ohm/km
Inductance	0.524	mH/km
Capacitance	0.14	uF/km

Another parameter that should be considered is the resistance due to the skin effect parameter or AC resistance. The skin effect is the tendency of the current to get concentrated around the cable edges and it is proportional and dependent on the signal frequency. Cables are designed to deliver signals at 50 Hz; hence, the skin effect factor is not significant and usually the AC resistance is not provided by the manufacturer. Nevertheless, considering the skin effect is vital as the communication signal used in this work is modulated at frequencies in the kHz range. AC resistance can be modeled as a real parameter that is frequency-dependent and it will be added algebraically to the cable impedance parameter. To estimate this factor, Carson's equation for modeling distribution cables is used. The total impedance of the cable will be given by: [37]

$$Z = \left(R_{DC} + \left(9.8696 * 10^{-04} * f\right)\right) + j\omega L \quad [Ohm/Km] \qquad (7)$$

Where: f is the signal frequency and ($9.8696*10^{-04}$ *f) is the AC resistance.

Chapter 3: Materials and Experimental Setup

In this short chapter, the experimental setups that have been used in this thesis are discussed. This thesis included two setups that were implemented in the lab. The first setup was used to obtain the frequency response of distribution transformer while the second setup was used to verify the simulation and the theoretical results.

3.1 Experimental Setup of SFRA Measurement:

In the laboratory the frequency response of a distribution transformer was measured using the SFRA method. The specifications of the experimental transformer are listed in Table 7.

Table 7: Experimented distribution transformer specifications

Apparent Power	**20 kVA**
Low Voltage Side	220 V
Low Voltage Side Windings Resistance	0.20 Ω
High Voltage Side	20 kV
High Voltage Side Windings Resistance	433 Ω

The SFRA experimental setup is composed of an Arbitrary Function Generator (AFG 310 Sony Tektronix), oscilloscope (Tektronix TDS), and single phase distribution transformer (20 kVA, 20/0.220 kV). Figure 5 shows the instruments that were used in the lab to measure the frequency response of the distribution transformer. Figure 6 shows a zoomed view of the transformer.

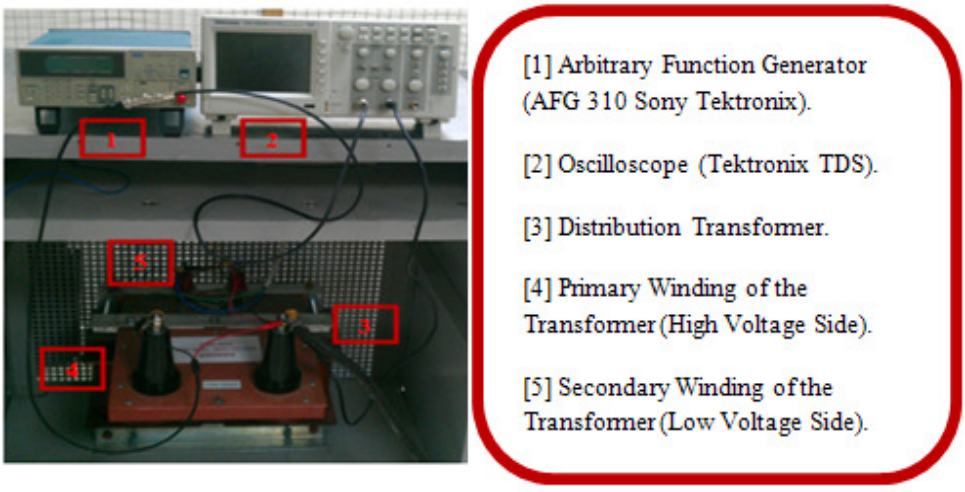


Figure 5: Laboratory experimental setup-Frequency Response Measurement

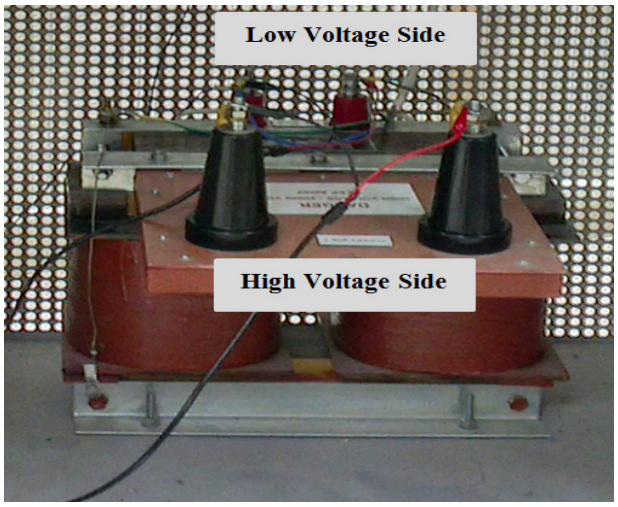


Figure 6: Distribution transformer 20 kVA, 220/20 kV

Transformers are considered as asymmetric devices. One of the reasons that causes transformers to be asymmetric is the difference in winding ratio between the primary and secondary winding terminals. Therefore, the frequency response should be measured from the high voltage side to the low voltage side and vice versa.

3.2 Experimental Setup of Verifying the Simulation Results:

The setup that was used in the lab to verify the simulation results was composed of Agilent M9331A, Agilent M9210, a 20 kVA (20/0.22 kV) distribution transformer, and variable attenuators. The experimental setup is shown in Figure 7.

Figure 7: Experimental setup to verify the results in the lab

An Agilent M9331A module was used to generate the BPSK signal. Figure 8 shows a zoomed view of the module.

Figure 8: Zoomed view of Agilent M9331A

Agilent M9331A is an Arbitrary Waveform Generator (AWG) and it is interfaced with MATLAB; hence, the BPSK signal is created in MATLAB and then generated by the module. An arbitrary sample of a BPSK signal is shown in Figure 9.

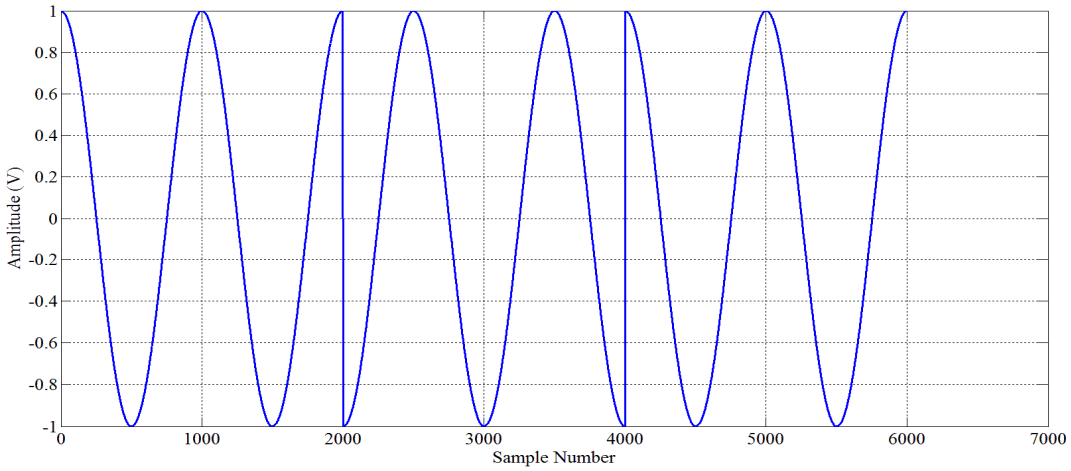


Figure 9: Arbitrary BPSK signal sample

As mentioned before, cables act as an attenuator element due to the high frequency nature of the transmitted signal. Because the distance between the transformer and the customer load is typically short, the cable attenuation effect is not significant. On the contrary, the cable that connects the substation with the customer transformer is long and will cause severe attenuation to the signal. In this test, attenuator elements are used to model the cable attenuation effect from utility substation up to customer transformer (long cable modeling). Different values of the attenuation elements are used to represent different cable lengths. Figure 10 shows a sample of an attenuation element that was used in the test.

Figure 10: Sample of the attenuation elements used in the practical experiment

The last component of the experimental setup in the practical verification of the simulation results is the data acquisition unit. To acquire the data, an Agilent M9210A module is used. The module has two channels; hence, the transmitted and the received signal after passing the transformer can be acquired. Agilent M9210A has a trigger input; therefore, the module can be programmed to start recording data once the signal is transmitted which makes the acquisition efficient. Figure 11 shows a zoomed view of the Agilent M9210A module.

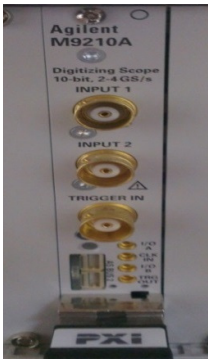


Figure 11: Zoomed view of Agilent M9210A

Chapter 4: Simulation and Experimental Results:

4.1 Frequency Response of Distribution Transformer:

One of the main contributions of this work is to send data at the resonance frequency of a distribution transformer, hence overcoming the filtering issue. Finding the frequency response of the transformer will allow us to allocate the resonance frequency. The method that will be used to find the resonance frequency is SFRA and it will be obtained for two cases: from the high voltage side to the low voltage side and vice versa. The SFRA test was performed using the experimental setup that was shown in Figure 5.

4.1.1 Frequency Response Measurement from High Voltage to Low Voltage Side:

A single-tone signal (sinusoidal signal) was injected from the AFG into the primary windings (20kV side), while at the secondary windings, output at the 220V side was measured using an oscilloscope. The frequency of the transmitted sinusoidal signal was swept from 1 kHz to 2 MHz in steps of 10 kHz while the amplitude was maintained at 2 V (peak to peak). The transmitted and the received signal amplitudes (peak-peak) were measured and tabulated. Figure 12 shows the block diagram of how the frequency response was measured in the lab.

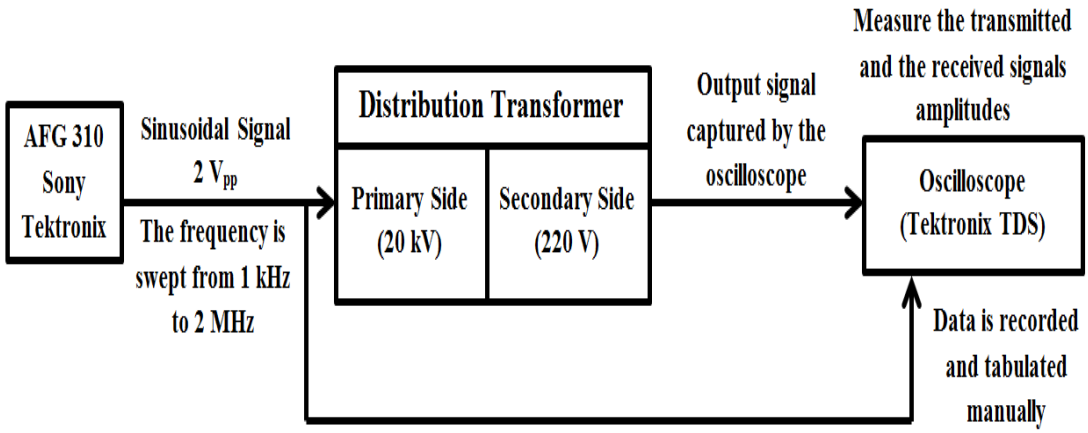
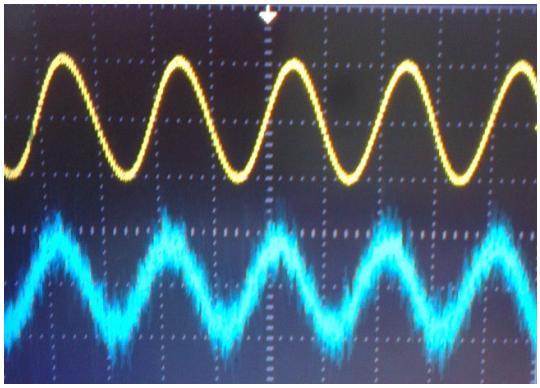


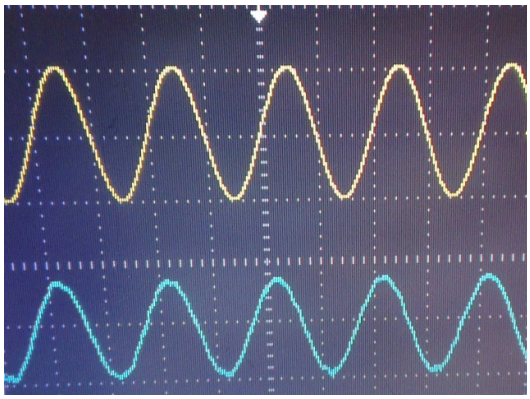
Figure 12: Block diagram of measuring the frequency response practically (high to low side)

It was noticed that the received signal (from the secondary side) was noisy; hence, the averaging option in the oscilloscope was used. Using the average option made the signal cleaner and made it easier to record its amplitude with high accuracy and precision.

Figure 13 shows a sample of the injected and output signals with and without the averaging technique.



(a)



(b)

Figure 13: (a) Input and output signal through transformer without averaging technique
(b) Input and output signals with averaging technique
Yellow signal is the input signal and the blue is the output from transformer

From the measured signal levels, the gain was calculated as a ratio of the output to the input voltage peaks. The voltage gain versus the corresponding frequency was depicted in Figure 14. Furthermore, the phase delay was measured between the input and the output signals; therefore, the frequency response in terms of gain and phase was recorded. It is worth pointing out that measuring the phase delay requires precise and accurate measurements; hence, the phase delay was measured only at resonance regions.

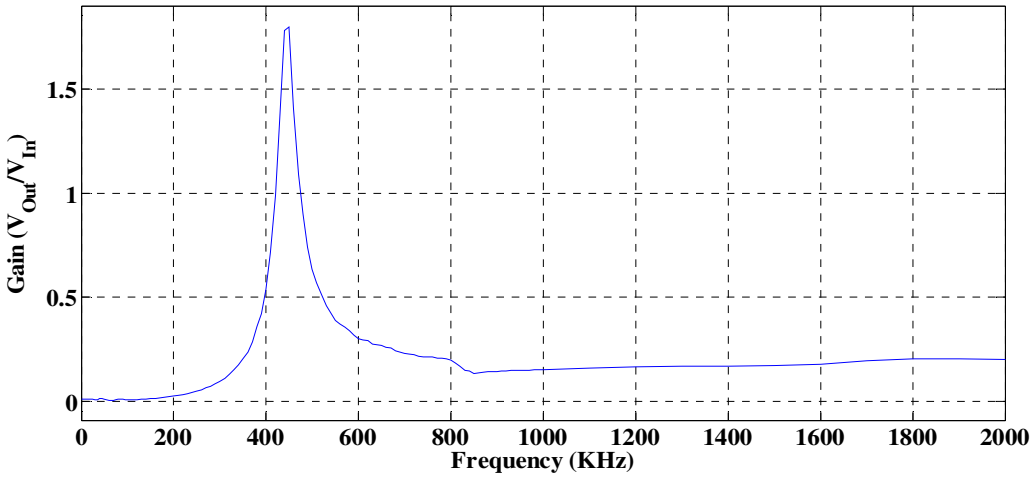
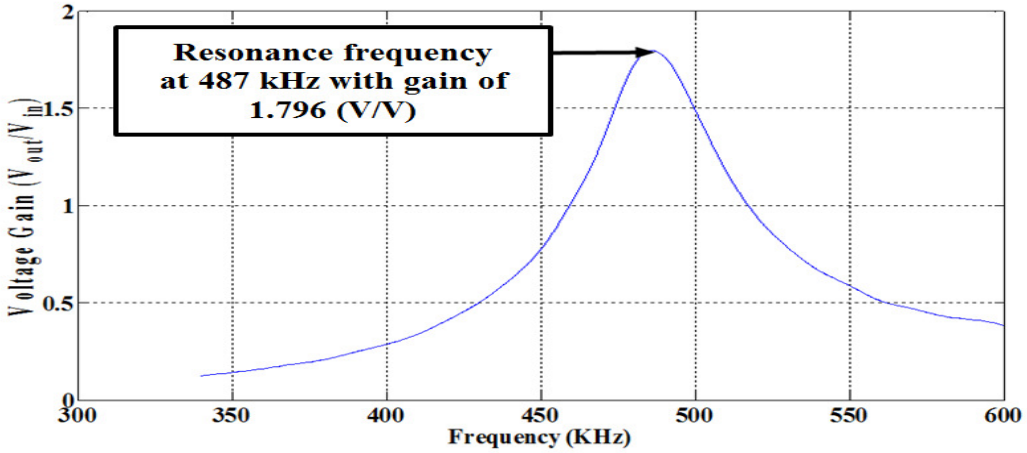
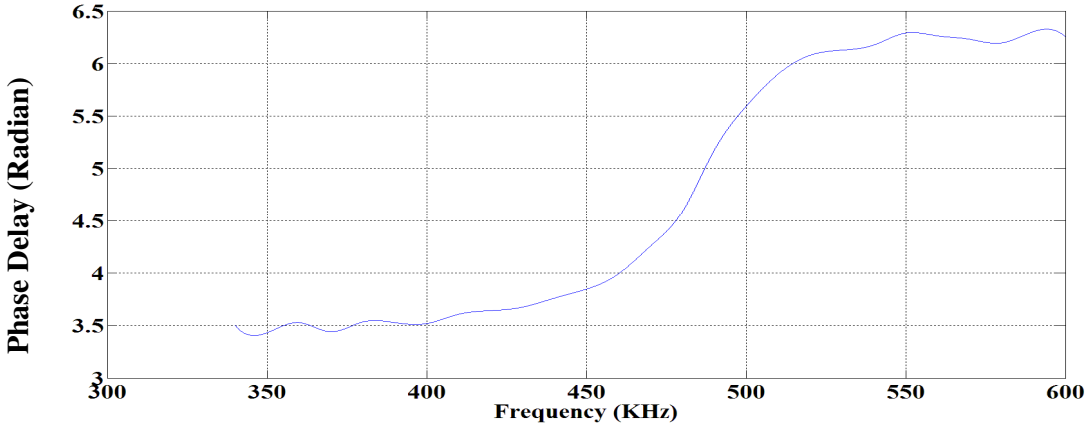


Figure 14: Frequency response of distribution transformer (Gain VS Frequency) from high voltage to low voltage side

In Figure 14, resonance phenomenon appears between 350 kHz and 600 kHz. A zoomed view of the gain response and its corresponding phase is shown in Figure 15.



(a)



(b)

Figure 15: Zoomed section of the frequency response at resonance showing (a) the gain response and (b) the phase response

From the results depicted in Figure 15, it can be seen that for the measured transformer, resonance occurs approximately at 490 kHz. Furthermore, it can be noticed that the gain is almost 2 (V/V) at resonance. This gain amplifies the communication signal; therefore, it is expected that the BER will be improved significantly. Moreover, the phase at resonance is linear which means that the system will not have any phase distortion issues. After completing the frequency response measurements, the results were imported into MATLAB and loaded as a communication channel (explained in the next sections). The response can be modeled using the transformer model at low frequency with added shunt and series capacitors representing the stray capacitors; for more information please refer to Appendix A.

4.1.2 Frequency Response Measurement from Low Voltage to High Voltage Side:

The frequency response from the low to high voltage sides of the same distribution transformer was analyzed by following the same procedure outlined in subsection 4.1.1 with only one difference. While capturing the frequency response from low to high voltage, the effect of the turns ratio of the transformer should be taken into consideration. As indicated in Table 7, the high voltage side is 20 kV while the low voltage side is 220 V. Therefore, moving from the low voltage side to the high voltage side will make the voltage step up by a factor of 90.90 (V/V). The step up/down factor is defined as the ratio of primary to secondary voltage which equals the turns ratio of the primary to secondary windings as indicated in Equation (8).

$$Transformer\ Step\ Up/Down\ Ratio\ = \frac{V_{Primary}}{V_{Secondary}} = \frac{N_{Primary}}{N_{Secondary}} \qquad (8)$$

The injected signal amplitude was 2 V_{PP}. Applying the same signal resulted in an output signal of amplitude 181.8 V which is out of the oscilloscope range. To overcome this problem, a voltage divider of 1:1000 was connected at the output of the transformer. The voltage divider output was recorded by the oscilloscope. Figure 16 illustrates the major blocks that were used to perform the experiment.

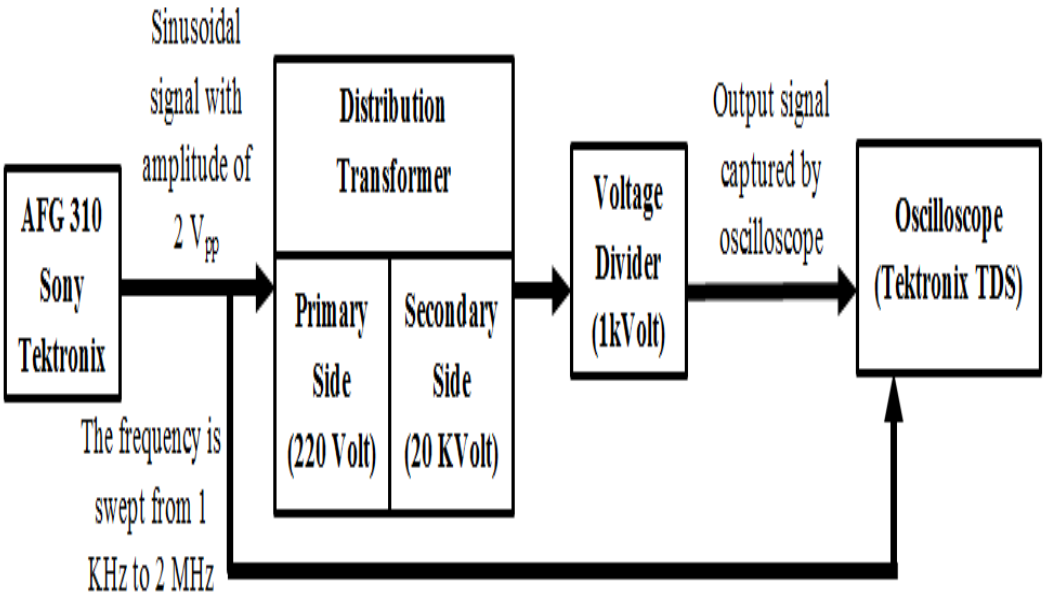


Figure 16: Block diagram of measuring the frequency response practically (low to high side)

After performing the required procedures of capturing the frequency response and taking into consideration the effect of the turn's ratio, the frequency response was obtained. Figure 17 shows the captured frequency response from the low voltage side to the high voltage side.

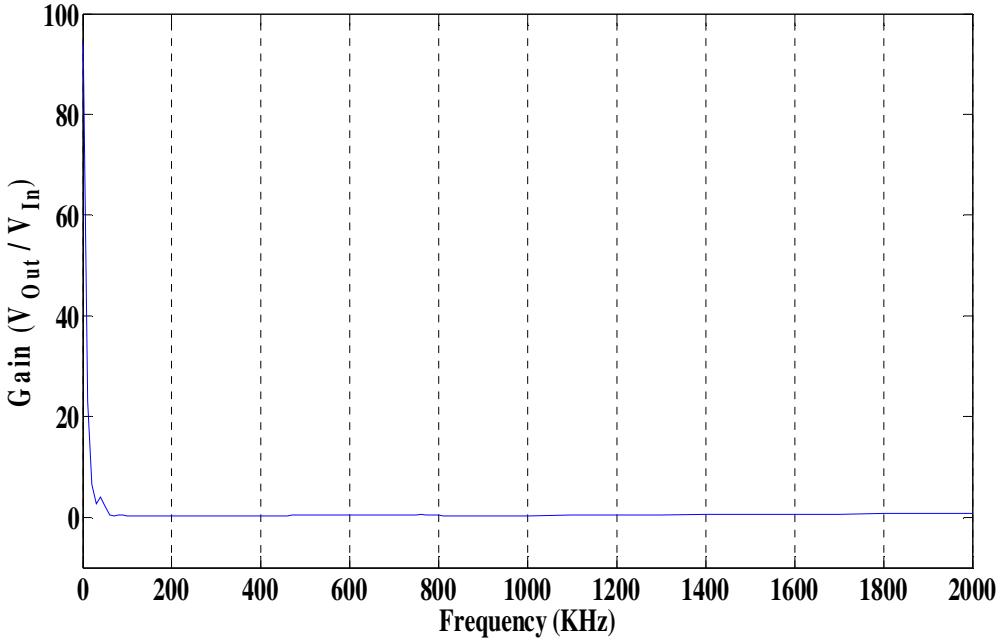


Figure 17: Frequency response of distribution transformer (Gain VS Frequency) from low voltage to high voltage side

The response showed a gain close to zero for all the frequencies above 100 kHz. Unlike the obtained results in subsection 4.1.1, there is no resonance in the kHz

spectrum. This result could be due to the small apparent power rating of the examined transformer. Having a low rating makes the geometry of the transformer smaller; hence, the stray capacitances will be small especially for the low voltage side of the transformer. As a result, resonance at the kHz spectrum will be unlikely. In the field, the installed distribution transformers in the grid usually have high ratings. For example, distribution transformers in the UAE have two standard ratings, i.e. 1000 and 1500 kVA. Having such a high rating transformer will result in high capacitance values at the transformer's windings, which may cause resonance at the kHz spectrum.

In this work, the transformer is modeled as a communication channel using the obtained frequency response. The behavior of the transformer can be evaluated by sending data through it which is an aspect of PLC technology.

In order to achieve the reliable communication objective, the transmitted data should be modulated. The aim of modulating the data is to protect the information from being distorted due to the impairments in the communication channel. There are two types of modulation categories: analog and digital modulation. Nowadays, it is preferred to select digital modulation as it is lower in implementation cost compared to that of the analog systems. Moreover, the advancement in digital communication enables data to be transmitted and received with a high data rate and at low BER.

Digital modulation includes several schemes. In this work, Binary Phase Shift Keying (BPSK) was selected to modulate the data that will be sent through the modeled transformer. The selection was based on the simplicity of the modulation scheme. The errors in the received signal were evaluated using BER.

4.1.3 Simulated Frequency Response Model as Communication Channel:

In order to examine the behavior of the transformer in the PLC network, the transformer will be modelled as a communication channel and a communication signal will be sent through it.

The generated signal was transformed into the frequency domain by means of FFT and passed through the simulated channel. After that, the converted communication signal is multiplied by the frequency response of the channel. Finally, the product is converted to the time domain by IFFT. Figure 18 illustrates the described steps of how to model the behavior of the transformer in the PLC application using the obtained frequency response.

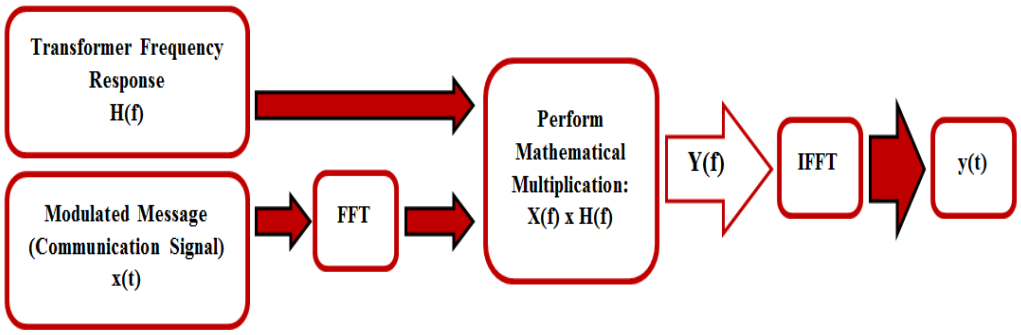


Figure 18: Investigating the transformer behavior in a PLC application using its frequency response

4.1.4 Sending a Signal from High Voltage to Low Voltage Side:

To evaluate the response of the transformer within the PLC application, a random generated message in MATLAB is sent at a range of frequencies including the resonance frequency where the results were compared and generated. Further, the sent message was BPSK modulated. Operating around the resonance frequency includes two considerations:

- Carrier frequency
- Bit rate

Carrier frequency is an important parameter as modulating the message at resonance or non-resonance frequency will control the quality of the received message. In the presented model, it is anticipated that if the message is modulated at resonance frequency, the signal will be amplified with a gain of 2 (V/V). On the other hand, modulating the signal at a frequency away from resonance will cause the signal to get attenuated.

The effect of the bit rate is another vital aspect that should be considered. The obtained response has a finite bandwidth between 300 kHz and 600 kHz; hence, the bit rate of the modulated signal should fall within the bandwidth of the transformer resonance. The bandwidth of the modulated signal can be controlled by setting the bit rate as it is the reciprocal of the carrier time.

4.1.4.1 Effect of carrier frequency over the BER performance:

The generated bits were modulated by BPSK modulation scheme at a sinusoidal carrier frequency of 440 kHz at a fixed bit rate of 5 kbps. After that, the carrier frequency was swept to 550 kHz in steps of 10 kHz for each bit rate. In order to make the simulation more realistic, white noise was added to the transmitted signal,

then filtered with the obtained frequency response of the transformer. To recover the data and evaluate the system response, a matched filter was used. The designed matched filter provides optimum and quick bit reconstruction which makes calculating the BER fast and efficient. Finally, the BER was calculated and plotted for a given range of Signal-to-Noise Ratio (SNR) out of the Monte Carlo simulation. Figure 19 represents the block diagram of the described procedures and illustrates the major blocks in simulating the communication application.

In Figure 19 a BPSK signal with added white noise is filtered with the transformer response and then reconstructed with a matched filter. The matched filter output represents the data as peak points where the peaks' signs identify the constructed bits. Using comparator logic, the data are converted from peaks to a bit stream by taking the signs of the peaks. The BER is calculated between the received and the transmitted bits.

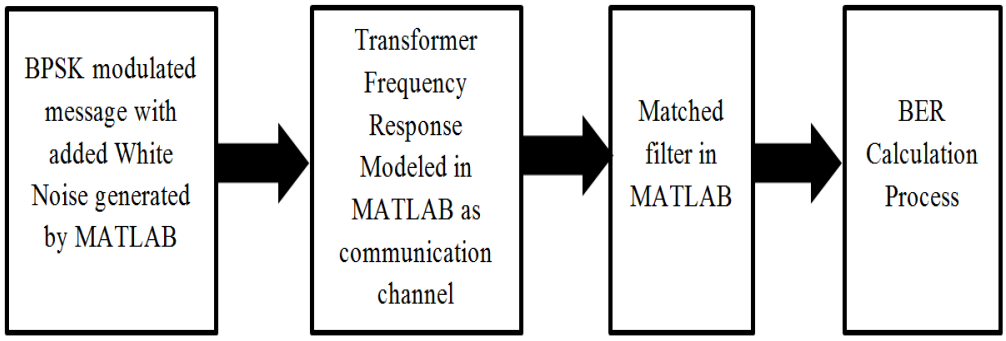


Figure 19: Functional blocks of testing the communication application

In Table 8, the results of the simulation are presented where the horizontal axis represents the SNR values and the vertical axis shows the carrier frequencies at given data rates. BER values were reduced as the carrier frequency approaches the resonance and then started to increase after exceeding the resonance. It can be seen that the best performance (as highlighted in the table), where the BER is minimum, occurs at a resonance frequency of 490 kHz. At an SNR of 2 dB and frequency of 490 kHz, BER was $4.35e^{-4}$

Table 8: BER results for bit rate 5 kbps

Bit Rate (kbps)	Carrier Frequency (kHz)	Bit Error Rate at given SNR										
		SNR 0 dB	SNR 1 dB	SNR 2 dB	SNR 3 dB	SNR 4 dB	SNR 5 dB	SNR 6 dB	SNR 7 dB	SNR 8 dB	SNR 9 dB	SNR 10 dB
5	440	0.1900	0.1659	0.1416	0.1144	0.0870	0.0559	0.0444	0.0274	0.0128	0.0061	0.0035
5	450	0.1348	0.1089	0.0841	0.0644	0.0435	0.0244	0.0148	0.0087	0.0043	0.0009	0.0000
5	460	0.0791	0.0574	0.0357	0.0235	0.0120	0.0039	0.0015	0.0000	0.0000	0.0000	0.0000
5	470	0.0339	0.0189	0.0061	0.0039	0.0013	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000
5	480	0.0076	0.0035	0.0020	0.0009	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
5	490	0.0083	0.0035	0.0004	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
5	500	0.0217	0.0104	0.0057	0.0011	0.0002	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000
5	510	0.0454	0.0326	0.0207	0.0115	0.0035	0.0013	0.0002	0.0000	0.0000	0.0000	0.0000
5	520	0.0876	0.0705	0.0520	0.0272	0.0183	0.0096	0.0041	0.0013	0.0004	0.0002	0.0000
5	530	0.1276	0.1179	0.0800	0.0624	0.0435	0.0241	0.0148	0.0061	0.0041	0.0011	0.0000
5	540	0.1707	0.1407	0.1226	0.0850	0.0670	0.0431	0.0294	0.0180	0.0102	0.0046	0.0017
5	550	0.2016	0.1733	0.1489	0.1302	0.0950	0.0702	0.0481	0.0357	0.0237	0.0109	0.0033

As the frequency response of the tested transformer indicated a gain of 2 (Volt/Volt) at resonance, the signal was amplified making the SNR increase which caused better performance in terms of BER. In communication standards, it is required to have BER less than 10^{-3} and it can be seen from Table 8 that this was satisfied for SNRs greater than 2 dB [37].

A general comparison that shows the effect of the carrier frequency can be visualized in Figure 20 while keeping the bit rate fixed. Operating away from resonance frequency causes the signal to get attenuated; hence, reconstructing data will encounter some errors in identifying the bits and this explains the curves that are above the AWGN channel BER curve. Furthermore, it can be seen that the BER curve that was obtained at resonance is below the theoretical curve of the AWGN channel. Theoretical curve sets the minimum BER that can be achieved for a given SNR given the channel is AWGN. Nevertheless, sending the modulated message at resonance seems to achieve better BER results than the theoretical level. The reason is because at resonance there is gain. This gain will amplify the signal leading to an increase in SNR which causes the BER to *appear* better than the theoretical limit.

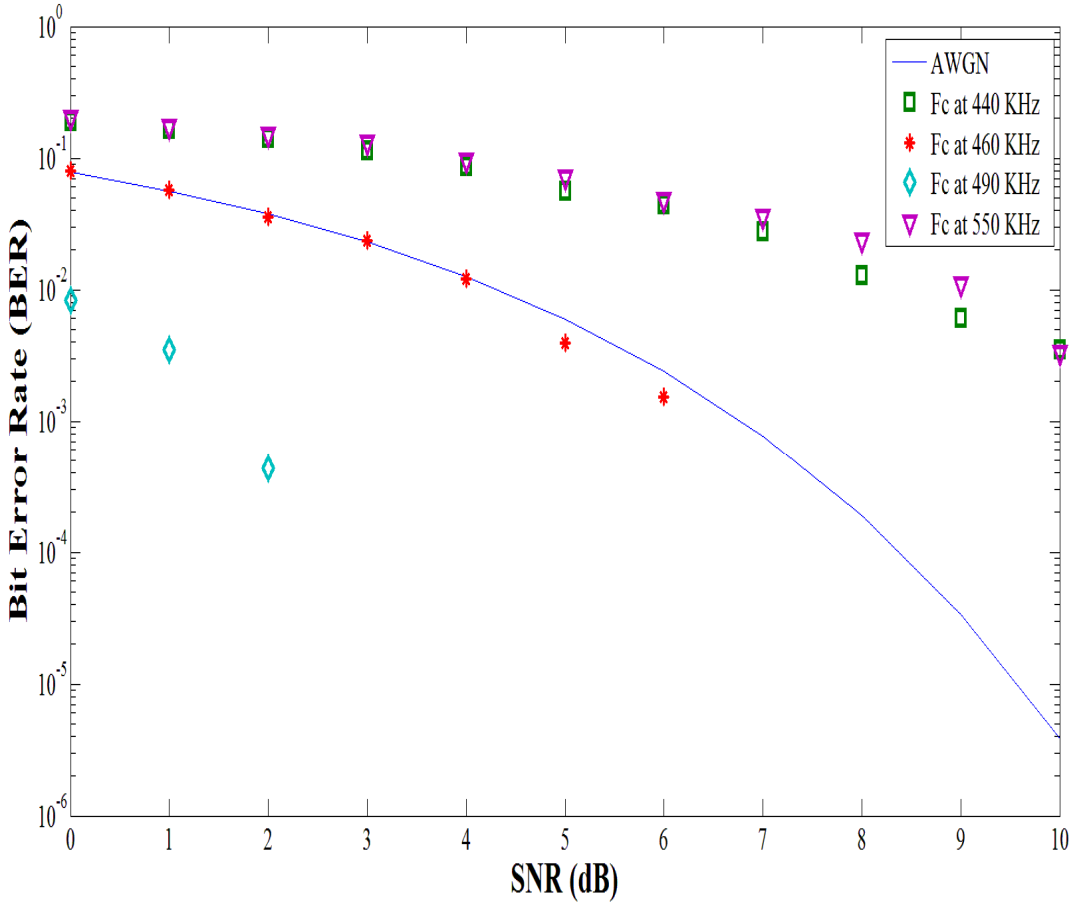


Figure 20: Sample of BER results for bit rate 5 kbps

4.1.4.2 Effect of bit rate over the BER performance:

The other point to analyze was the effect of varying the bit rate. To investigate the bit rate effect, the carrier frequency was fixed at resonance. By fixing the carrier frequency and plotting the BER curves corresponding to different bit rates, Figure 21 was obtained. It is evident that as the bit rate increases, the BER degrades. Consequently, the best performance of BER was obtained at the lowest bit rate (5 kbps). This observation is due to the bandwidth of the channel. If the data rate is low then it will fit better in the resonance bandwidth while a high data rate will require more bandwidth. As the data rate spectrum exceeds the resonance bandwidth, the communication signal will suffer from severe attenuation causing degradation in the system performance.

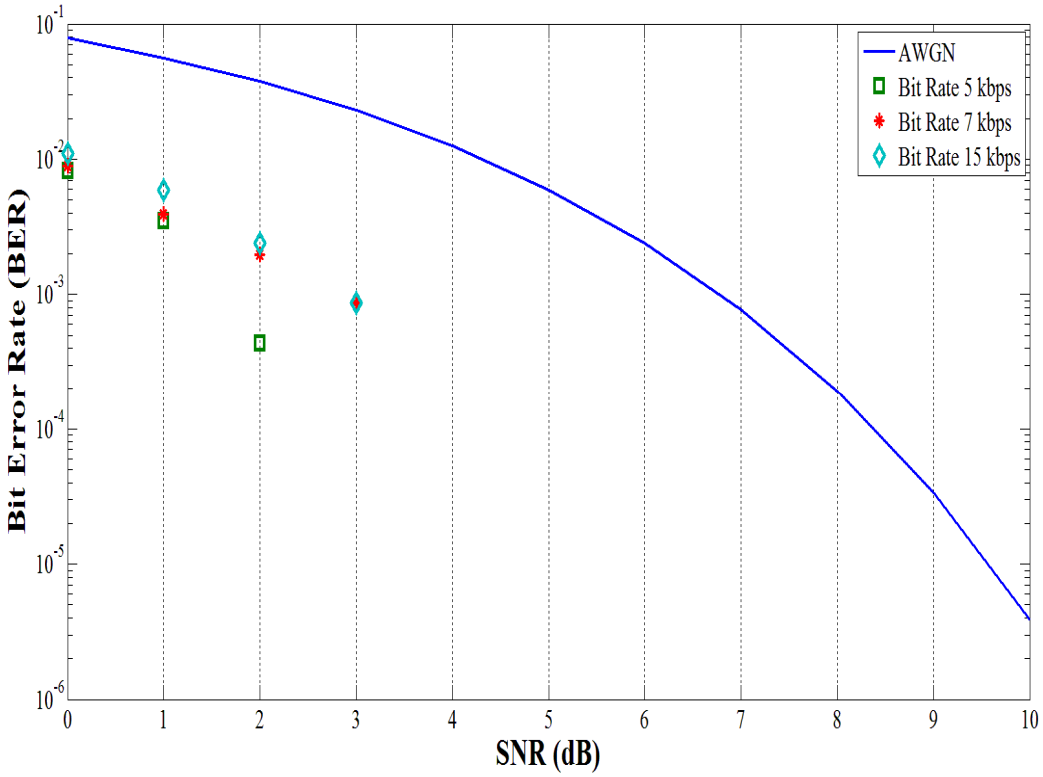


Figure 21: BER curves for different rates for carrier frequency 490 KHz

Nevertheless, it is seen that the curves in Figure 21 are better than the theoretical curve (AWGN channel). So, the system can be used to transmit data at high rates if the resonance frequency is utilized as the carrier frequency.

4.2 Transformer Response as Communication Channel in MATLAB

Using Test Text Message:

Sending a meaningful message instead of random bits simulates real life situations. In this section, a text message will be modulated and sent at different carrier frequencies, at different SNRs and at different bit rates.

Firstly, a text message is edited and saved using Notepad tool. After that, MATLAB is used to convert the text into bits. The next step is to modulate the converted bits using the BPSK modulation scheme at carrier frequency and defined SNR. Using the channel model, the modulated message is filtered through it. Finally the data is received and reconstructed and displayed in MATLAB workspace. The described sequence of events is shown in Figure 22.

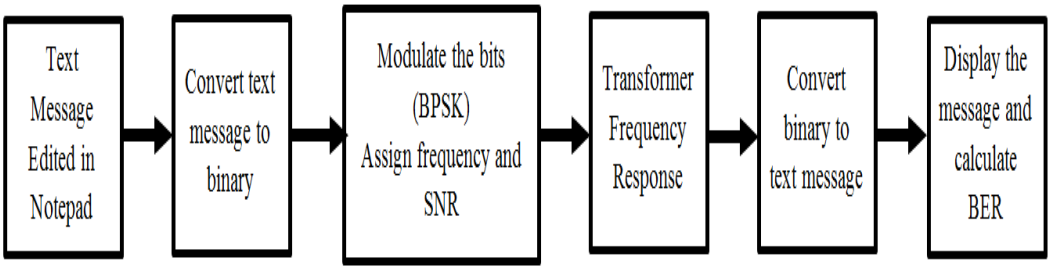


Figure 22: MATLAB flow chart for sending meaningful message through distribution transformer

Figure 23 shows the text message that was sent. The file was saved in the same directory as MATLAB to make it easier to read.

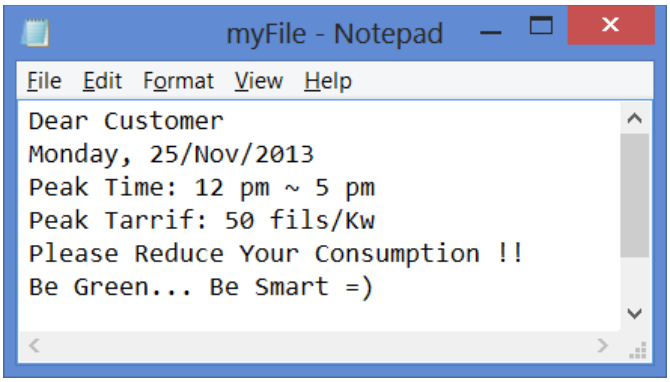


Figure 23: Text message that will be sent through the transformer

After loading the message, MATLAB directly converts the text file into a stream of binary data. The generated bits are then repeated an odd number of times, following the Monte-Carlo technique. At the receiver the average of the transmitted message is taken and this helps in lowering the probability of receiving wrong bits. The main drawback of this solution is the delay, given the message is sent several times. In this experiment, the message was repeated 7 times and sent through the channel.

After preparing the bit stream and modulating it, the stream is multiplied by a sinusoidal carrier which represents the BPSK modulation scheme. In order to make the system closer to reality, white noise was added. The added white noise level was determined by the targeted SNR level.

4.2.1 Effect of Carrier Frequency:

For this trial, the bit rate and the SNR were fixed. The bit rate is simulated to be 5 kbps and the SNR is 3 dB.

Figure 24 shows the received message in MATLAB workspace where the carrier frequency is around the resonance (490 kHz). Also, it indicates the bit error rate for this case and the number of errors in the message.

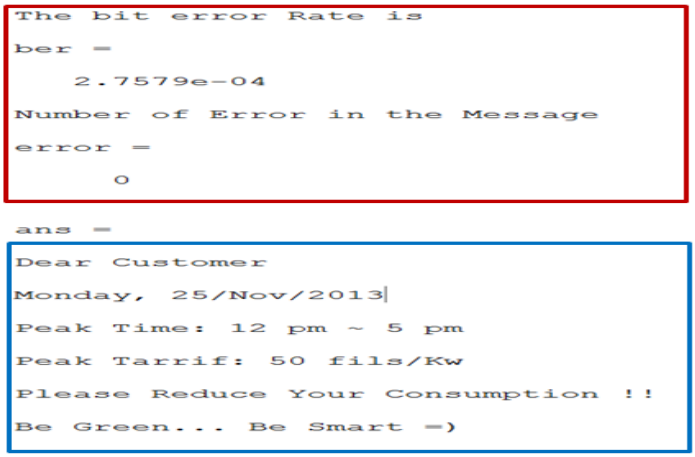


Figure 24: Received message in MATLAB workspace along with BER and number of errors in the message modulated at 490 kHz

As can be seen in Figure 24, the BER of the received message before correcting the bits is 2.76 *10^{-4}. After correcting the received message by averaging the transmitted message, there was no error in the message. By comparing the received message with the transmitted file shown in Figure 23, it can be validated that the message had been received successfully without any error.

Like the previous experiment, the SNR was fixed to be 3 dB and the bit rate was 5 kbps. The transmitted message is the same as the one shown in Figure 23 but at a carrier frequency of 400 kHz. By following the previous procedure, the results of sending message at 400 kHz are shown in Figure 25.

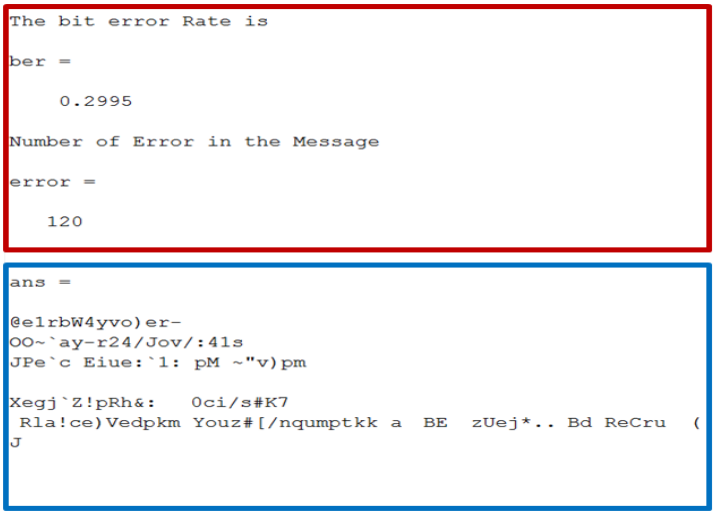


Figure 25: Received message in MATLAB workspace along with BER and number of errors in the message modulated at 400 kHz

As can be seen in Figure 25, the BER of the received message before correcting the bits is 0.2995. After correcting the received message by averaging the

transmitted message, there were 120 errors in the message. By comparing the received message with the transmitted file shown in Figure 23, it can be seen that the received message is different from the transmitted one. Hence, it can be concluded that sending the message at resonance frequency will result in better performance for the PLC technology.

4.2.2 Effect of SNR level:

One of the parameters that control the BER is the SNR level of the signal. In the previous experiment, the SNR level and the bit rate were kept constant while the carrier frequency effect was investigated. In this part of the work, the carrier frequency and the bit rate are fixed while the SNR is varied.

Like the previous experiment, the same message was sent through the frequency response. The procedures are the same as before with the following differences: the carrier frequency is fixed at 490 kHz and the bit rate is maintained at 5 kbps. Also, the signal is transmitted at SNR -5 dB and +5 dB.

The effect of varying the SNR was investigated by following the previously outlined procedure. The obtained results while changing the SNR to -5 dB are shown in Figure 26.

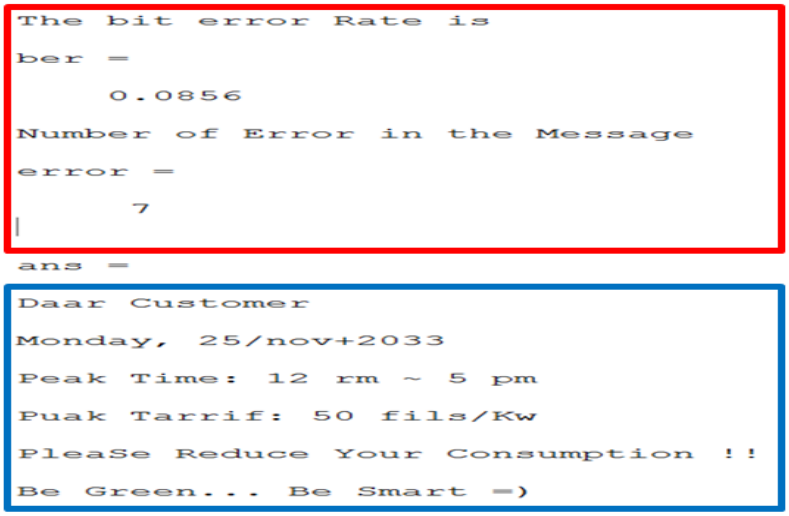


Figure 26: Received message in MATLAB workspace along with BER and number of errors in the message at SNR -5 dB

The BER of the received message before correcting the bits is 0.0856 as indicated in Figure 26. After correcting the received message by averaging the transmitted message, there were 7 errors in the message. By comparing the received

message with the original message, it can be seen that the received message was almost the same as the transmitted one. It is worth mentioning that for this trial, the SNR was low (-5 dB); nevertheless, the received signal was better than the theoretical curve. This is because the signal is transmitted at resonance with a gain of almost 3 dB.

When the SNR is increased to + 5 dB, the BER improves as depicted in Figure 27.

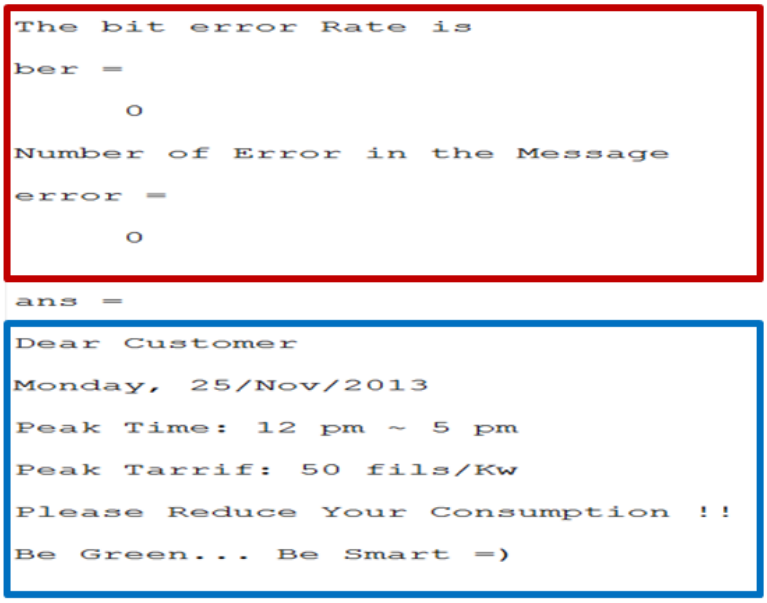


Figure 27: Received message in MATLAB workspace along with BER and number of errors in the message at SNR +5 dB

In Figure 27, the BER of the received message before correcting the bits is zero and there was no error in the message. It can be assured that the message was received successfully without any error by comparing it with the transmitted one.

4.2.3 Effect of Bit Rate:

In this part of the work, the effect of the bit rate is investigated while holding the carrier frequency and SNR fixed. As the topic is addressing the usage of resonance frequency of the transformer, the carrier frequency was assigned to be around resonance frequency (490 kHz). The SNR level and the bit rate will be fixed at 3 dB and 5 kbps respectively.

The results of the received signal at the output of the frequency response are shown in Figure 28.

```
The bit error Rate is
ber =
    2.7579e-04
Number of Error in the Message
error =
       0

ans =
Dear Customer
Monday, 25/Nov/2013
Peak Time: 12 pm ~ 5 pm
Peak Tarrif: 50 fils/Kw
Please Reduce Your Consumption !!
Be Green... Be Smart =)
```

Figure 28: Received message in MATLAB workspace along with BER and number of errors in the message at bit rate 5 kbps

As can be seen in Figure 28, the BER of the received message before correcting the bits is $2.76*10^{-4}$. After correcting the received message by averaging the transmitted message, there was zero error in the message.

By selecting the bit rate to be 5 kbps, it is expected that the BER performance will be acceptable. One of the main reasons is that the message will be within the transformer spectrum; hence, the message will not be attenuated as it will be in the transformer bandwidth. Also, the Inter Symbol Interferences (ISI), a kind of distortion due to an interference between the current symbol and the consequent one, will be minimum. Figure 29 shows the spectrum of the signal with respect to the transformer bandwidth.

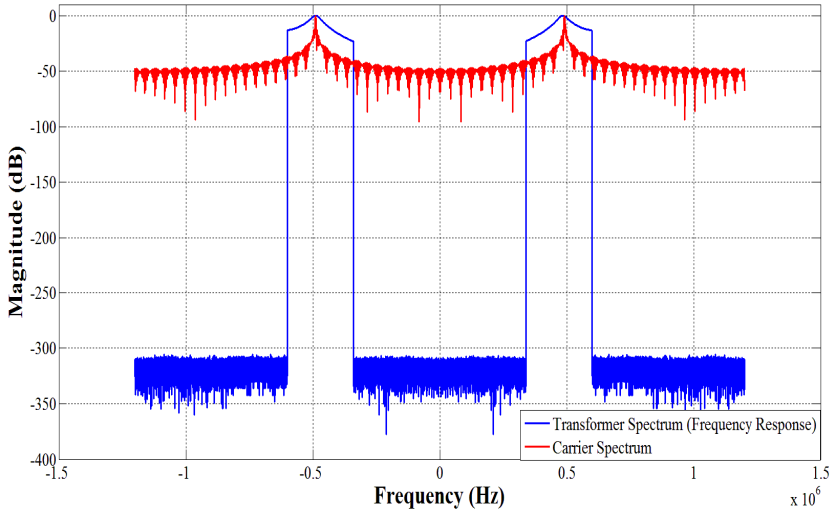


Figure 29: Carrier spectrum with respect the transformer bandwidth at bit rate 5 kbps

To study the effect of increasing the bit rate on the BER, the bit rate was increased to 40 kbps while all the previous parameters were fixed. The results of the received signal after being filtered by the transformer are shown in Figure 30.

```
The bit error Rate is
ber =
    0.0153
Number of Error in the Message
error =
     0
ans =
Dear Customer
Monday, 25/Nov/2013
Peak Time: 12 pm ~ 5 pm
Peak Tarrif: 50 fils/Kw
Please Reduce Your Consumption !!
Be Green... Be Smart =)
```

Figure 30: Received message in MATLAB workspace along with BER and number of errors in the message at bit rate 40 kbps

The BER of the received message before correcting the bits is 0.0153 and it dropped to zero after using the averaging technique to correct the received message.

To ensure the effect of the bit rate, the spectrum of the transformer over the carrier response is shown in Figure 31.

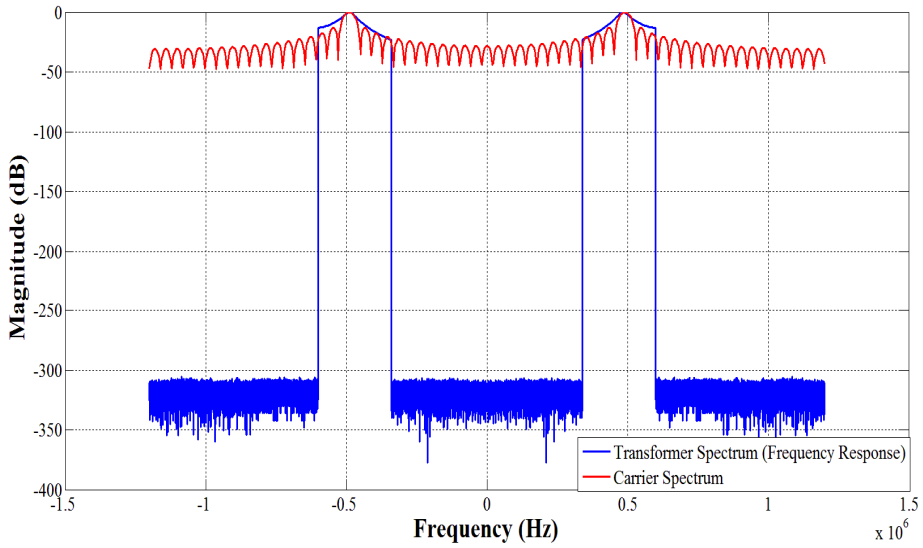


Figure 31: Carrier spectrum with respect to the transformer bandwidth at bit rate 40 kbps

As shown in Figure 31, the carrier spectrum almost fits the transformer bandwidth as the BER was higher than before.

Other factors have an influence over the BER such as the averaging rate at the receiver. For more details about averaging effect, refer to Appendix B.

4.3 Frequency Response of Distribution Cable:

The PLC network method is based on using the power cables and transformers to carry the communication signal from the destination to the source node. Hence, power cables are vital elements and should be modeled and their behavior towards the transmitted signals should be evaluated.

4.3.1 Obtaining the Frequency Response of Distribution Cable:

In this section, the frequency responses of the cable at different lengths are simulated using MATLAB at the frequency interval of the studied transformer.

Equation (6) with the parameters given in Table 6 and the AC resistance factor are all used to model the cable in the frequency domain. The cable was modeled in MATLAB with only two variables: cable length and signal frequency.

Initially, the cable length is assumed to be 10 meters and the signal frequency is swept from 350 Hz up to 600 kHz. After that the cable is simulated for the same spectrum and for length settings of 100 meters and 1000 meters. The cables' frequency responses from 50 Hz up to 2 MHz, like the transformer SFRA test spectrum, included 3 sets of lengths: 10, 100 and 1000 meters. These are shown in Appendix C.

4.3.1.1 Effect of Cable Length:

Initially, a 10 meter distribution cable length was simulated. Figure 32 shows the gain and the phase response of the simulated cable frequency response around the transformer's resonance frequency band.

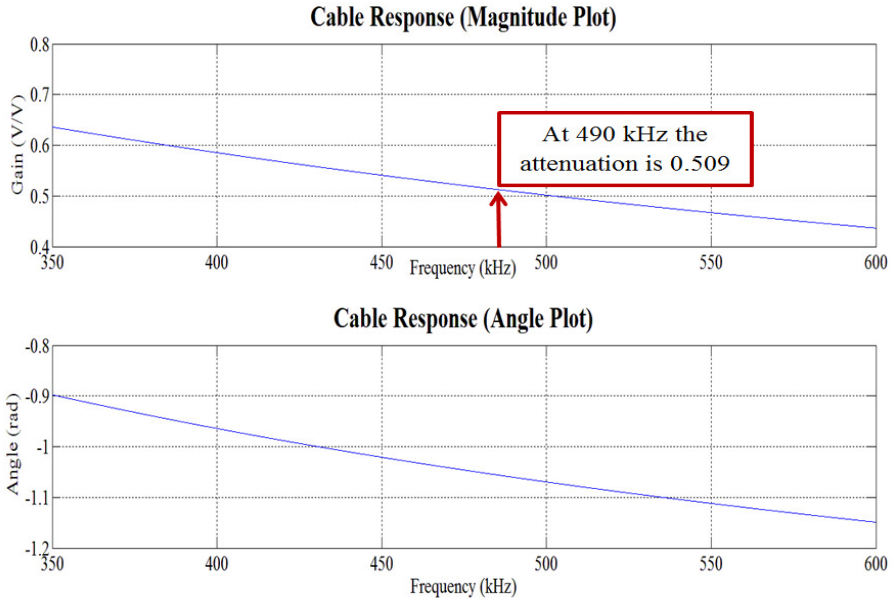


Figure 32: Frequency response of 10 meter distribution cable

As can be seen from Figure 32, the cable acts as an attenuator with a factor around 0.509 (V/V) and the phase response of the cable is approximated to be linear.

By increasing the cable length to 100 meters, it is expected that the attenuation factor will increase. By repeating the previous simulation while keeping all the previous parameters fixed while changing the cable length to 100 meters, the frequency response was obtained as shown in Figure 33.

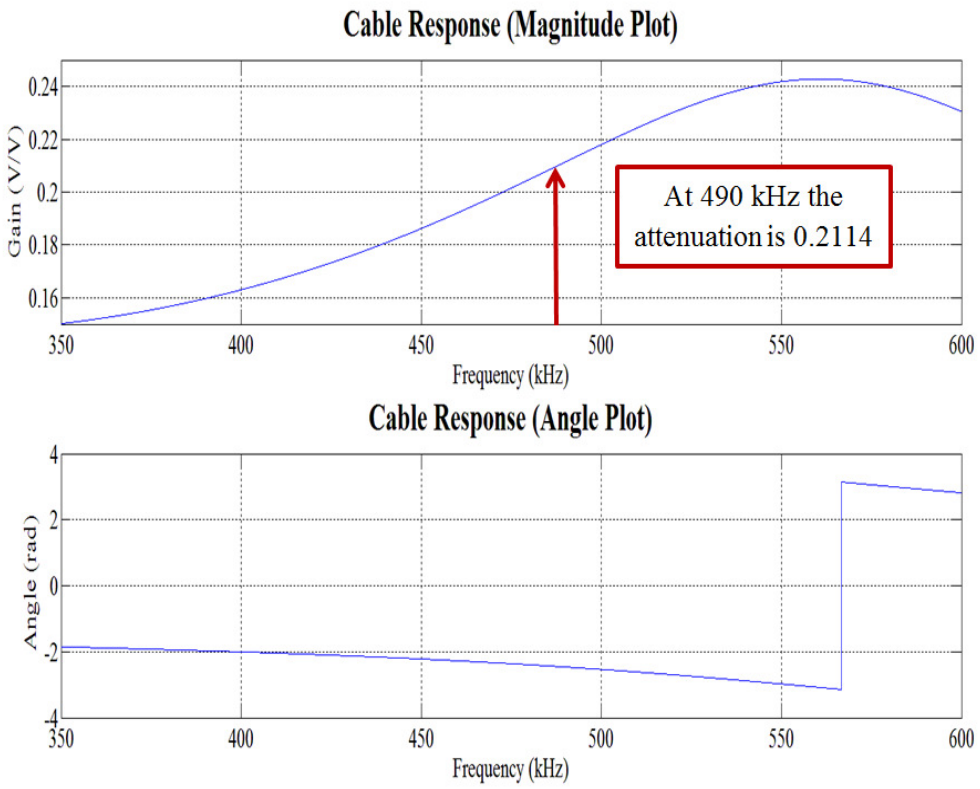


Figure 33: Frequency response of 100 meter distribution cable

The simulation result shown in Figure 33 indicates that the attenuation factor in the 100 meter cable is 0.2114 (V/V) which is higher than the 10 meter cable length case. Also, Figure 33 shows that the phase response of the cable is approximately linear which reduces signal distortion.

Finally, the cable length was increased to 1000 meters. By keeping all the previous parameters fixed, the frequency response was obtained as shown in Figure 34.

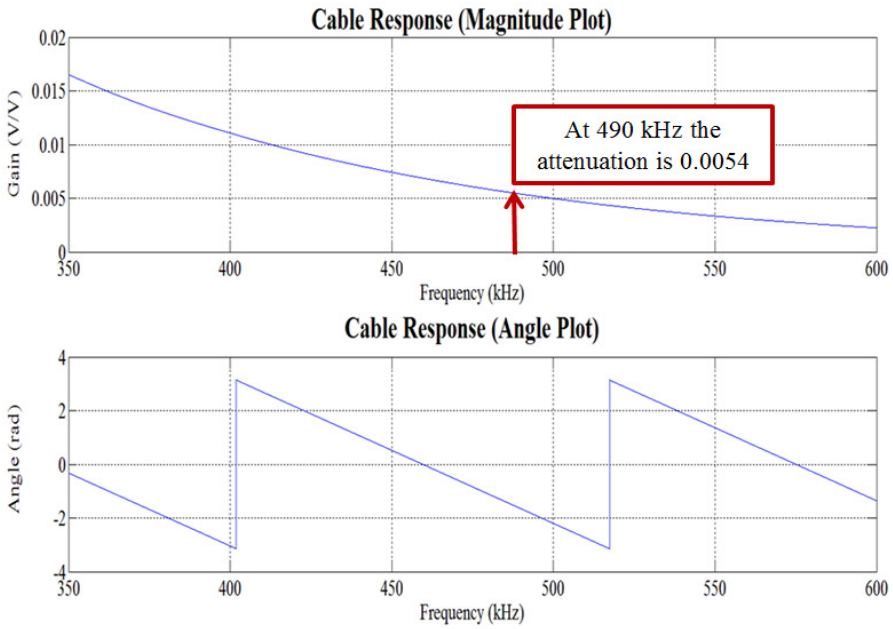


Figure 34: Frequency response of 1000 meter distribution cable

As anticipated, the attenuation factor is more severe for longer cables as it is around 0.005 (V/V) at the frequency of interest. Like the previous simulations, the phase response of the cable is linear, which reduces the signal distortion. The simulation results indicate that the increase in the cable length leads to an increase in the attenuation factor due to an increase in the RLC elements.

4.3.2 Effect of transformer aging on resonance frequency:

One of the major factors that may affect the resonance frequency is the aging of the transformer winding. Aging influences several components and parameters in the transformer such as the winding orientation and the elements' dielectric properties. In this work, the effect of aging on the transformer resonance frequency was investigated.

To accelerate the aging of the transformer, the transformer was subjected to several internal flashovers. This resulted in the flow of high currents that might have caused some internal damage in the transformer windings. The tested transformer was a dry-type transformer; therefore, any internal damage that might have occurred inside the transformer is not recoverable.

The frequency response of the distribution transformer was measured again following the same procedure highlighted in section 4.1.1. The SFRA test result verifies that there was a shift in the transformer frequency response as shown in

Figure 18. As shown, the resonance frequency moved from 490 kHz to 470 kHz with a small degradation in the maximum gain, from 1.797 to 1.735 (V/V). The bandwidth of the resonance in the transformer stayed almost the same: around 40 kHz. So it may be important to investigate the frequency response of the transformers on an annual or a semiannual basis to ensure that there is no shift in the resonance frequency.

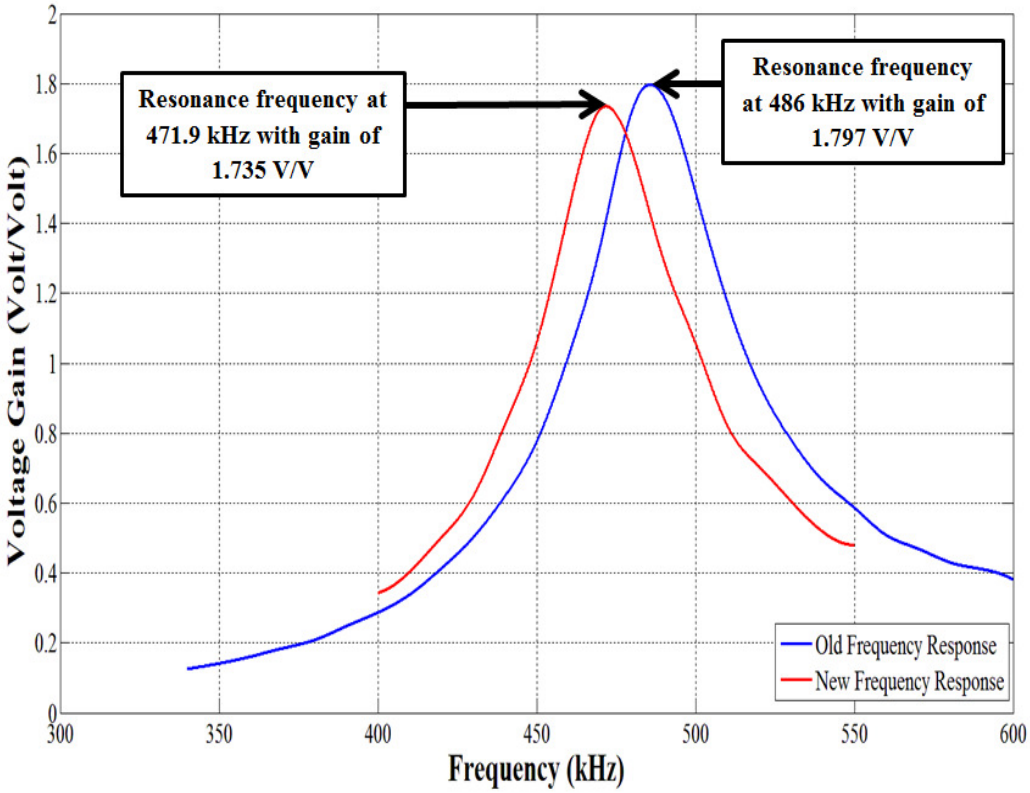


Figure 35: New and old frequency response of the transformer

4.4 Experimental Implementation and Simulation Verification:

In previous sections, the simulations' results indicated that the best BER performance was obtained at resonance frequency. Moreover, the simulation concluded that the distribution cable acts as an attenuator at high frequencies and the attenuation factor is a function of the cable length; consequently, the attenuation increases as the cable length increases.

To verify the simulated results, BPSK signals were sent through the distribution transformer and the distribution cables were modeled as attenuator resistors in the lab. This connection represents a case scenario where a communication signal is sent from the utility substation to the customer load.

Random bits modulated at resonance and non-resonance frequencies were modulated in BPSK scheme. The modulated message was created in MATLAB and generated by the AWG Agilent M9331A. The AWG unit was cascaded with attenuation elements representing the cable effect and was connected with the high voltage side of the transformer (20 kV). On the other side of the transformer, the low voltage side (220 V), the signal was measured by the Agilent M9210A module. This connection models a message that gets transmitted from the utility substation up to customers' loads. Figure 36 shows the blocks of the experiment. It is worth mentioning that the experimental test was performed after studying the aging effect of the transformer. Hence the new frequency response characteristic in Figure 35 was used.

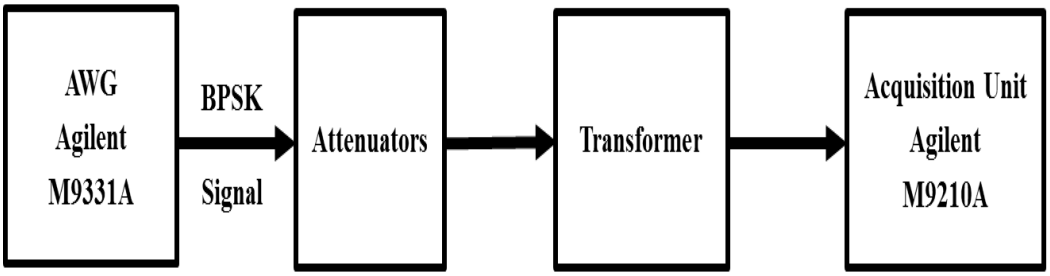


Figure 36: System blocks of the experiment setup

The practical test was implemented in two phases. The main criterion to investigate in these two phases was the effect of the resonance frequency while the bit rate was fixed. In the first phase, a random message of bits was modulated at the resonance frequency and in the second phase, the message was sent at non-resonance frequency. The bandwidth of the transmitted data for both phases was selected to fit within the bandwidth of the resonance with minimum attenuation. Since the frequency response indicated that the bandwidth is 40 kHz, the message bandwidth was set to be 20 kHz. This ensured that the message was transmitted completely in the transformer bandwidth and reduced the BER.

Before verifying the simulation results, the new frequency response shown in Figure 35 was verified experimentally by calculating the gain of a random modulated message at 490 kHz. From Figure 35, it was expected that the gain of the message would be 1.2 V/V at 490 kHz. Figure 37 shows a zoomed view of the transmitted and received signal.

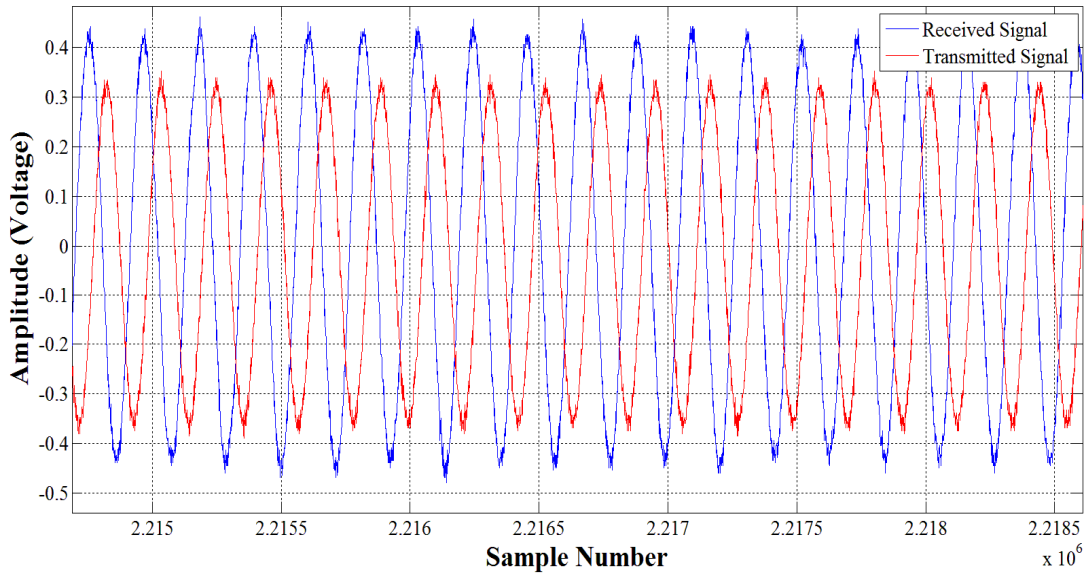


Figure 37: Transmitted and received signal at 490 kHz

As shown in Figure 37, the peak value of the received signal is 0.42 V while the peak value of the transmitted signal is 0.34 V. Therefore, the gain of the output signal with respect to the input is 1.23 V/V which matches the expected value of the new frequency response at 490 kHz.

After verifying the frequency response, the simulation results were verified. Initially, the data was transmitted directly to the transformer without any attenuation element. After that, an attenuator element was inserted in the path between the AWG and the transformer. The attenuator value was swept from 10 to 52 dB in steps of 10 dB and the transmitted signal voltage was maintained to be at the 0.34 V peak. The BER was calculated for all cases including the no attenuator case. Table 9 summarizes the BER results versus the attenuator value while the signal was sent at resonance frequency.

Table 9: BER results versus the attenuator value for message sent at resonance frequency 470 kHz

Attenuator Element Value	BER
No Attenuator (Direct Connect)	0
10 dB	0
20 dB	0
30 dB	0
40 dB	6.5e-3
52 dB	2.563e-1

As shown in Table 9, the BER was zero up to 40 dB attenuation. This means that the bit reception is achievable with zero errors as long as the cables are attenuating the signals by a factor less than 40 dB. If the cables are providing higher attenuation, then repeaters or amplifiers must be placed in the signal route to overcome the signal attenuation in the cables and in turn lower the BER. Furthermore, increasing the transmitted signal power could help to overcome the attenuation in the cables.

To verify the effect of the carrier frequency, the same experiment was performed but at 550 kHz (non-resonance frequency). The transmitted signal voltage amplitude was 0.34 V peak and the bit rate was maintained to be around 20 kHz. By testing the same attenuator elements and calculating the BER for each case, a summary of BER versus attenuator elements for signal propagating through the transformer is shown in Table 10.

Table 10: BER results versus the attenuator value for message sent at 550 kHz

Attenuator Element Value	BER
No Attenuator (Direct Connect)	0
10 dB	0
20 dB	0
30 dB	3.48e-2
40 dB	2.796e-1
52 dB	4.570e-1

By comparing the results obtained in Table 10 with the ones in Table 9, it can be concluded that the performance at resonance frequency is better than that at non-resonance frequency. Sending data at resonance resulted in zero BER up to a 40 dB attenuation factor before the transformer, while sending data at non resonance resulted in zero BER for attenuation values less than 30 dB. It is worth mentioning that the sent data in phase two was modulated at 550 kHz, which is close to the resonance frequency. It is expected that modulating data at frequencies that are farther than the resonance will result in a higher degradation in BER. This observation highlights the importance of sending data at resonance frequency.

Chapter 5: Conclusions and future work

A major challenge when attempting to deploy PLC technology is the existence of transformers in the signal route. Transformers act as a low pass filter with a cut off frequency around 300 Hz. This degrades the communication signal because the signal is modulated at higher frequencies in the kHz and MHz range. This research introduced a novel solution to overcome excessive signal attenuation in distribution transformers for PLC in smart grids. The proposed solution avoids classical hardware bypassing and does not require sophisticated modulation schemes. It explores the resonance that occurs in transformer windings at the kHz range to transmit the communication signal. The transformer is modeled as a network of resistors, inductors and capacitors. As the frequency increases, stray capacitors start to build and hence increase the complexity of the overall network. This results in several resonance frequencies in the kHz and MHz ranges that can be used to pass the signal. The selection of the kHz band is due to the global availability of this band for PLC applications. Moreover, operating at this frequency range would reduce the Electromagnetic Interference (EMI) because wireless applications operate at a higher frequency. Reducing the EMI will reduce the noise in the system and it will lead to an overall improvement in the system's operation.

Several methods can be used to obtain the frequency response of distribution transformers. In this work, the Frequency Response Analysis (FRA) technique was implemented. This technique measures the amplitude and phase response due to the application of a swept sinusoid at one terminal of a transformer winding. An FRA measurement of 20kVA (220/20kv) indicated that there is a resonance at 490 kHz with a gain of 2 V/V and bandwidth 40 kHz. The captured frequency response is then loaded as a communication channel in MATLAB. Then digitally-modulated BPSK signals (at resonance and non-resonance frequency) are transmitted through the modeled transformer. Sending data at 490 kHz within the 40 kHz bandwidth resulted in BER values better than the AWGN channel because of the associated gain in the transformer. In addition, the simulation verified that sending data at non-resonance frequencies or outside the resonance bandwidth will result in worse BER compared with the resonance case and AWGN channel. The effect of distribution cables from the utility substation up to the customers' distribution transformers was also investigated. The simulation showed that the cable at high frequency acts as an

attenuator with a value that depends on the cable length as well as the signal frequency. The BER was calculated for a variable attenuator cascaded with the transformer. By sending a BPSK signal at resonance with a bandwidth of 20 kHz, the BER was zero for cases where the attenuation is less than 40 dB. The research also showed that sending data at resonance frequency has the potential to be an effective method for improving data communication using PLC for smart grid application.

Future work can include investigating three phase transformers. Furthermore, the study can involve transformers with higher ratings similar to the ones that are used in the field. The transformer aging phenomenon forms another challenge that should be investigated over the deflection in the resonance frequency and the rate of deflection per year.

Another topic that should be investigated is the capability of a low-cost monitoring system for resonance frequency. Typically, SFRA tests are costly and regular transformer testing to check the resonance frequency is impractical. This is because the available commercial technology is offline and requires disconnecting the transformer. Developing a system that can measure the SFRA online will be a vital additional work.

An elaborate work can be done on this topic, including for example, a resonance track and lock sequence at the transmitter and destination nodes to tune to the exact resonance frequency of the distribution transformer.

References

[1] "Global Smart Grid Federation," May 2012. [Online]. Available: http://www.globalsmartgridfederation.org/smartgriddef.html. [Accessed 10 December 2012]

[2] K. Moslehi and R. Kumar, "A Reliability Perspective of the Smart Grid," *IEEE Transactions on Smart Grid,* vol. I, no. 1, pp. 57 - 64, 2010.

[3] Y. Nozaki, T. Tominaga, N. Iwasaki and A. Takeuchi, "A technical approach to achieve smart grid advantages using energy management systems," in *International Conference on Wireless Communications and Signal Processing (WCSP), 2011* , Nanjing, 2011.

[4] A. Haidine, B. Adebisi, A. Treytl, H. Pille, B. Honary and A. Portnoy, "High-speed narrowband PLC in Smart Grid landscape — State-of-the-art," in *ower Line Communications and Its Applications (ISPLC), 2011 IEEE International Symposium on*, 2011.

[5] R. Depuru, L. Wang, V. Devabhaktuni and N. Gudi, "Smart meters for power grid — Challenges, issues, advantages and status," in *Power Systems Conference and Exposition (PSCE), 2011 IEEE/PES* , Phoenix, AZ , 2011.

[6] "Scotland Government," April 2006. [Online]. Available: http://www.scotland.gov.uk/Publications/2006/04/24110728/11. [Accessed 2 December 2012].

[7] B. A. Kader, "GulfNews," 11 November 2013. [Online]. Available: http://gulfnews.com/news/gulf/uae/general/uae-energy-demand-to-reach-40-000-mw-by-2020-1.1253985. [Accessed 7 January 2014].

[8] M. Amin, "IEEE Smart Grid," IEEE, January 2011. [Online]. Available: http://smartgrid.ieee.org/january-2011/67-toward-a-more-secure-strong-and-smart-electric-power-grid. [Accessed 20 December 2013].

[9] K. Larsen, "Renewable Energy Focus," November 2009. [Online]. Available: http://www.renewableenergyfocus.com/view/5030/smart-grids-a-smart-idea/.[Accessed 20 December 2012]

[10] E. A. Committee, "Energy Organization Department in the United States," December 2008. [Online]. Available: http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/final-smart-grid-report.pdf. [Accessed 12 November 2012]

[11] B. Herron, "Smart Grid.TMCNET Database," December 2009. [Online]. Available: http://smart-grid.tmcnet.com/topics/smart-grid-fa/articles/70889-smart-grid-solution-copenhagen.htm.

[12] "Find Solar-Partner of American Solar Energy Society," December 2012. [Online]. Available: http://www.findsolar.com/index.php?page=rightforme. [Accessed 20 December 2012]

[13] Y. Chia-Han, G. Zhabelova, Y. Chen-Wei and V. Vyatkin, "Cosimulation Environment for Event-Driven Distributed Controls of Smart Grid," *IEEE Transactions on Industrial Informatics,* vol. IX, no. 3, pp. 1423 - 1435 , 2013.

[14] D. Heirman, "What makes Smart Grid — Smart — And who is in the "game"?," *Electromagnetic Compatibility Magazine, IEEE ,* vol. I, no. 2, pp. 95 - 99 , 2012.

[15] "Blue Green Alliance," [Online]. Available: http://www.apolloalliance.org/downloads/resources_ApolloReport_022404_122748.pdf. [Accessed 4 January 2014]

[16] S. G, A. S and Z. W, "For the Grid and Through the Grid: The role of Power Line Communications in the Smart Grid," *Proceedings of the IEEE,* vol. 99, no. 6, pp. 998 - 1027, January 2011.

[17] R. Ma, H. Chen, Y. Huang and W. Meng, "Smart Grid Communication: Its Challenges and Opportunities," *IEEE Transactions on Smart Grid,* vol. IV, no. 1, pp. 36 - 46 , 2013.

[18] H. Hassanein and G. Takahara, "Viability of Powerline Communication for the Smart Grid," in *2012 26th Biennial Symposium on Communications (QBSC)*, 2012.

[19] A. Haidine, B. Adebisi, A. Treytl, H. Pille, B. Honary and A. Portnoy, "High-speed narrowband PLC in Smart Grid landscape — State-of-the-art," in *IEEE International Symposium of power Line Communications and Its Applications (ISPLC), 2011* , 2011.

[20] C. Kikkert, "MV to LV transformer PLC bypass coupling networks for a low cost Smart Grid rollout," in *Innovative Smart Grid Technologies Asia (ISGT), 2011 IEEE PES* , Perth, WA, 2011.

[21] J. Huang, H. Wang and Y. Qian, "Smart grid communications in challenging environments," in *IEEE Third International Conference on Smart Grid Communications (SmartGridComm), 2012* , Tainan, 2012.

[22] S. J. Chapman, *Electric Machinery Fundamentals*, Fourth Edition ed., McGraw-Hill , 2005.

[23] W. Black, "Data transmission through distribution transformers without bypass components," in *2010 IEEE International Symposium on Power Line Communications and Its Applications (ISPLC),* , Rio de Janeiro, 2010.

[24] V. Krishnan, "Transformer bypass circuit," in *2005 International Symposium on Power Line Communications and Its Applications*, 2005.

[25] A. Cataliotti, V. Cosentino, D. Di Cara, P. Russotto and G. Tine, "On the use of narrow band power line as communication technology for medium and low voltage smart

grids," in *Instrumentation and Measurement Technology Conference (I2MTC), 2012 IEEE International* , 2012.

[26] K. Razazian, M. Umari, A. Kamalizad, V. Loginov and M. Navid, "G3 PLC Specification for Powerline Communication: Overview, System Simulation and Field Trial Results," in *2010 IEEE International Symposium on Power Line Communications and Its Applications (ISPLC)*, 2010 .

[27] K. Razazian and J. Yazdani, " Utilizing beyond CENELEC standards for smart grid technology," in *2011 2nd IEEE PES International Conference and Exhibition on Innovative Smart Grid Technologies (ISGT Europe)*, 2011.

[28] E. Al Murawwi, Application Of Signal Processing Techniques For Sweep Frequency Response Analysis Of Power Transformers, Abu Dhabi: Master Thesis, Electrical Engineering Deaprtment, The Petroluim Institute, 2013.

[29] A. SINGH, A Multi-Layer Neural Network Approach to Identification of Mechanical, Vancouver: Doctor Of Philosophy Thesis, Electrical and Computer Engineering Deaprtment, The University of British Columbia, 2009.

[30] E. M. J.R. Secue, "Sweep frequency response analysis (SFRA) for the assessment of winding displacements and deformation in power transformers," *Electric Power Systems Research,* vol. 78, no. 6, pp. 1119-1128, June 2008.

[31] Y. Shibuya and S. Fujita, "High frequency model and transient response of transformer windings," in *Transmission and Distribution Conference and Exhibition 2002: Asia Pacific. IEEE/PES* , 2002.

[32] K. Sandeep, K. Mukesh and S. C., "Diagnosis of Power Transformer Through Sweep Frequency Response Analysis and Comparison Methods.," in *XXXII National Systems Conference*, 2008.

[33] G. M. Kennedy, J. A. McGrail and A. J. Lapworth, "Transformer Sweep Frequency Response Analysis (SFRA)," *Energize,* pp. 28-33, October 2007.

[34] A. Sadiku, Fundamental of Electric Circuits, Fourth ed., New York: McGraw Hill, 2009.

[35] S. Galli and T. C. Banwell, "Deterministic Frequency domain Model for the Indoor Power Line Transfer Function," *IEEE journal on selected areas in communications,* vol. 24, no. 7, pp. 1304 - 1316, July 2006.

[36] B. Tan and J. Thompson, "Cornel University Library," 17 March 2012. [Online]. Available: http://arxiv.org/abs/1203.3879. [Accessed 11 December 2012].

[37] W. H. Kersting, Distribution System Modeling and Analysis, Florida: CRC Press, 2002.

[38] E. Standards, "ETSI Standards," April 2008. [Online]. Available: http://www.etsi.org/deliver/etsi_ts/125100_125199/125111/07.01.00_60/ts_125111v070

100p.pdf. [Accessed 10 November 2012]

[39] D. Shaver, "Narrowband PLC Solutions for AMI Achieve Long Distance Communication and Flexibility with Immediate Market Impact," in *2011 IEEE International Conference on Consumer Electronics (ICCE)*, 2011.

[40] J. D. Glover, M. S. Sarma and T. J. Overbye, Power System Analysis and Design, Fifth Edition ed., Stamford: CENAGE Learning, 2012.

Appendix A: RLC transformer model at high frequency and its frequency response

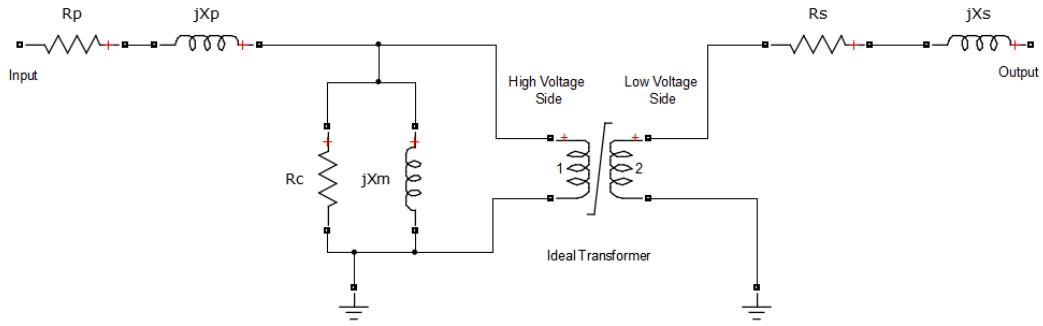
SFRA results can be almost obtained by adding capacitors modules, representing the stray capacitors, to the transformer low frequency model. Adding the capacitors will make the system resonates at certain frequencies. Using high frequency RLC meter the capacitances between high voltage terminal and ground, low voltage and high voltage terminals, and low voltage terminal to ground were measured. As an assumption, these three primary stray capacitances were used to characterize the resonance in the studied transformer. Table 11 summarizes the obtained capacitances values.

Table 11: Summary of stray capacitors results

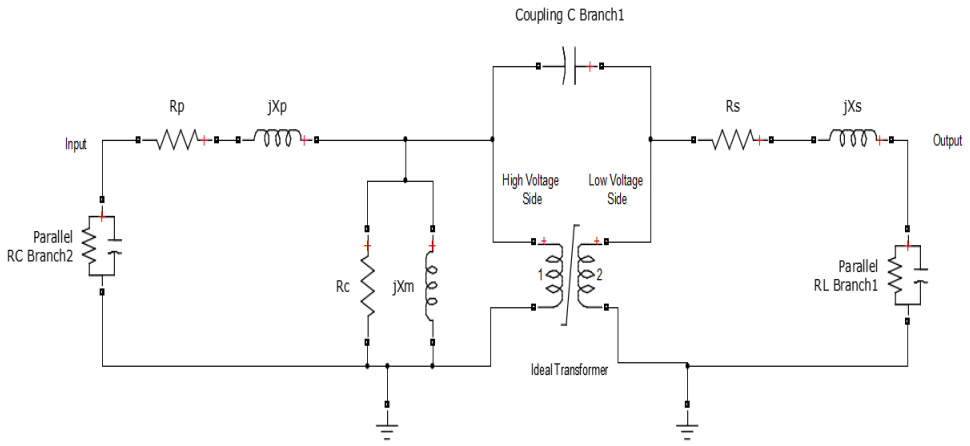
Stray Capacitance Description	Value (Farad)
High Voltage to Ground	$990.2 * 10^{-12}$
High Voltage to Low Voltage	$370 * 10^{-12}$
Low Voltage to Ground	$149 * 10^{-15}$

As depicted in Table 11, the highest stray capacitance value is between high voltage terminal and ground while the lowest is between the low voltage side and the ground.

Figure 38 (a) shows the low frequency transformer model and Figure 38 (b) shows the same model along with stray capacitors modules.



(a)



(b)

Figure 38: (a) Transformer low frequency model, (b) transformer low frequency model with stray capacitors (models system behavior at high frequency)

By studying the frequency response of the transformer along with stray capacitors, modeling the transformer at high frequency specifically at kHz range, the gain response was almost similar to the obtained SFRA results as shown in Figure 39.

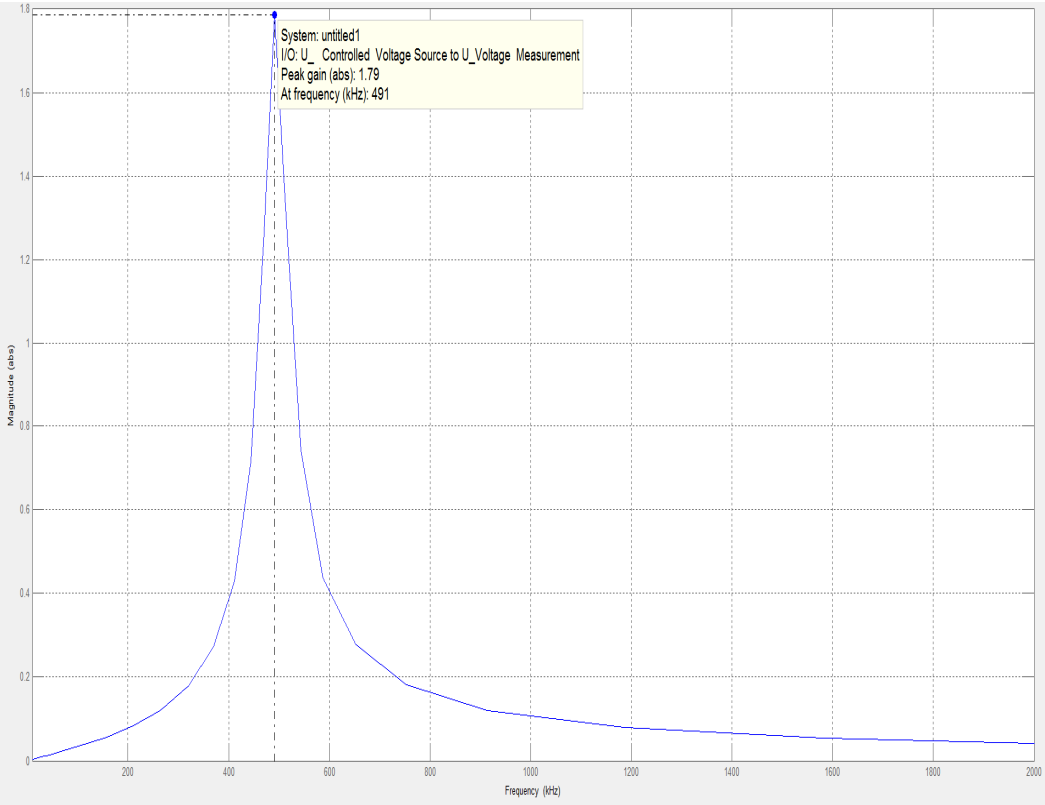


Figure 39: Gain response of transformer model with stray capacitors

Appendix B: The effect of the averaging rate at the receiver over the BER

The signal at the receiver is the average of several messages that were sent. In all studied trials the message was sent 7 times. Reducing the number of the transmitted copy reduces the ability to correct the received message. Considering the case in 4.2.3 at bit rate 40 kbps, Figure 40 shows the received message if it was sent 3 times rather than 7.

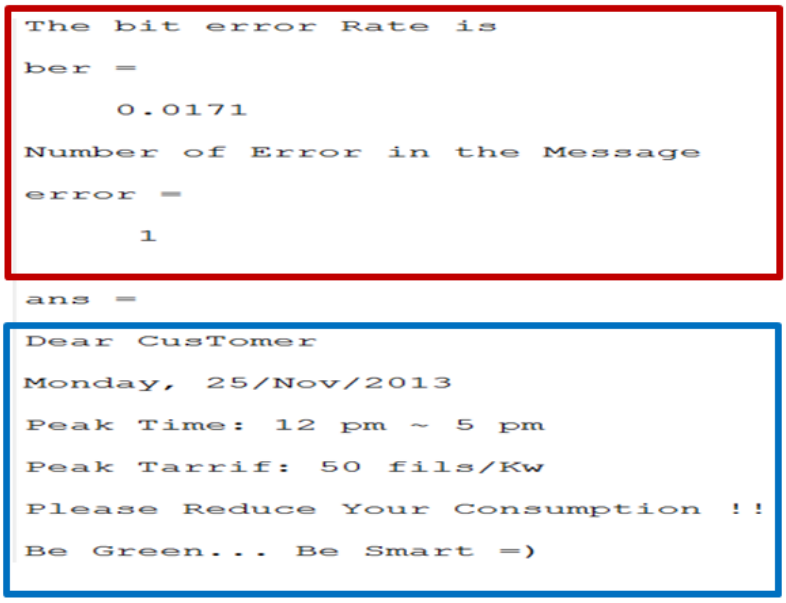


Figure 40: Received message in MATLAB workspace along with BER and number of errors in the message at bit rate 40 kbps with 3 times repeat

By sending the message three times rather than seven, the BER before correcting the bits is 0.0171. After correcting the received message by averaging the transmitted message, there was 1 error in the message. By comparing the received message with the transmitted file shown in Figure 23, it can be validated that the received message had been received properly. So, the number of the times that the signal is sent is another important factor. Increasing the number of copies will improve the results but it will cause more delays to the system

Appendix C: Simulation of cable response up to 2 MHz for cable lengths of 10, 100, and 1000 meters

Effect of Cable Length:

Initially, 10 meter distribution cable length is simulated. Figure 41 shows the gain and the phase response of the simulated cable frequency response.

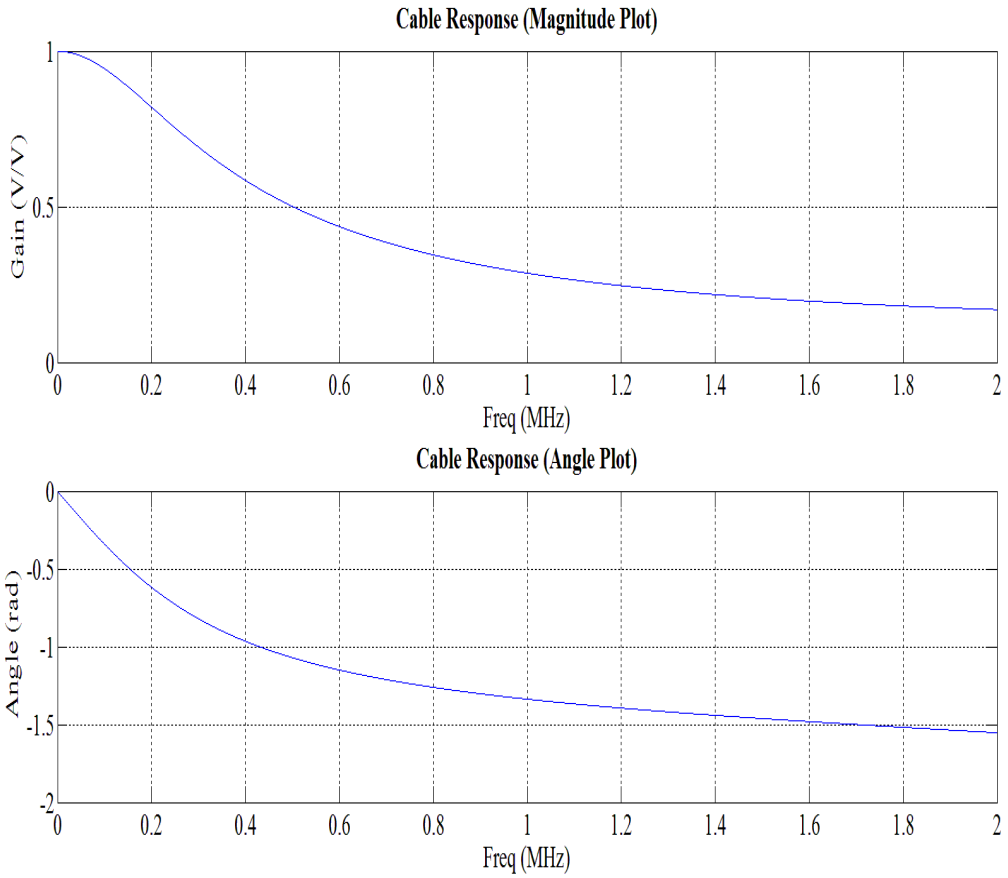


Figure 41: Frequency response of 10 meter distribution cable

As it can be seen from Figure 41, the cable attenuates the signal more severely at higher frequencies. The phase response of the cable is approximated to be linear if the bandwidth of operation is windowed. Overall, the work highlights the operation in kHz bands and as it can be seen the attenuation in this band is lower than the attenuation in the MHz band due to primarily the skin effect of the cable. Sending the signal in kHz band in cable length of ten meters will cause an attenuation of less than 12 dB as shown in Figure 42.

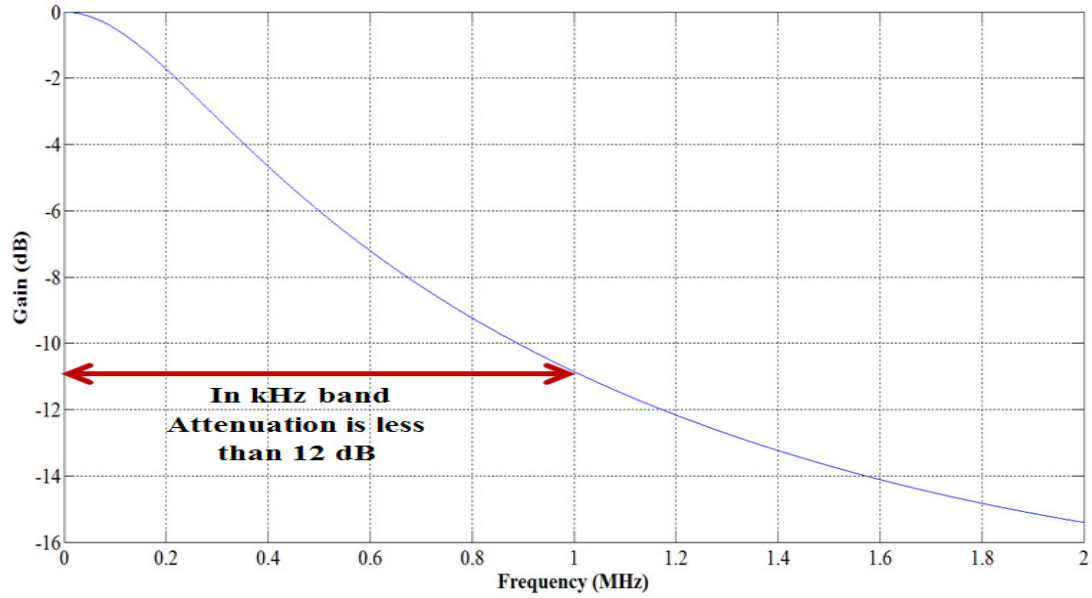


Figure 42: Frequency Response of 10 meter distribution cable (dB)

By increasing the cable length to 100 meters, it is expected that the attenuation factor will increase. By repeating the previous simulation while keeping all the previous parameters fixed while changing the cable length to 100 meter, the frequency response was obtained as shown in Figure 43.

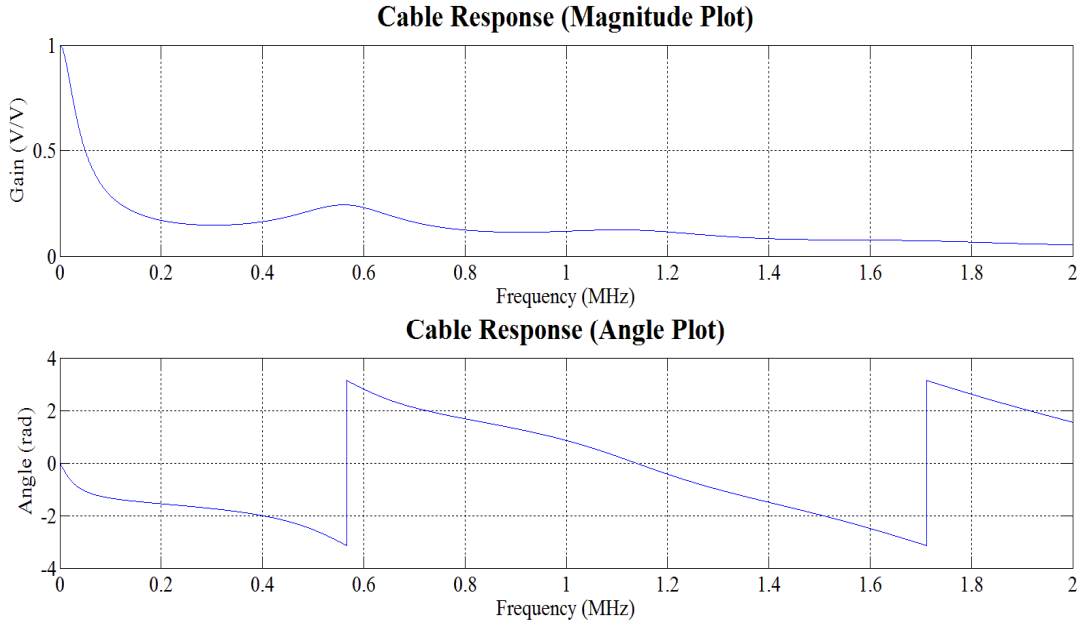


Figure 43: Frequency response of 100 meter distribution cable

As it can be seen from Figure 43the attenuation in the 100 meter cable is higher compared with the 10 meter cable length case. Further, the cable attenuates the signal severely as the frequency increases. Also, the phase response of the cable is approximately linear which reduces signal distortion. Sending the signal in the kHz band in cable length of 100 meters causes an attenuation of around 20 dB as shown in Figure 44.

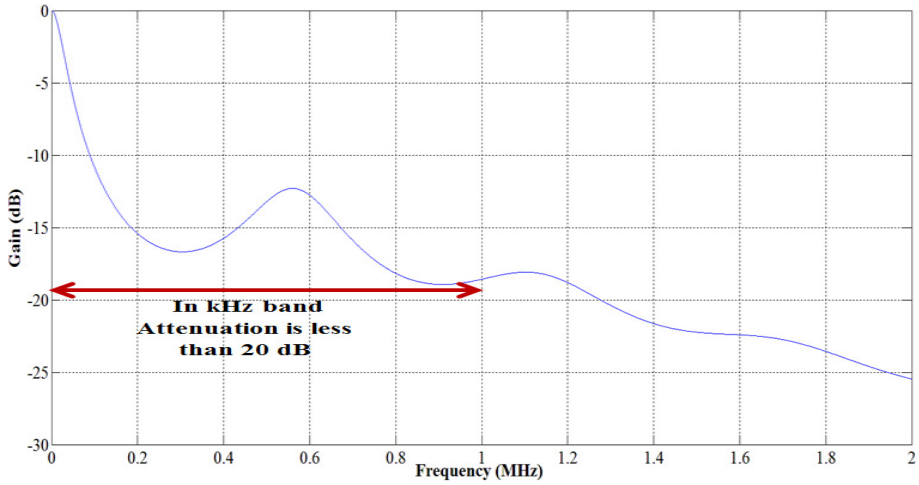


Figure 44: Frequency Response of 100 meter distribution cable (dB)

In this part of simulation, the cable length is increased to 1000 meters. By maintaining all the previous parameters fixed, the frequency response was obtained as shown in Figure 45

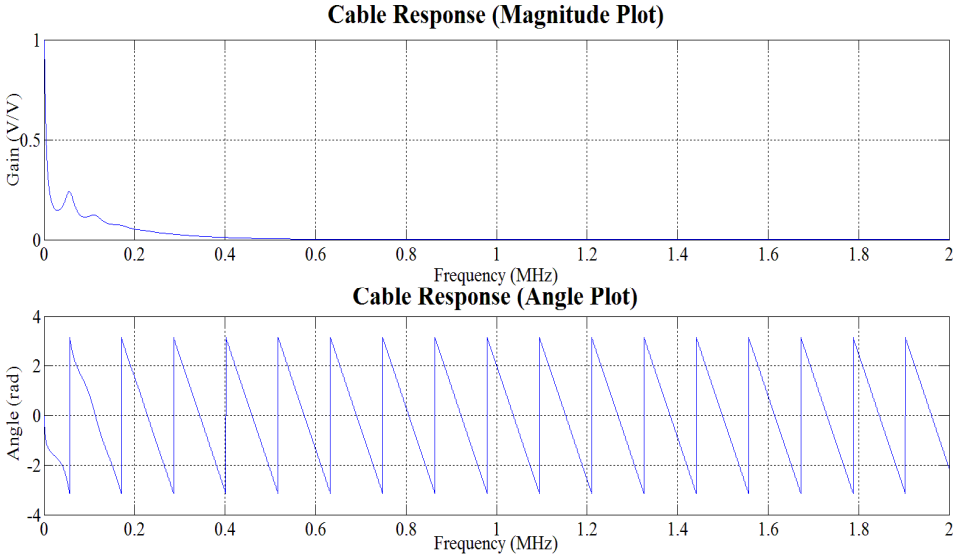


Figure 45: Frequency response of 1000 meter distribution cable

As it can be seen from Figure 45, the attenuation in the 1000 meter cable is higher than all the previous cases. Furthermore, the attenuation in the cable increases significantly as the frequency increases. Like the previous simulations, the phase response of the cable is linear which reduces the signal distortion. Sending the signal in kHz band in cable length of 1000 meters will cause an attenuation of around 80 dB as shown in Figure 46.

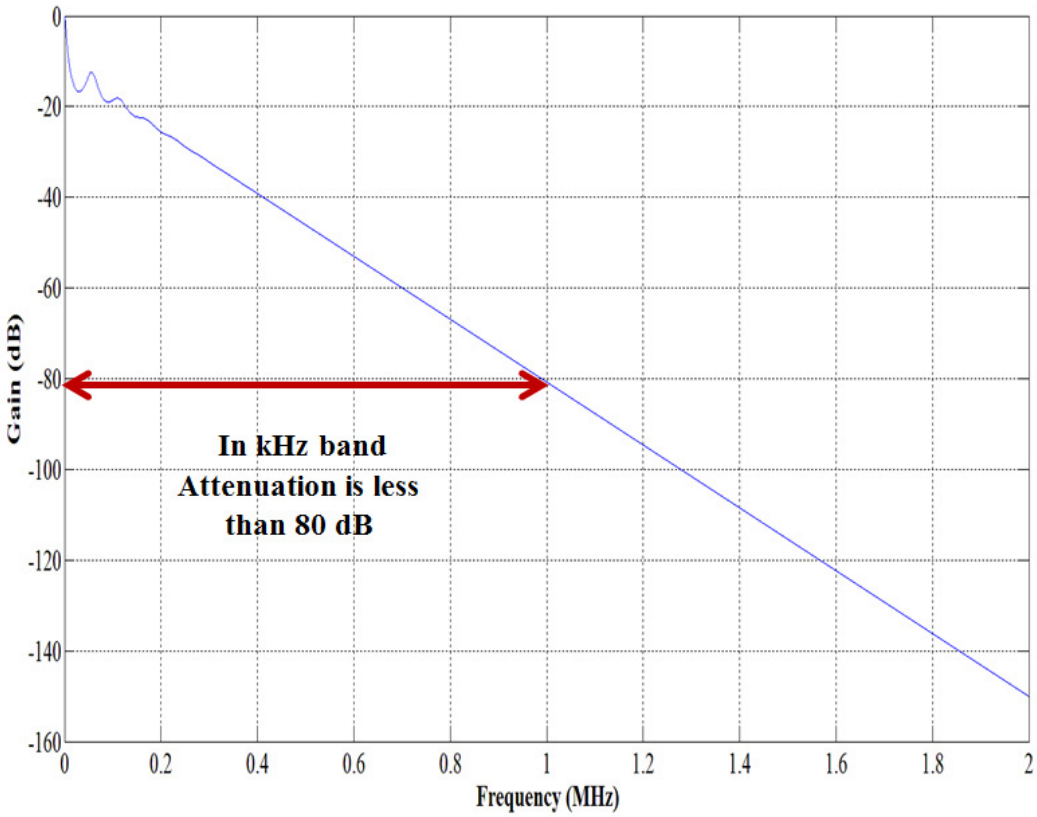


Figure 46: Frequency Response of 1000 meter distribution cable (dB)

So in summary, transmitting signals at the kHz will not reduce the EMIs only, but will also reduce the cable attenuation.

Vita

Youssef El Haj is a Lebanese researcher and engineer. He was born in 28th December, 1989 in Sharjah in UAE where he lived and was raised. Youssef completed his high school education from Shola school in Sharjah with 99.4%. He joined American University of Sharjah (AUS) in 2007 and graduated with magna cum laude degree honor as Electrical Engineer and minoring in computer engineering. In 2012 Youssef joined the master program in AUS as graduate teaching assistant to work in one of the hottest and most developing fields: Smart Grid. Youssef main research interests are drives control and power electronics, solar panels, and Smart Grid field. His educational background included electronics, drives, control, and high voltage.