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DESIGNING A PLC MODEM FOR SMART GRID APPLICATIONS

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A thesis submitted by Gökhan SATILMIŞ in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE** is approved by the committee on 07.07.2015 in Department of Electrical Engineering, Electrical Power Systems Program.

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Gökhan SATILMIŞ

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LIST OF SYMBOLS

F	Frequency
Ω	Ohm
Z	Impedance

LIST OF ABBREVIATIONS

IEEE	Institute of Electrical and Electronics Engineers
PLC	Power Line Communication
AFE	Analog Front End
SG	Smart Grid
NIST	National Institute of Standards and Technology
AMI	Advance Meter Infrastructure
AMR	Advanced Meter Reading
DA	Distribution Automation
DG	Distributed Generation
DOE	Department of Energy
HAN	Home Area Networks
DLC	Direct Load Control
DER	Distributed Energy Resources
EV	Electric Vehicles
DA	Distribution Automation
VAC	Voltage at Alternating Current Circuit
HV	High Voltage
VA	Reactive Power
F	Frequency
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
SNR	Signal to Noise Ratio
GUI	Graphical User Interface
DB	Decibel
Prime	PoweRline Intelligent Metering Evolution
OFDM	Orthogonal Frequency Division Multiplexing
SPI	Serial Interface Peripheral
BPSK	Binary Phase Shift Keying

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ABSTRACT

DESIGNING A PLC MODEM FOR SMART GRID APPLICATIONS

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MSc. Thesis

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Power Line Communication (PLC) is one of the most cost effective solutions to Smart Grids as it is both easy to install and requires no additional wiring. This makes it a promising technology that can be used to exploit the existing electrical infrastructure as a communication medium.

Current research at Yildiz Technical University concerns PLC Modems for Bus Bar Systems and Smart Homes. Our research began with measuring the impedances from Bus Bar Systems to Transformers at Narrow Band PLC Frequencies. An Analog Front End (AFE03x) Chip manufactured by Texas Instruments was used in the design of a PLC Modem.

A point-to-point communication was also implemented using a TMDSPLCV3 PLC Kit in order to better estimate the performance of the AFE chip and channel. Data rates, Bit Error rates and Signal-to-Noise ratios were plotted under different electric loads in the Smart Home laboratory. The results of the Impedance Bus Bar Systems and power line showed the suitability of PLC. Moreover, the AFE performance was satisfied under the various applications and a plc modem was designed based on a reference design.

Key words: Power Line Communication, Smart Grids, Modems

ÖZET

AKILLI ŞEBEKELER ALT YAPISINA UYGUN BİR PLC MODEM TASARIMI VE UYGULANMASI

Gökhan SATILMIŞ

Elektrik Mühendisliği Anabilim Dalı

Yüksek Lisans Tezi

Tez Danışmanı:Doç. Dr. Bülent Vural

Elektrik bir yüzyıldan fazla süredir hayatımızda ve küresel olarak erişelebilir durumdadır. Akıllı Şebekelere uygun bir haberleşme teknolojileri şeçenekleri arasında Elektrik Hatları Üzerinden Haberleşme Tekniği herhangi bir fazladan kablolama maliyeti gerektirmediğinden en gözde yöntemlerden biridir. Bu sayede kolay kurulum ve mevcut elektrik hatlarını bir haberleşme kanalı olarak kullanılmasının önünü açmaktadır.

Yıldız Teknik Üniversitesindeki hali hazırda yapılan araştırma ağırlıklı olarak PLC Modemlerin Akıllı Ev ve Bus Bar iletim hatlarına yönelik kullanımı şeklindedir. Bus Bar iletim sistemlerinin, elektrik kablolaların ve trafonun empedansının dar band PLC frekans bandında ölçümü ile başlamıştır.

Ayrıca noktadan noktaya haberleşme için modem kurulmuş ve elektrik yükleri altında testler gerçekleştirilmiş. Bu testler sonucuda haberleşme kalitesini gösteren sinyal gürültüsü seviyesi ve bilgi aktarım hızı grafiksel olarak sunulmuştır. Bus Bar iletim hatlarının ve elektrik kabloların empedans sonuçları PLC haberleşmesi için en uygun ortam olduğunu göstermektedir. Buna ek olarak testler sırasında AFE çipi gerekli performansı sağlamıştır. Son olarak referans tasarıma bağlı kalarak tek katmanda bir PLC Modem tasarlanmıştır.

Anahtar Kelimeler: Elektrik Hatları Üzerinden Haberleşme Tekniği, Akıllı Şebekeler, Modem

CHAPTER 1

INTRODUCTION

1.1 Literature Review

By definition, Power line Communication (PLC) is a type of communication technology that doesn't require any additional cables or antennas [1]. PLC is an alternative communication medium for places where there is electricity. Therefore, PLC's coverage is as wide as electricity coverage.

Nowadays, Smart Grids (SG) is a buzz word in the electrical engineering literature. The SG has many functionalities such as Advanced Metering Infrastructure, Distribution Automation, Distributed Generation, Substation Automation, Flexible AC Transmission Systems and Demand Responses. All these functionalities require a communication medium. As a result, a two-way flow of information will enable a two-way flow of energy in the context of SG.

PLC is a promising technology for Smart Grid applications because the infrastructure already exists and it has a wider coverage as opposed to wireless and wireline communication. These advantages have led to idea of this thesis which is designing and implementing a PLC modem for Smart Grid Applications.

1.2 Objective of the Thesis

The objective of this thesis is to better understand the feasibility of using power lines as a communication medium in a smart home at Yildiz Technical University in Istanbul, Turkey. This was accomplished by testing a PLC modem manufactured by Texas Instruments under different electric loads and taking impedance measurements at the PLC frequency band for various cable lengths. Impedance measurements were also conducted for both the bus bar transmission line and the transformer. Finally, based on the Texas Instruments PLC modem reference design, a PLC modem was schematized and prepared for manufacturing. However, unlike the reference design, only one layer connects to the Analog Front End layer and Transformer layer. This change made the PLC Modem smaller than the original.

1.3 Hypothesis

Power lines and Bus Bar transmission lines have low insertion and return losses. Therefore, they can be used as a communication medium. In addition, transformers don't have any resonance in the PLC frequency band and can be used in the designed modem. Lastly, communication through power line is established under different loads in the Smart Home.

CHAPTER 2

SMART GRID

2.1 Introduction

Electrical grids have been around since the 19^{th} century. Conventional grids transport energy from where it is produced - coal plants, hydroelectric dams, nuclear power plants – to our homes and industrial areas where it is consumed instantaneously. Grids are typically seen as infrastructure components like high voltage transmission lines crossing the countryside or neighborhood substations for distributing power. Moreover, the traditional grid is designed for the requirements of the 1950s when we simply didn’t use that much energy from power outlets. Today our energy requirements have increased dramatically due to sophisticated technology such as smart phones, smart TVs, air conditioners and electric cars.

Earlier technology required an enormous, centralized power plant that fed power over an electro-mechanical grid. The produced power flowed only one direction; from the power plant to where it was consumed. There was simply no ability nor reason to establish two-way communication between users and grids interactively.

However, in the last three decades, we have witnessed a tremendous evolution in telecommunication networks with communication technologies including cellular, GPS, cable, satellite TV and the Internet blossom and mature. On the other hand, the traditional grid remains both analog and electro-mechanical in spite of the remarkable evolution in information and communication technology. The pace of technological innovation shows no signs of abating and the demands for reliable electricity continue to place ever increasing pressure on an electrical supply infrastructure that is not keeping up with technological advances. This mismatch between supply and demand has led to the idea of the Smart Grid.

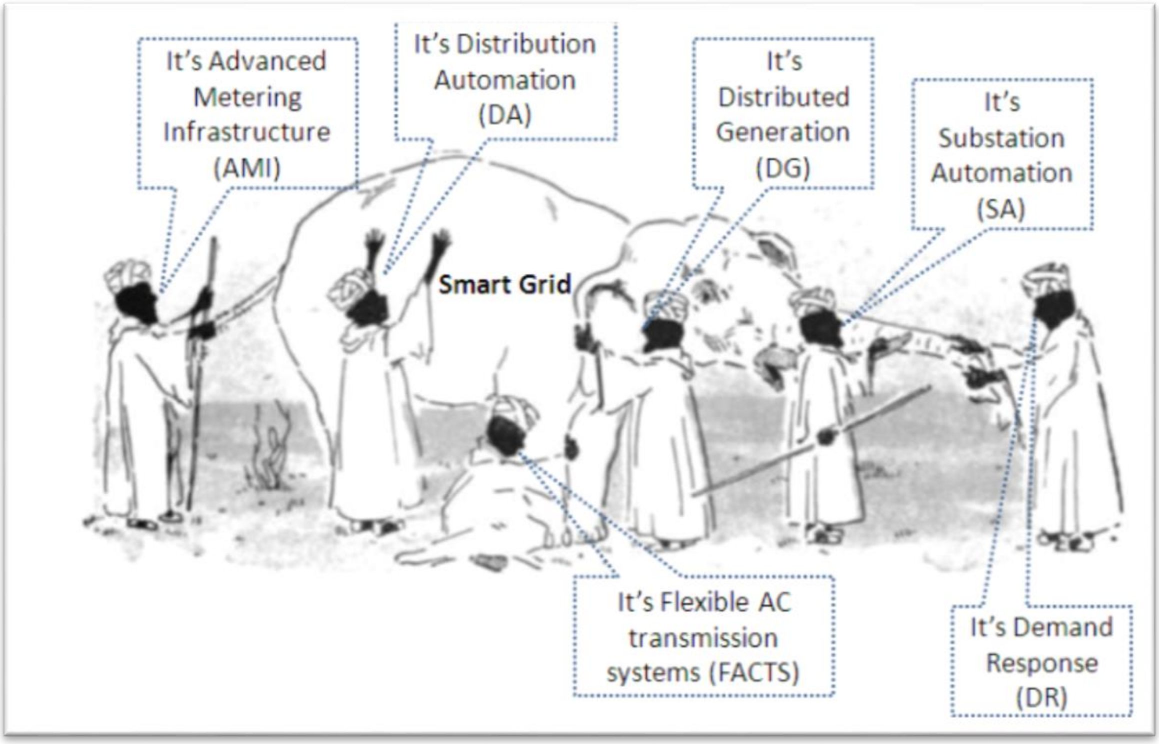

Figure 1 what is a Smart Grid? [2]

Note: Bush, S.F. and Books24x7 Inc., (2014). Smart grid communication-enabled intelligence for the electric power grid, Chichester, West Sussex, U.K.: John Wiley & Sons Ltd., Copyright 2014 by Wiley Press. Adapted with permission.

The figure above shows an old blind man trying to understand an object by touching, pulling and listening to it. Yet each action, occurring in a different place, yields a different interpretation. Our current capabilities are like this old man. We are trying to combine the ideas of Advanced Metering Infrastructure, Distribution Automation, Distributed Generation, Substation Automation, Flexible AC Transmission Systems and Demand Responses into a single concept called the "Smart Grid." Why? Because each of these elements is integral to its functioning.

2.2 Smart Grid Communications

The promise of Smart Grids lies in its ability to modernize electricity generation, distribution, and consumption by combining the two-way flow of electricity with the two-way flow of information. Because the Smart Grid depends on the increased use of communication and information technology, sufficient access to communication facilities is vital.

Table 1 Smart Grid Functionalities and Communication Needs [3]

APPLICATION	NETWORK REQUIREMENTS			
	BANDWIDTH	LATENCY	SECURITY	BACKUP POWER
Advanced Metering Infrastructure	10-100 kbps/node, 500 kbps for backhaul	2-15 sec	High	Not necessary
Demand Response	144 kbps - 100 kbps per node/device	500 ms - several min	High	Not necessary
Wide Area Situational Awareness	600 - 1500 kbps	20ms - 15 sec	High	24 hour supply
Distributed Energy Resources and Storage	9.6 - 56 kbps	20 ms - 15 sec	High	1 hour
Electric Transport	9.6 - 56 kbps, 100 kbps is good target	2 sec - 5 min	Relatively High	Not necessary
Distribution Grid Management	9.6 - 100 kbps	100 ms - 2 sec	High	24-72 hours

Most of the existing communication and networking technologies can be used with SG applications including traditional twisted-copper phone lines, cable lines, fiber optic cable, cellular, satellite, microwave, Wi-MAX, power line carrier, and broadband over power line as well as short-range in-home technologies such as Wi-Fi and Zig-Bee.

In the future, Smart Grids will probably use a variety of communication technologies that will have multiple applications. Each of these types of technologies can best be understood under the circumstances in which they will be used. Based on work previously completed by both NIST and FERC, the United States Department of Energy has determined that there are six functional categories within Smart Grids. These are listed in Table 1 along with their communications needs.

2.2.1 Advance Metering Infrastructure

Advanced Metering Infrastructure (AMI) refers to the ability to automatically read meters. In the Smart Grid environment this would be integrated with Home Area Networks (HANs) by connecting smart meters, smart appliances, electric vehicles, and on-site electricity generation or storage devices, together with in-home displays in order to control energy loads during peak demand periods.[3]

Most HAN applications do not need wide bandwidth. Therefore, the amount of information to be transmitted will likely be between 10 and 100 kbps per node/device and the ideal latency for HAN applications should be between 2 and 15 seconds.

The communications needs of HAN applications are both low power and short-distance. The technologies currently being used or considered for on-site communications include 2.4 GHz Wi-Fi, the 802.11 wireless networking protocol, Zig-Bee, which is based on the wireless IEEE 802.15.4 standard, the Bluetooth protocol, and Home-Plug, a form of power-line networking that carries data over existing electrical wiring. While standardization has not been agreed upon yet, the main technology that is currently popular is Zig-Bee, followed by Home-Plug. Both Zig-Bee and Home-Plug share the advantages of being wireless, low power, cost effective and flexible. These parameters will play a critical role if the HAN is to connect with smart appliances.

AMI functionality will probably be based on the communication technology used. As PLC applications are used for relaying meter data and other internal communications over a utility power line it is the best option for AMI functions in rural, low-density areas, where wireless coverage is still in progress. While PLC has wide coverage and theoretically can go as far as the power cables can go, it has a very low-bandwidth - often below 20 kbps - and this is probably not enough to meet the requirements of real-time AMI at the per-device level, which is about up to 100 kbps.

To enable more advanced applications such as real-time pricing, a two-way communications system is necessary and lower latency may also be needed. However, the enormous amount of data that may be collected from all the devices in homes sharing a single neighborhood node will most likely require bandwidths in excess of the 500 kbps range. Realistically speaking, current AMI networks will probably be unable to function with such large amounts of data.

2.2.2 Demand Response

Increasing the utilization of Demand Response (DR) is the most widely taken step by utilities to make a smarter power grid. DR is the reduction of electrical energy use as a response to rising prices or heavy loads on the system. The most important advantage of DR is that it can significantly reduce peak loads.

With Direct Load Control (an energy management system), it's possible to repeatedly cut consumption by powering down appliances during moments of peak load. The next step in this process would be automated DR, which would allow on-site devices to respond to changing conditions such as shifting load consumption.

Energy management systems like Direct Load Control will become a reality through DR devices. For example, it could transmit pricing information directly to the appliance leaving the customer with the option to reduce electricity use manually. Another variation of DR would have electricity use at the home or business offloaded to distributed generation sources at the customer's location. [3]

Depending on the complexity of the system the communication requirements of DR applications will differ. For instance, sending a simple shut-off command to a home appliance requires little bandwidth and can be achieved with today's technology. However, if DR were coupled with AMI the bandwidth needs of such a system would increase dramatically. Additionally, latency is a critical feature of DR and estimates suggest a broad time range, from 500ms up to several minutes, will be achieved. [3] The delay of DR commands because of high latency would seriously influence the effectiveness of the system as a whole. Furthermore, since utilities using DR will mostly depend on it as a grid management tool, reliability will also be vital. On the other hand, unlike AMI, DR is expected to be used only during brief periods of time, matched with periods of peak energy usage.

With DR, communications would be passed along to the HAN, using the Zig-Bee networking protocol or others to transmit orders to devices. Other implementations could employ more up-to-date communications technologies, including broadband, and next-generation cellular such as LTE, Wi-Fi, or Wi-MAX. Taking advantage of these higher bandwidth systems will allow for two-way communication and the use of more time-sensitive applications.

2.2.3 Wide-area situational awareness

As demands on the existing power supply system continue to increase preventing disruptions is becoming a prominent goal for Smart Grids. Because of the interconnectedness of the existing grid structure problems in one locality can quickly spread to a wider area. Such a domino effect is a well-known problem and is why the ability to monitor the entire supply system is of crucial importance. Wide area situational awareness attempts to address this problem by using a set of technologies that improves countrywide monitoring thus enabling utilities to gain a complete and dynamic picture of the grid.

One of the main technologies used in wide-area measurements are synchrophasers. While synchrophasor technology is being combined with other SG technologies, the topmost kind of synchrophasor implementation uses phasor measurement units to provide accurate voltage and current phasor measurements. Readings from different locations can be time tagged which means that readings, accumulated over time from different locations, can be aggregated thus forming a wide area picture of the power supply at any one moment in time.

2.2.4 Distributed Energy Resources and Storage

Distributed energy resources (DERS) are small-scale power generation sources that are located close to where the electricity is going to be used (e.g., the home or business) and provide an alternative (or enhancement) of the electricity supplied by the traditional power grid. Well-known DERS include renewable energy sources such as wind and solar power along with such devices as electric vehicle batteries, fuel cells, micro-turbines and energy storage systems. Yet, while the adoption of these energy sources increases, a remaining challenge exists in how to better incorporate them into the existing grid. In this regard Smart Grids hold great promise in their potential to more uniformly integrate distributed renewable energy resources.

These new energy technologies will require a multi-directional communication structure. In order to fully integrate the technology the flow of energy must be multi-directional, from home to utility, utility to home and from home to home and this is a radical shift away from the unidirectional flow that is currently in use. Furthermore, renewable electricity generation is intermittent and somewhat arbitrary. This means that effective communication will be critical for efficient energy use and control. For instance, real-time net metering (which is a measure of the electricity drawn from the grid minus the energy delivered to a premises via on-site sources) is one necessary enhancement. Another improvement would be the ability to distribute overload energy that flows back to the grid using communication technologies that have information on instantaneous electricity generation in areas around the grid. Short term DER generation predictions based on weather reports are another potential. Finally, it has been suggested that Smart Grid technology could allow the islanding of DERs with local energy loads effectively acting as a micro grid.

2.2.5 Electric Transportation

The recent interest in electric vehicles (EV) and their current development has been a significant improvement for consumers because it allows them to reduce their dependence on petrol. EV's may also be used as energy storage devices, so they can help to feed energy back to the grid during peak usage times. With millions of EVs, it would be possible to store excess energy during periods of low demand and then feed it back to the grid when necessary.

As hybrid cars become more popular and the technology progresses, utilities will face more difficulties. For example, being able to provide sufficient energy for millions if not hundreds of millions of EV's is not possible with the existing infrastructure, especially during peak load times such as rush hour.

Furthermore, the charging of EVs must be monitored in order to prevent overloading of service transformers in a neighborhood. A high current EV charger is similar to connecting one or two additional homes to a transformer. Therefore, plugging many EVs into public charging stations will necessitate appropriate load distribution. And, as with in-home charging, public charging will need to match supply and demand.

Communication technologies will play an important role not just for monitoring and controlling load distribution but also for billing purposes. Currently, EV charging stations are not well-integrated with EV manufacturers and utility companies. This has created a situation that is akin to a mobile customer only being able to use their mobile provider's base station. This results in both inefficiency and low adoption rates of EV technology. There needs to be both standardization and compatibility of communication between EV charging stations, utility companies and vehicle manufacturers.

2.2.6 Distribution Grid Management

The distribution grid is the part of the power supply structure that steps down voltage from transmission lines, through distribution substations, and delivers electrical energy to consumers. It also acts to isolate faults before they impact other parts of the grid. Presently the distribution grid functions with a minimum of automation and intelligence. Yet as the assimilation of DERs into the grid continues, maintaining a reliable power supply will become more challenging.

Incorporating distribution automation (DA) into the grid management system will allow utilities to use automated technology to remotely monitor and control the distribution network through automated decision-making. With DA, alarming and automatic feeder switching will increase fault detection, isolation and restoration. This should lead to less frequent power outages or when they do occur, would be of short duration. This could easily be accomplished by providing repair crews with accurate locations of circuit problems and also by sectioning off faulted circuits. In this way fewer customers would be affected.

Because of the role DA plays in stopping problems quickly and before they can spread, they represent one of the least latency-tolerant Smart Grid applications. They have needs of less than 1 second of latency for alarms and warning communications and sub-100 milliseconds for messaging between peer-to-peer nodes inside RF mesh networks. The maximum latency of DA applications would not be longer than two seconds. Bandwidth needs would probably be between 9.6 kbps – 100 kbps.

2.3 Summary

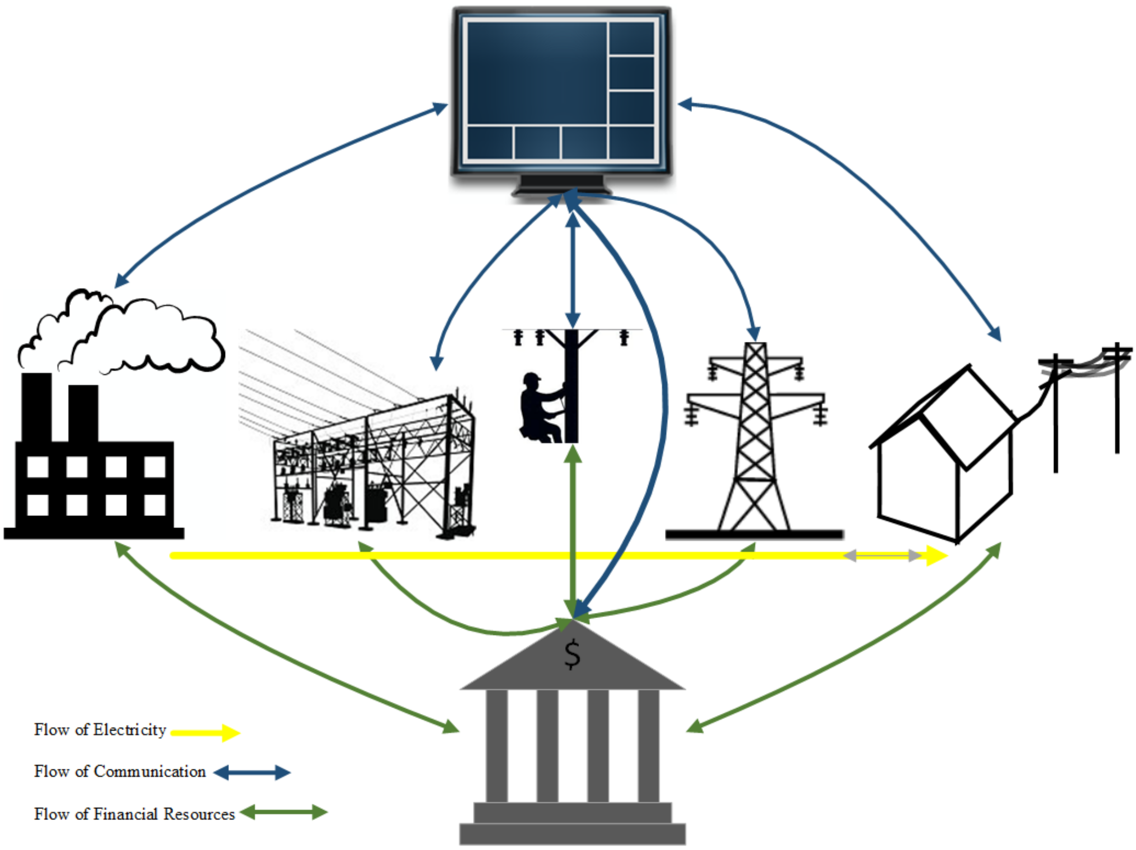

Figure 2 Interactivity of the Domains of Smart Grids

Figure 2 is an illustration of a Smart Grid. The flow of electricity starts at the point of generation, then flows to a distribution substation next to transmission cables and finally to the point of consumption. With conventional grids this flow is one-way. However with smart grids the flow is two-way between transmission and the consumer reflecting the incorporation of DERS. Another difference with traditional grids is the importance of the flow of communication. Operations management (signified by the topmost icon) connects all of the domains in a two-way flow of information that is both dynamic and real-time. In sum, there are numerous advantages to migrating to Smart Grids including increased reliability via distribution grid management, load adjustment and load balancing using AMI and DR, increased sustainability through DERS, greater flexibility in network topology with wide area situational awareness and an overall increase in efficiency. In conclusion, SG uses communication and information technology to create a power grid that is more efficient, reliable, safe, and durable while minimizing expensive investments in new production capacity.

CHAPTER 3

POWER LINE COMMUNICATION

Power Line Communication (PLC) is the transmission of information signals over existing electrical wires. Many of these wires were installed over a century ago and their only purpose was to deliver power to cities and other residential areas. Letting electricity into our lives revolutionized how we live and work and furthered the industrial revolution. At present, another revolution is currently underway, one that revolves around information as opposed to energy.

The current Information Age requires both wire-line and wireless communication technologies and is highly popular as can be seen through the wide adoption of the internet, and GSM technologies. As a result of the advances made in the Information Age, there has been a constant demand for more and better access to communication technology**.** Power line communication (PLC) stands to become a more promising alternative to other communication technologies such as ADSL, GSM and satellite due to its universal coverage and by exploiting current electrical cables. Thus anywhere electricity exists PLC can also be implemented. This has the additional advantage of keeping costs low as there is no need to install new cables or base stations while maintenance costs would remain stable. PLC is also relatively easy to set up and the same medium is used to both power up devices and send and receive data.

Home automation systems are the most obvious applications of PLC technology. At present these systems are generally implemented through ethernet or wireless modems and require a CAT5 type cable wiring. Wireless modems also provide large bandwidth but this can be disturbed by many factors such as walls and antenna blind spots. The ‘smartness’ of Smart Homes is the type of communication technology that is used to monitor energy and/or control home appliances and in this sense PLC has significant importance for Smart Homes as it bypasses wireless technology and its limitations.

3.1 History

The idea behind Power Line Communication (PLC) is not new, although its origins are not well-known. The history of PLC started in 1838 when inventor Edward Davy suggested a solution that allowed remote meter measurements for battery levels. [4] In 1897, the first patent for remote measurements was submitted. In 1950, the first PLC application, known as Ripple Control was employed over electrical networks with a carrier frequency ranging from 100 Hz to 1 kHz[1]. The initial goals of PLC were remote on/off switching of public lights. Later on, the first industrial PLC system named Pulsadis appeared in France in 1960[1].

When the first CENELEC band appeared its frequency ranged from 3 to 148.5 kHz. It allowed bidirectional communications over low voltage that could be used for meter readings as well as a diversity of applications related to home automation fields [5]. From the 1990s to now, there have been various standards committees but no single standard PLC frequency band has been agreed upon. Thus, a number of different technologies have been developed that vary in bit rate speeds over the last several decades.

In Table 2, the changes in speed of PLC Technologies are classified. As can be seen, Home plug is very popular with both low bit rate and high bit rate.

Table 2 Low and High Speed PLC Technologies [1]

High Bit Rate	Passport
	ASCOM
	Main.net
	HomePlug 1.0
	Spidcom

Table 2 (cont'd)

	DS2
	HomePlug AV
	HP BPL
Low Bit Rate	X10
	CEBus
	Home Plug CC

3.2 Modems

A modem (modulator-demodulator) is a device that modulates an analog signal to encode digital information, and demodulates the signal to decode the transmitted information. [6]

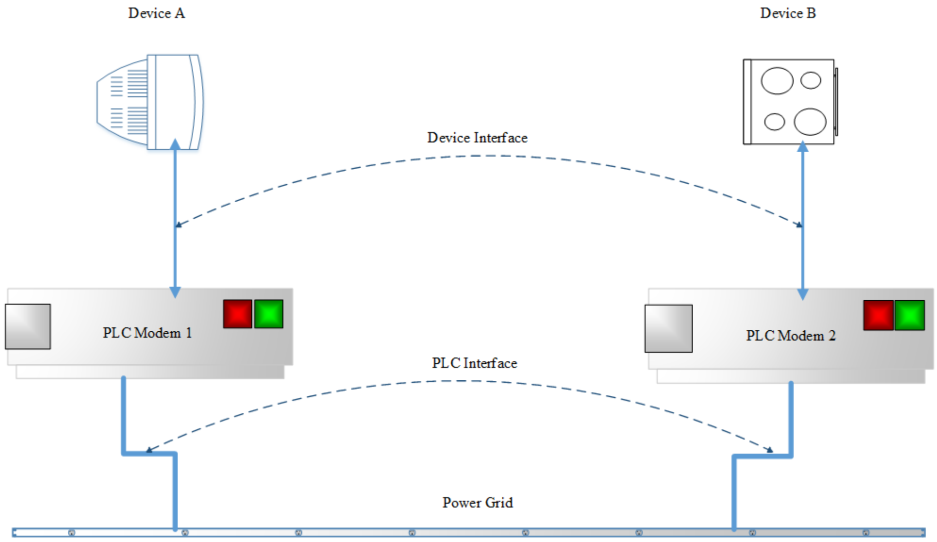

Figure 3 Communications over Power Grid[5]

A simple transmitting and receiving modem in a power grid transmission link is depicted in Figure 3.

In this configuration, the power grid is a channel similar to wireless communication, which takes place in free space. The impedance of free space can be found by dividing the magnitude of the electric field strength and magnetic field strength.[7]

$$Z = \frac{|E|}{|H|} = 120\pi = 376.73031\ldots\Omega \tag{3.1}$$

Nevertheless, there is constant impedance in the air while the impedance in the power grid changes continuously.

3.3 Impedance

Electrical cables are designed to transmit voltage at either 220 or 110 and alternating at a line frequency of 50 or 60 Hz depending on the country standard. The physical parameters of cables have both advantages and disadvantages when used for a communication medium. Impedance is one of the most important of these parameters in terms of consistent communication.

Electrical cables are characterized by their impedance ‘Z’ which can be resistive, inductive or capacitive depending on the electrical network and is affected by operating frequency, age and design. Since all devices are constantly being connected and disconnected to the power socket, the impedance doesn’t have a fixed value.

Modeling of electrical wires is becoming crucial because it allows for the estimation of dc loss, skin effect and other electromagnetic losses. With these parameters, one can plot the feasibility of the location where communication over electrical wires should be established. For this reason, a typical two-wire cable was measured via Network Analyzer over a wide frequency band.

In Figure 4, the impedance of an electrical wire changes dramatically by variant frequency. On the other hand, the average impedance of an electrical line is stable and can be found by the formula:

$$\mathrm{Z} = \sqrt{\frac{L}{C}} \tag{3.2}$$

Where

L = $\mu\mathrm{H}/m$ (linear inductance of the electrical line)

C= $\mu\mathrm{F}/m$ (linear capacitance of the electrical line)

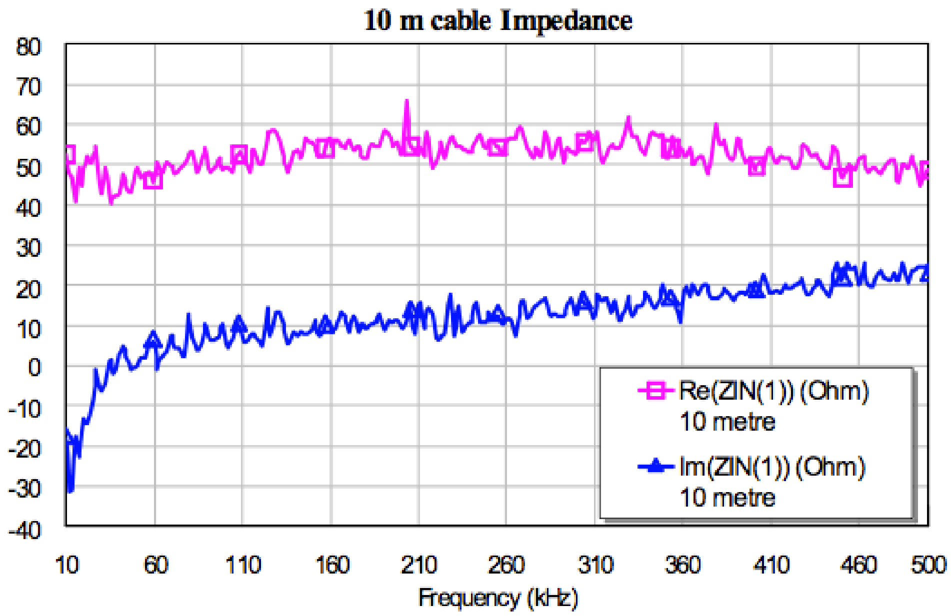

Figure 4 Impedance of Electrical Wire

Thanks to research done by Downey and Sutterlin,[1] it is possible to model electrical circuits that are equivalent to an electrical line and this is shown in Figure 5. These circuits have all the necessary parameters including resistance, inductance and capacitance. Loads from devices such as hairdryers, halogen lamps and vacuum cleaners change the impedance of these electrical lines.

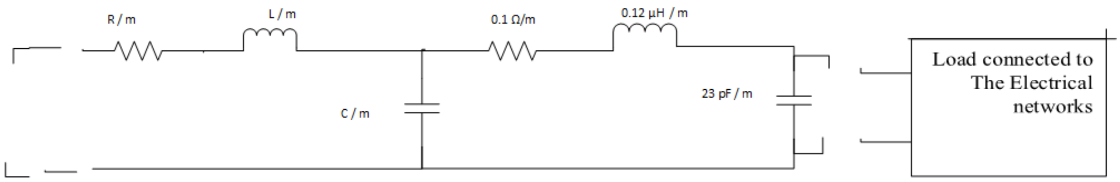

Figure 5 Schematic Circuit of an Electrical Line modeled by Downey and Sutterlin[1]

Furthermore, modeling is a way of estimating how well the PLC signal travels in the electrical network. The impedance of an electrical line can be found by the following equation:

$$Z = R(f) + sxL \quad (\Omega) \tag{3.3}$$

R (f) (is the resistance of cable as a function frequency)

S (is the cable diameter)

L (is the line inductance)

3.3 Attenuation

As electromagnetic waves are attenuated through the air from antennas, the electrical signal loses power as a function of the distance travelled through copper wires. Variations in impedance in electrical networks cause mismatches such as multipath effects. In general, signal attenuation in the home changes from 20 dB to 60 dB depending on the topology and wiring characteristics.

Table 3 Attenuation of Principal Equipment on an Electrical Network [1]

Electrical Equipment	Attenuation
Electromechanical meter	15 dB
Electronic Meter	15 dB
Circuit breaker	5 dB
Power Strip	10 dB
Electronic meter and circuit breaker	20 to 30 dB
Electromechanical meter and circuit breakers	30 dB
	50 dB

As seen in Table 3, attenuation is critical for estimating the performance of communication. Therefore, it is important to model electical wires at the PLC Frequency Band. In addition, high frequency cable modeling helps to estimate resistive and skin effect losses. These parameters become useful when installing PLC Modems in different locations. Although we can transmit high bit flow from transmitter modems, the receiver modems will decide the quality of communication based on the recovered bits.

3.4 Coupling

Designing a line coupling circuit is an important aspect of power line modems because it is the interface between electrical networks and modems. There are two types of coupling methods, capacitive and inductive.

Capacitive coupling is used mainly for PLC Modems. It is called capacitive coupling because the PLC Modem connected to an outlet is viewed as capacitance. However, inductive coupling is more efficient. An electromagnetic induction technique is used either between two electrical wires or between an electrical wire and a coil wound around the wiring. PLC injectors are mainly used to connect PLC Modems to electrical wiring using a neutral cable.

The coupling circuit has two goals: first, preventing high voltage damage that is coming from the harmonics of electricity, and second, to couple the PLC signal to and from the ac mains. A simple coupling circuit is shown in Figure 6:

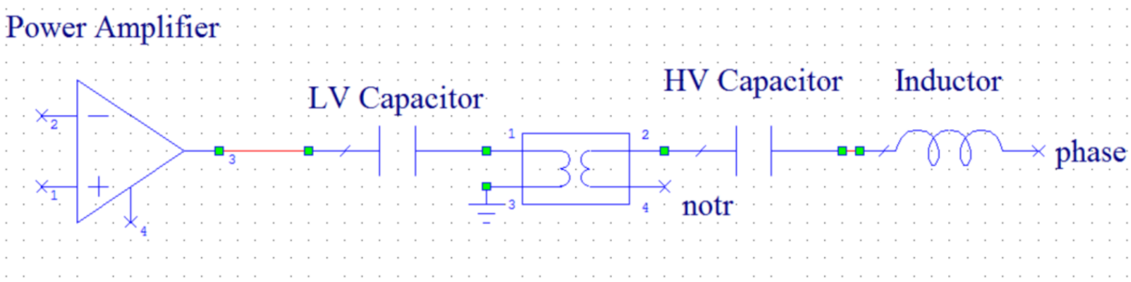

Figure 6 Coupling Circuit[8]

The high-voltage capacitor (HV Cap) blocks the low-frequency main's voltage by forming a voltage divider with the winding inductance of the line coupling transformer.[8] In many applications, a maximum reactive power (VA limit) on the HV Cap may be required. To meet this requirement, the HV Cap value is calculated by the following equation.

$$HVCap = \frac{VALimit}{VAC^2(2x\pi xF)} \tag{3.4}$$

The inductor is required when driving low line impedances. Because the HV Cap generally is about 470 n F, the impedance of the 470 n F capacitance at 40 kHz is around 8.5 Ω. Moreover, having the resonant frequency both for a HV Capacitor and inductor is suggested, so the value of the inductor is 12.8 µ H and the capacitor is 470 n F. The inductor's size is important for enduring the maximum load current and its value can be calculated by the following equation:

$$L = \frac{1}{(2x\pi xf^2)} \tag{3.5}$$

Most power-line communication transformers have turn ratios between 1:1 and 4:1 with low leakage inductance, and around 1-mH of winding inductance. Figure 7 shows the equivalent circuit formed with the HV Cap and the line coupling transformer.

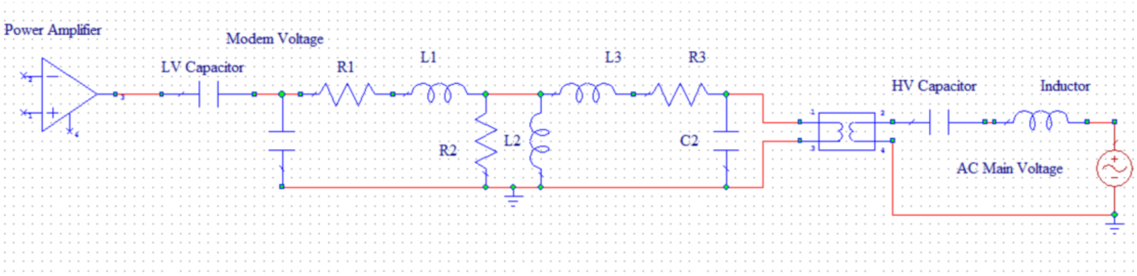

Figure 7 Voltage Divider with HV Cap and Transformer Equivalent Circuit[8]

Choosing the optimal turn ratio is highly dependent on two variables, first maximum output swing capability, and second the maximum output current capability of the PA. If the power supply voltage and target load impedance have already been determined, the turn ratio can be found by the following equations:

$$\frac{PA{,}V_{out\_peak}}{PA{,}I_{out\_peak}} = R_{load} x (\frac{N_1}{N_2})^2 \tag{3.6}$$

$$\text{Turn Ratio} = \frac{N_1}{N_2} = \sqrt{\frac{PA{,}V_{out\_peak}}{(R_{load}) x PA{,}I_{out\_peak}}} \tag{3.7}$$

3.5 Noise

Noise is a random fluctuation in an electrical signal, a characteristic of all electronic circuits.[9] In terms of communication, noise is an error, an unwanted random disturbance of signal in the communication channel. There are many type of noises such as thermal, flicker, shot, burst and transient-time noises.

Unlike noise modelled in wireless communication such as additive white Gaussian noise, noise in the PLC Channel has a dynamic characteristic. This is due to constant connection and disconnection to the power outlet from activities like plugging in laptops and turning lights and TVs on and off.[10]

In the PLC Channel, noise is generated by impulsive or burst types which have sudden step-like transitions between two or more discrete voltages or current levels at random and unpredictable times.[9] There are many algorithms for achieving noise reduction. For example, Bit Error Rate (BER) is improved by 1 dB through the help of a new distance metric under the hair dryer load.[11]

3.6 Channel

The channel in a PLC system is a cable, bus bar or any type of material that can carry voltage with different magnitudes within the grid. The electrical supply system has three network layers based on high, medium and low voltage cables.

High voltage cables are above ground cables used to connect power stations with large supply regions and as such they cover long distances. Their voltage ranges between 110 kV to 380 kV. Medium voltage cables cover shorter distances with voltage ranges between 10 kV to 30 kV. They are primarily used for delivering power to non-residential customers such as industrial and commercial enterprises. In contrast to high voltage cables, medium voltage ones run both above and below ground. The power of low voltage cables range between 230V to 400 V, or 110 V in the USA, and supply energy for residential customers. The distance traveled is considerably shorter than for medium and high voltage cables and is rarely more than a few hundred meters. In crowded urban areas these cables are usually underground. However, in rural areas these may be placed in an above ground network.

CHAPTER 4

DESIGING A PLC MODEM

A PLC modem can be divided into 3 parts: the transformer, an analog front end and the processor. Although power line impedance is not a part of the modem its characteristics still play an important role in terms of communication quality including point-to-point communication between the transmitter and receiver modem. In Figure 8, the parts of a PLC modem and its power lines illustrate how the communication signal travels

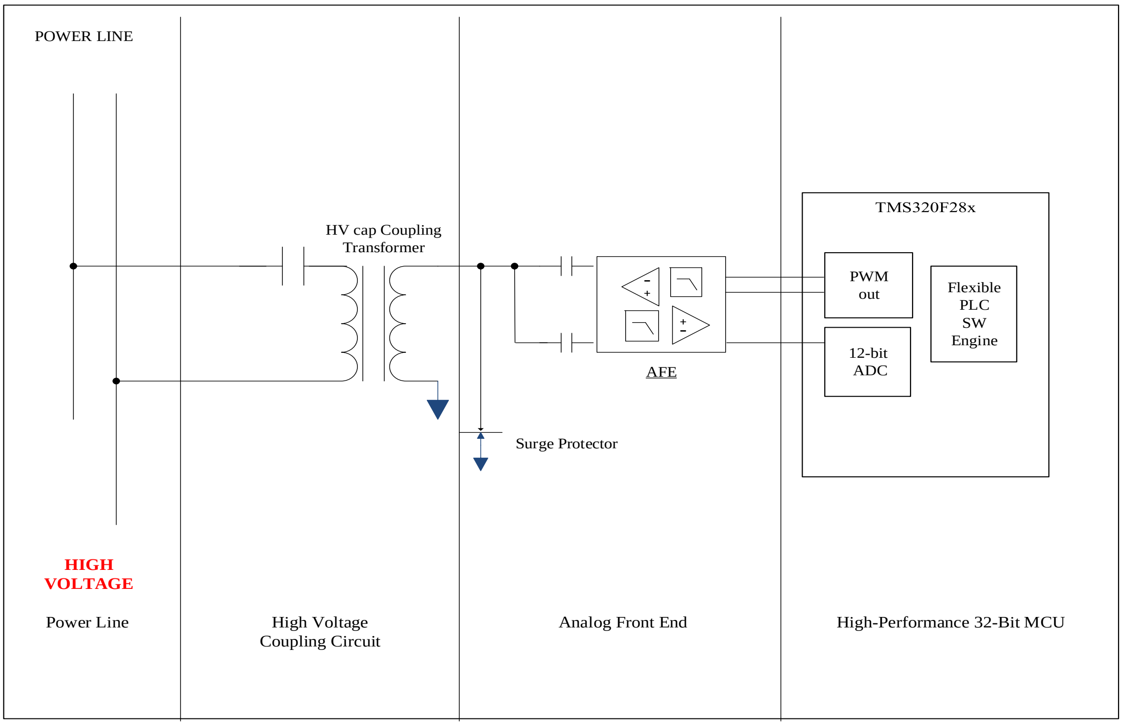

Figure 8 PLC MODEM

through the power line in an analog form and later couples to a transformer and reaches the AFE input. AFE is the heart of stable communication and its purpose is to filter unwanted signal, amplify the signal when sent to the power line and/or recover the signal when it is received and then hand it over to the processor. Moreover, the parameters of the communication quality such as bit error rate and signal to noise ratio can be plotted by the help of a graphical user interface on the PC.

Figure 9 shows the major connectors and features of a PLC modem from Texas Instruments. Through this modem, it is possible to change the frequency band and communication protocols. PLC-lite, a communication protocol that is specifically designed for PLC applications by Texas Instruments, is installed by default. However, there are other commercial PLC protocols such as G3-PLC and Prime. When changing the frequency band, for instance going from Cenelec A to Cenelec B, jumper connections must be reconfigured. This change helps the circuit to use the different values of the capacitors.

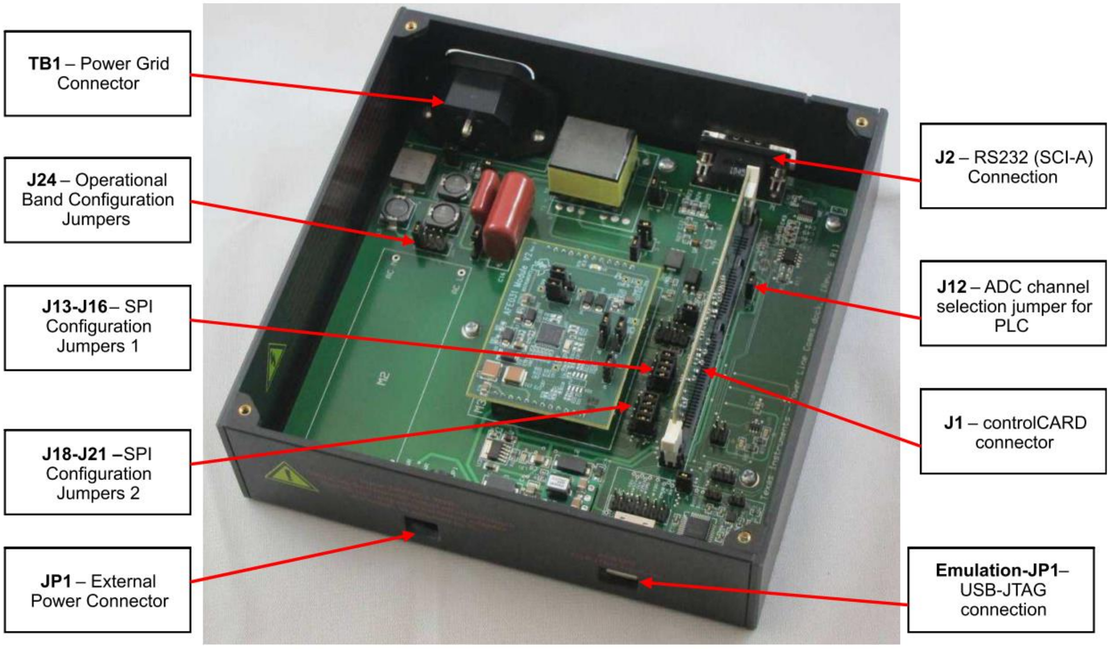

Figure 9 PLC Modem from Texas Instruments[12]

4.1 Testing A PLC Modem in the Smart Home

There is a Smart Home at the Electrical Engineering Department in Yildiz Technical University. It is referred to as smart because it enables home energy management, integrates renewable energy sources between the home and grid and establishes a communication network in the home. [13] using smart that monitor and control energy on demand via wireless and wire-line communication technologies. The renewable energy sources are integrated into the grid starting from low to high voltage depending on the capacity of the renewable energy source. A wind turbine is established on the campus as well as a solar panel on the ceiling of the Smart Home. Moreover, a battery is also installed to complete the energy cycle from generation to storage. The role of the battery is to power the smart home when there is no wind for the turbines or at night.

Communication inside the smart home is established by Zig-Bee. Smart plugs use the Zig-Bee communication protocol for sending and receiving energy usage information about connected devices.

Two PLC Modems that were designed by Texas Instruments were tested under two different electrical loads; a hair dryer and vacuum cleaner. By the help of a zero configuration graphical user interface (GUI), the bit error rate (BER), signal-to-noise (SNR) ratio and log bit error rate were plotted. In Figure 10, the point-to-point modem set up is shown.

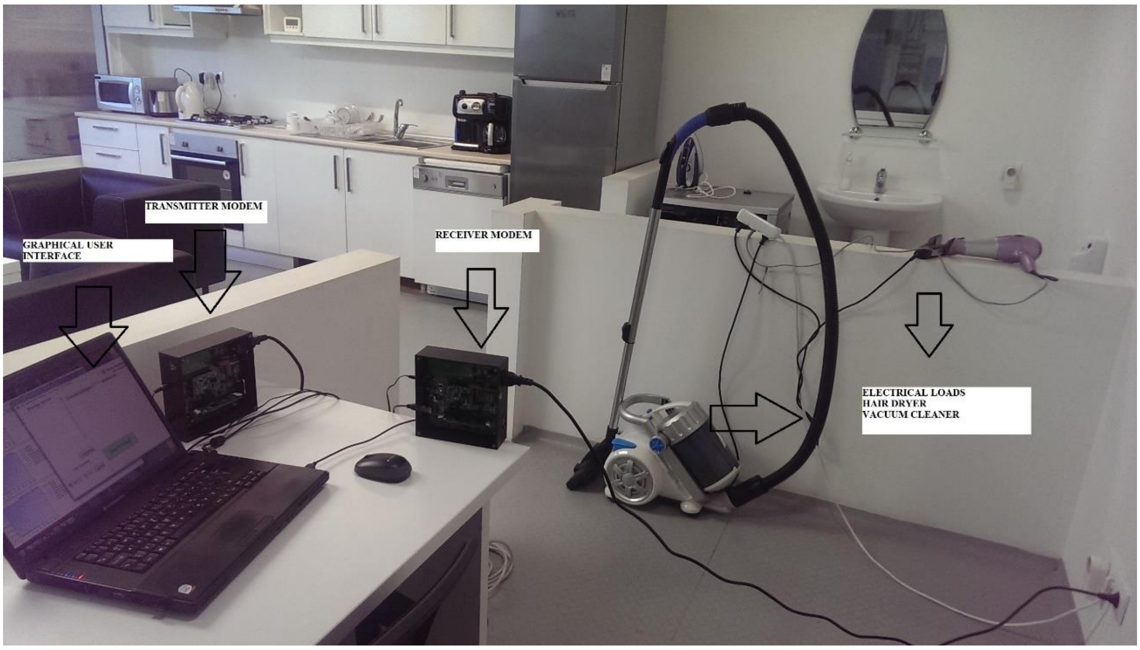

Figure 10 Point-to-Point Modem Setup

In Figure 11, the result of point-to-point modem setup is shown for 25 seconds. In Figure 12, the time frame was increased in order to better understand the performance of communication between each modem. As it can be seen in Figure 12, the SNR level changes from 12 dB to 18 dB and at times the peak levels are higher than 20 dB.

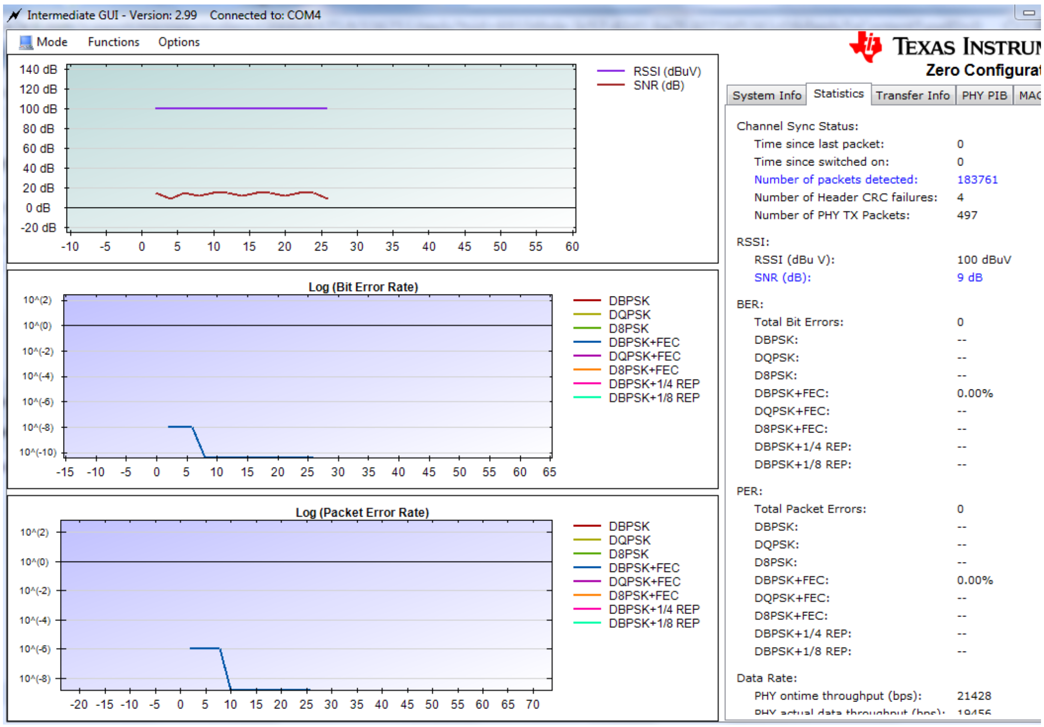

Figure 11 Intermediate GUI Parameters

Texas Instruments provides different type of protocols for PLC modems namely PLC-Lite, Prime, and G3-PLC. By flashing the modem with hex code that is associated with the specific protocol, it is possible to change protocols depending on needs. PLC-Lite is low data rate, based on Prime-OFDM with BPSK and supports point-to-point or point-to-multipoint communication. Prime protocol is specifically designed for metering applications. Moreover, prime makes it possible to enable the building of smart grids for open, public and non-proprietary telecommunications architecture. Lastly, G3-PLC is designed for medium and low voltage lines for AMR and other smart grid applications. G3-PLC gives a larger bandwidth than PLC-Lite and Prime. Finally, G3-PLC supports point-to-point, Star and Mesh network topology.

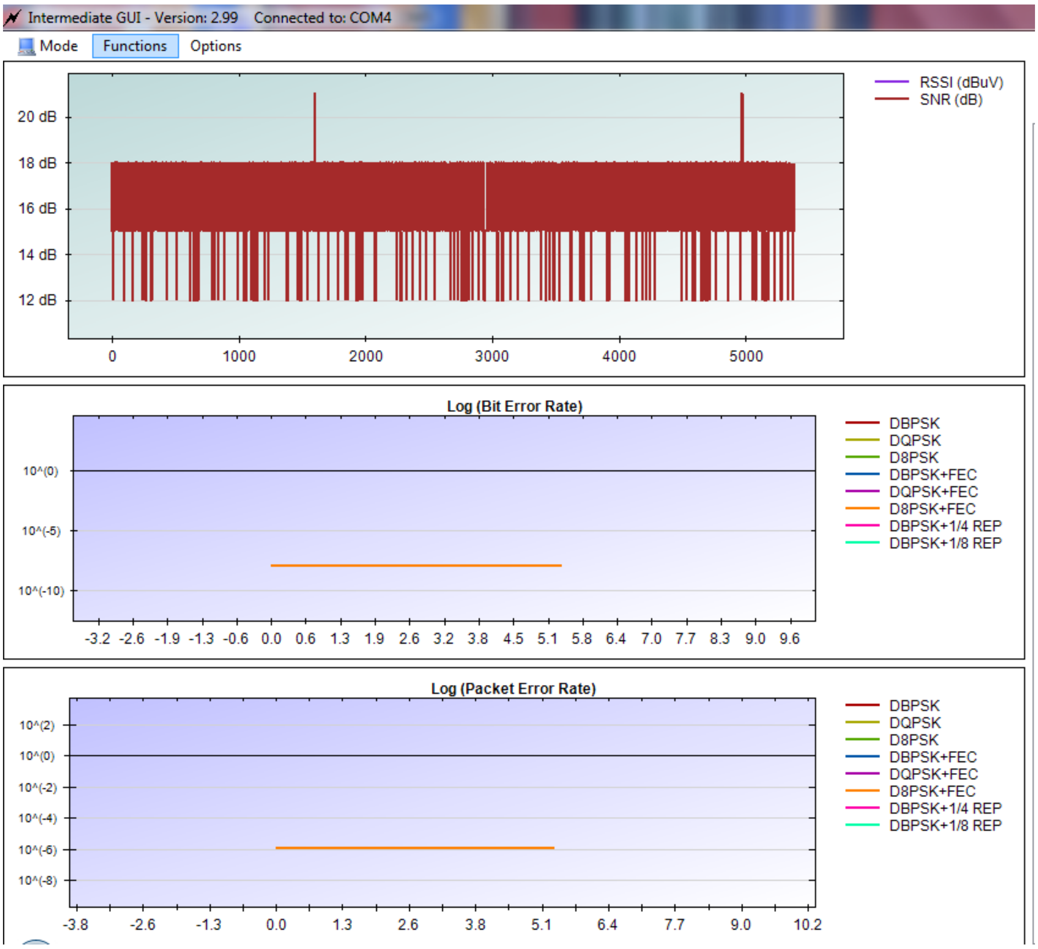

Figure 12 Intermediate GUI Parameters

4.2 Impedance Measurement of Bus Bar Transmission Line

Power line communication is strongly affected by the impedance of transmission lines. Therefore, impedance measurements of bus bar transmission lines were done before designing the PLC Modem. A Rohde & Schwartz Vector Network Analyzer was used to measure the impedance of the bus bar transmission line. On the first measurement set up, a continuous bus bar was selected and on the second set up, a discontinuity bus bar was selected and the impedance difference was compared.

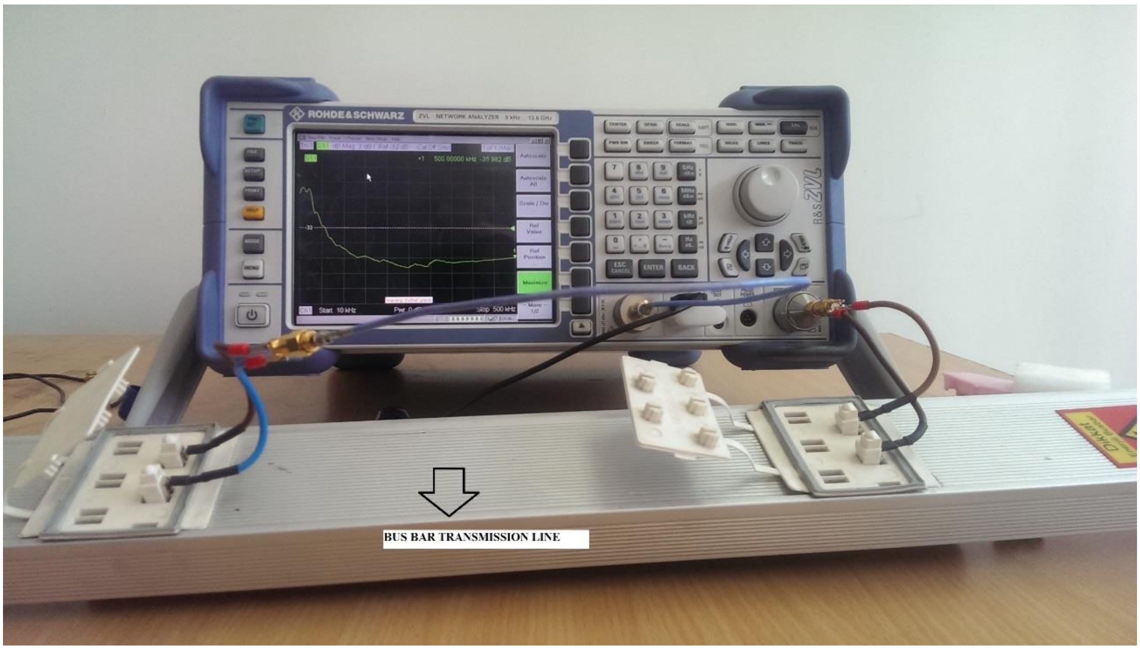

Figure 13 Bus Bar Measurement Setup

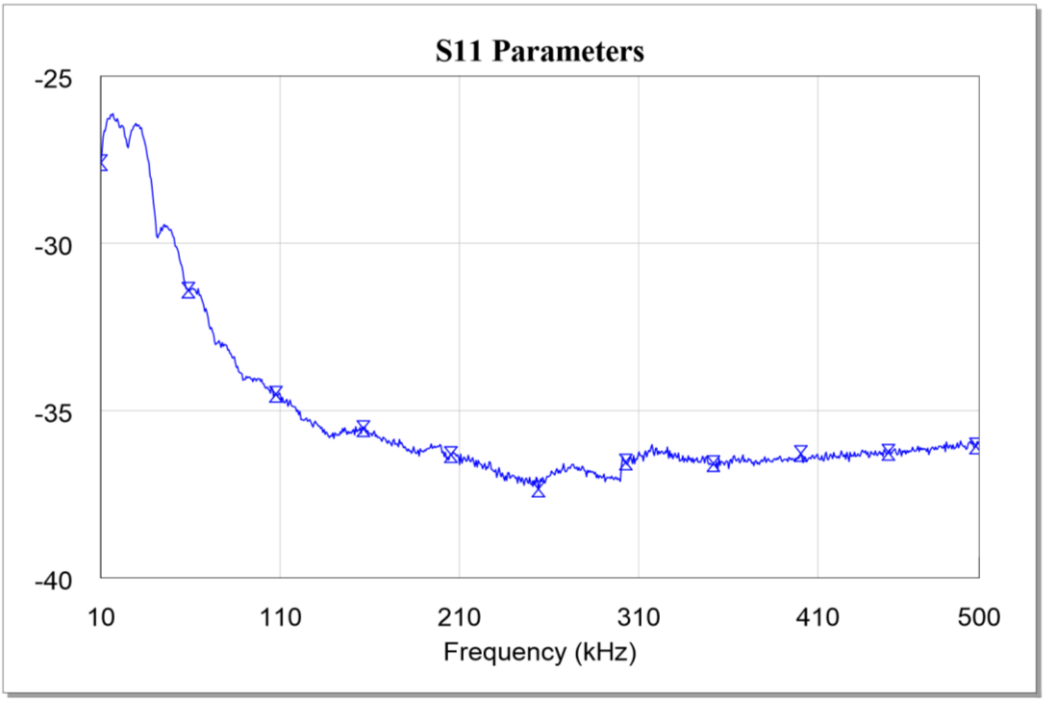

Figure 14 S11 Parameters

The return loss is low at 136 kHz and can be seen in Figure 14.

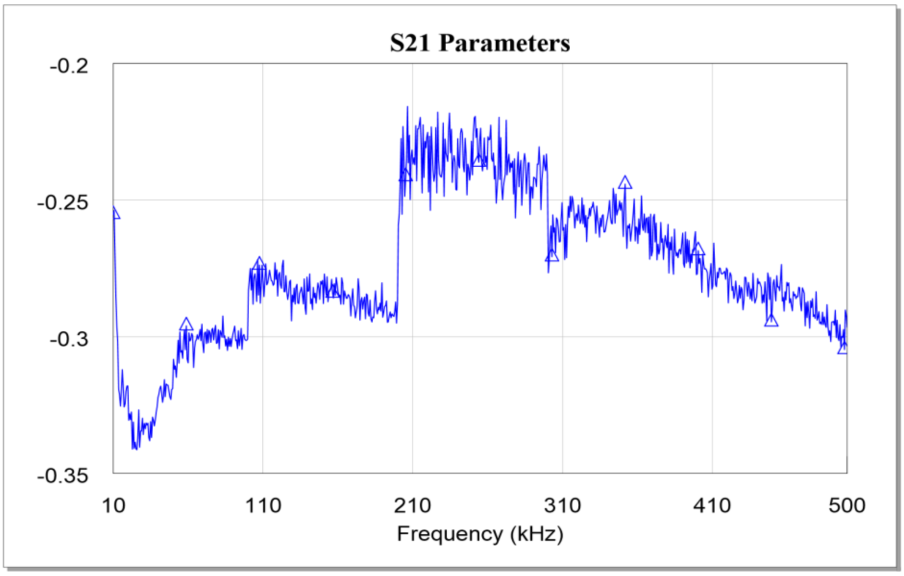

Figure 15 S21 Parameters

The insertion loss is also low at 136 kHz and can be seen in Figure 15.

4.3 Impedance Characteristics of Transformer at PLC Frequency Band

Modelling of a transformer is a critical concept for PLC. There has been ongoing research on modelling power transformers for SWER line applications.[14] However, for modem applications it is enough to see the frequency response of the transformer. By using the frequency response, if any resonance occurs it will be found in the spectrum.

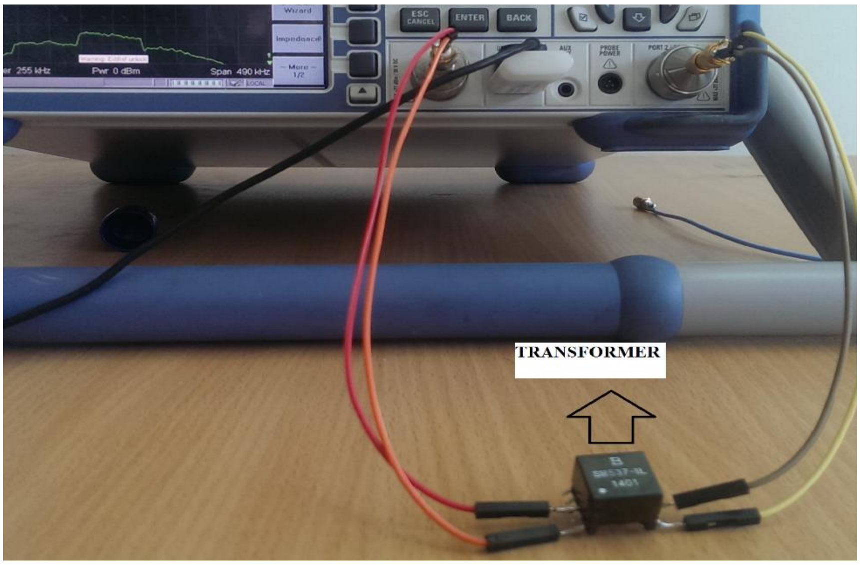

Figure 16 Impedance Measurement of Transformer

Transformer S parameters are generally used for estimating insertion and return loss. In the measurements taken at Yildiz the insertion loss was 0.4752 dB and return loss was 16.68 dB as shown in Figure 17. Moreover, the transformer didn't have any resonance on the narrow PLC frequency band.

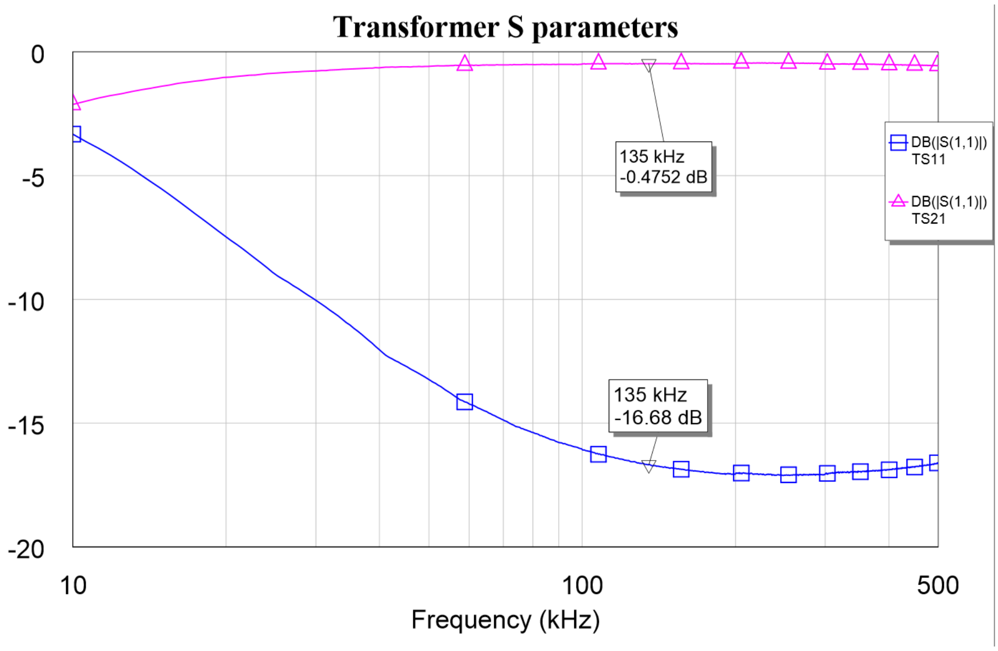

Figure 17 S parameter of Transformer

In Figure 18, the magnitude of transformer impedance is shown and its value change sharply between 10 kHz to 110 kHz, later the value stabilizes around 60 ohm. Since the magnitude consists of both real and imaginary parts, those values are also shown in Figure 19.

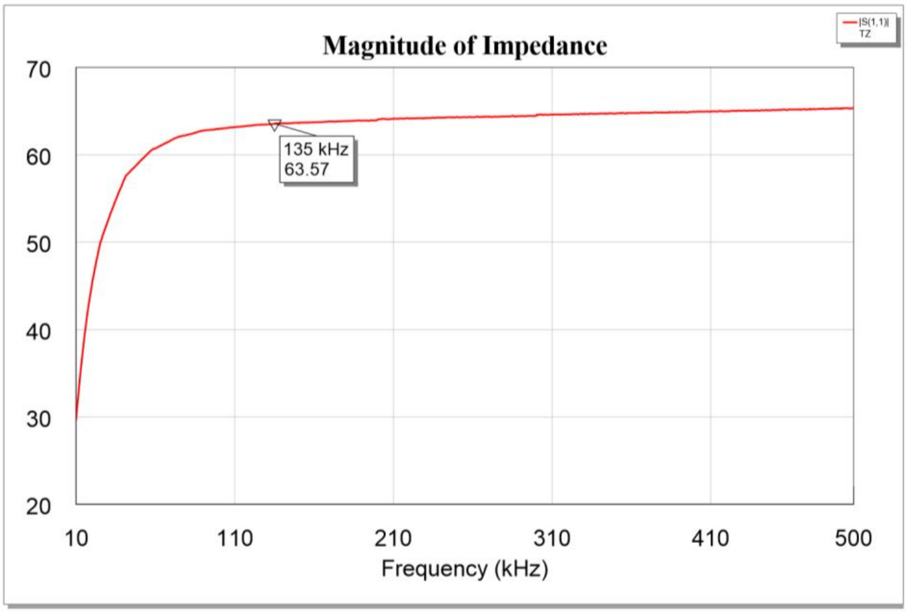

Figure 18 Magnitude of Impedance

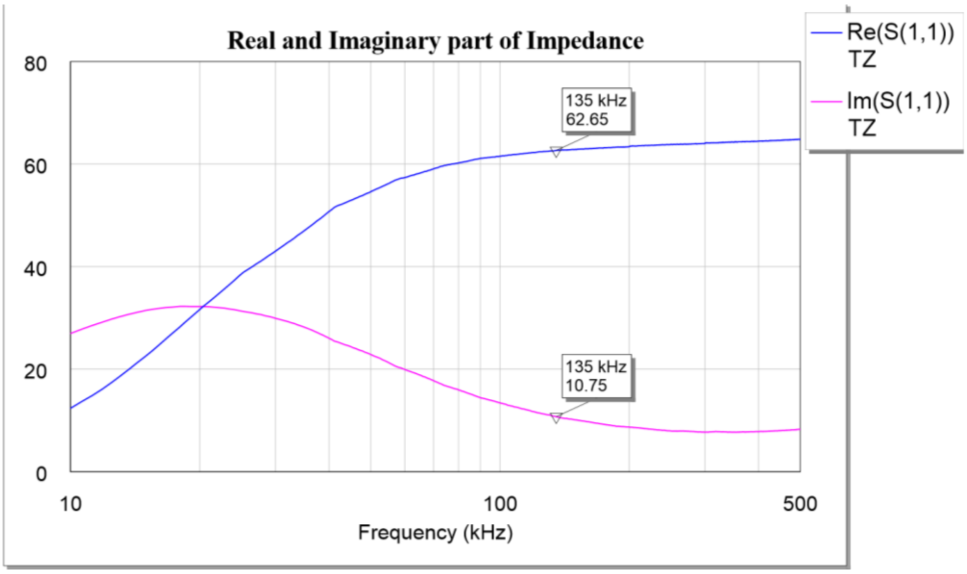

Figure 19 Real and Imaginary parts of Impedance

4.4 Analog Front End Chip by Texas Instrument

Texas Instrument specifically designed the Analog Front End (AFE03x) for power line applications and has eight different functional blocks. In table 5, these functional blocks are explained.

Table 4 Function of AFE[8]

PA	Power Amplifier and associated bias circuitry
TX	Tx_ Filter and Tx_PGA
RX	Rx_Filter and Rx_PGA1 and Rx_PGA2
ERX	Two wire receiver support circuitry
ETX	Two wire transmitter support circuitry
DAC	Digital to Analog Converter Block
ZC	Two zero crossing detectors
REF1	Midscale bias generator for PA block
REF2	Midscale bias generator for TX, RX, ERX, ETX blocks

AFE is the bridge between the analog and digital signal so its performance effects both. On the one side, AFE talks to the microcontroller by a serial peripheral interface and on the other side, AFE receives the analog signal from the power line.

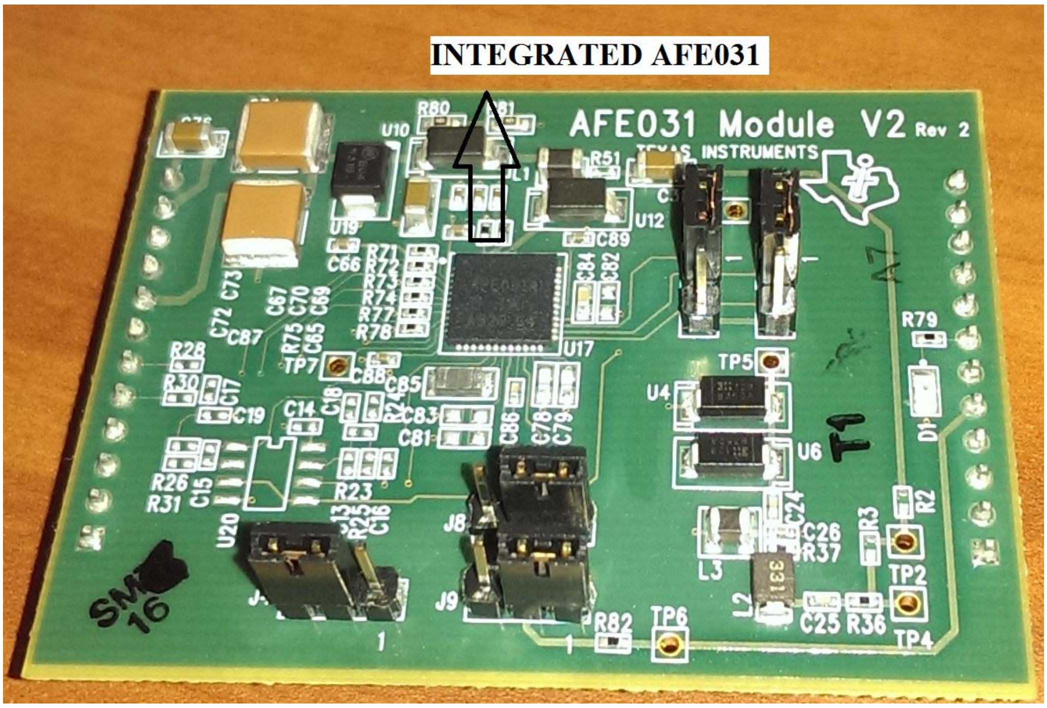

Figure 20 Integrated AFE031

AFE has four wires to transmit information to a processor such as the TMS320F28X. As illustrated in Figure 21, the pins have the following functions

- DIN : Data input driven by the master
- DOUT: Data output driven by the slave
- SCLK: Clock sourced by the SPI master
- CS: Chip select driven by the master to select the slave[8]

There are transmitter chains, receiver chains, a passive band pass filter, zero crossing detectors and two-wire support circuitry in the AFE. Starting from the transmitter chain, the path includes four separate circuit functions: DAC, Tx_PGA, Tx Filter, and the PA.

- The DAC block features a 10-bit, rail-to-rail DAC
- The TX programmable gain amplifier (PGA) features four different gains:

–12 dB, –6 dB, –3 dB, and 0 dB.

- The Tx Filter response works with either the Cenelec A band or the Cenelec B, C, and D bands
- The rate power amplifier block is up to 26 V at 1.5 A.[8]

The receiver chain includes three circuit functions which are Rx_PGA1, Rx Filter, and Rx_PGA2.

- The Rx_PGA1 has four different gains: –12 dB, –6 dB, 0 dB, and 6 dB
- The Rx Filter Response block can be adjusted for either the CENELEC A band or the CENELEC B, C, and D bands
- The Rx_PGA2 also has four different gains: 0 dB, 12 dB, 24 dB, and 36 dB[8]

The passive band pass filter has a degree of four orders and is suggested for applications where high performance is needed. Basically, the filter blocks any unwanted out-of-band signal from reaching the AFE.

The zero crossing block contains two independent zero crossing detectors. The purpose of these components is to detect a zero voltage level when the ac main signal is over-passed. This information is needed for synchronization purposes. In the design, only one zero crossing detector is used. However, depending on the phase, such as three-phase applications, multiple zero crossing detectors can be used.

Lastly, the two-wire support circuitry blocks ERX and ETX support two modulation techniques which are amplitude shift keying and on off modulation.

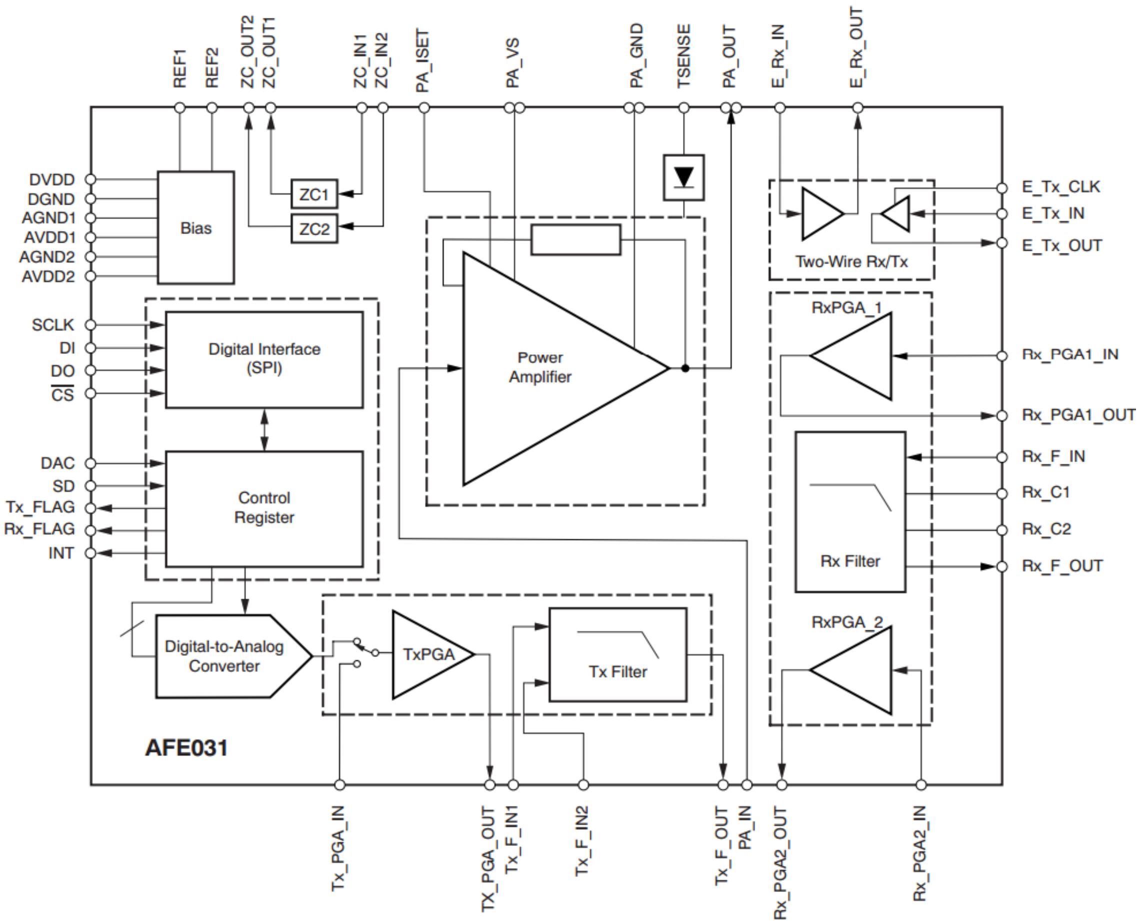

Figure 21 Function Blocks[8]

4.5 DSP Processors and Peripheral Explorer Kit

The Peripheral Explorer Kit is an evaluation board for experimenting with software in the C2000 F28x family of microprocessors. Texas Instrument provides communication protocols such as PLC-Lite and G3-PLC for the F28069 DSP processor. By the help of flashing hex code to the DSP processor, the Zero Configuration GUI can be used to send data or determine the quality of communication.

In Figure 22, the features of the peripheral explorer kit are illustrated which include audio-in, IR Receiver, PWM Pins, Potentiometer, etc. The Serial Peripheral Interface (SPI) is used for communicating between AFE and DSP. SOMI, SIMO and CLK pins are connected by jumpers between the designed modem and peripheral explorer kit. AFE needs two different voltage levels which are 3.3 V and 15 V. The peripheral explorer kit provides 3.3V, therefore an external power supply adapter was used to feed the designed modem.

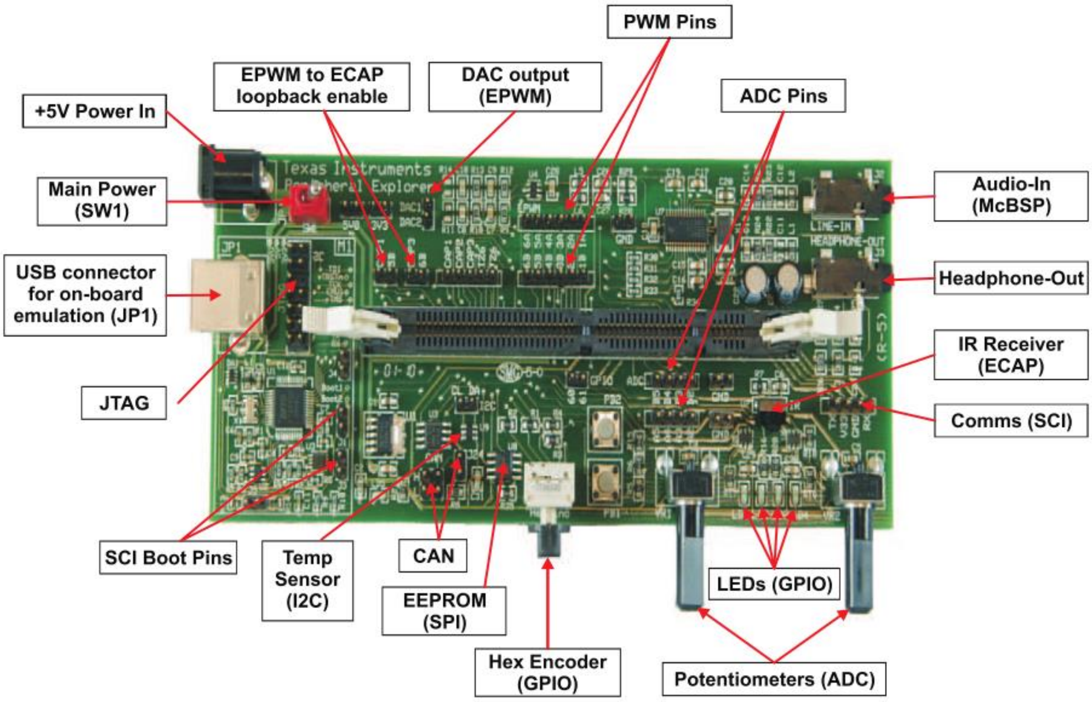

Figure 22 Key Features of kit[15]

4.6 Schematics and Layout of Modem

Based on a reference design by Texas Instruments, the AFE layer was drawn in the Altium Design Environment. In the reference design, different frequency bands can be configured by changing the capacitor values within the circuit. For example, Cenelec A B and C_1 and C_2 values are 680 pF and for Cenelec B, C and D band C_1 and C_2 the values are 270 pF and 570 pF, respectively. However, it is impractical to change the values of the capacitor when changing the frequency band. Therefore, all capacitors are placed in the AFE and it became possible to vary the frequency band by jumper selection as shown in Figure 23.

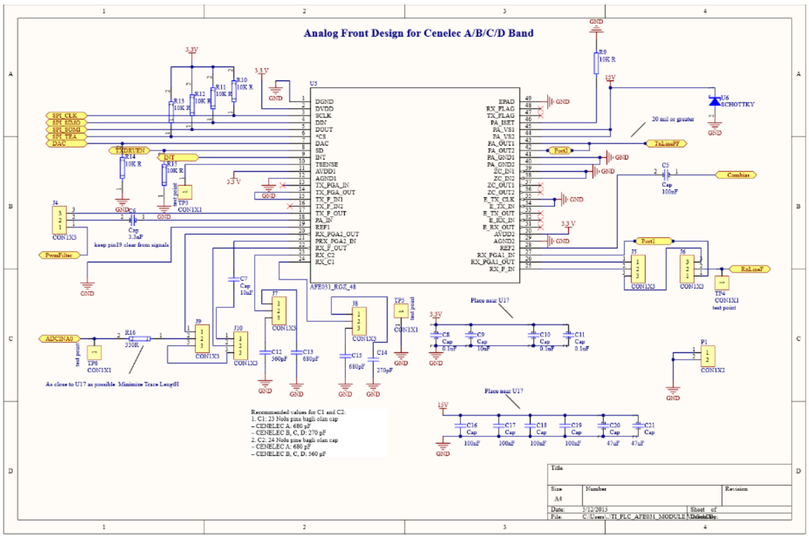

Figure 23 Analog Front Design for Cenelec A/B/C and D Band

In Figure 24 and 25, the passive RX filter and TX filter are schematized for both the receiver and transmitter chains. The filter’s main purpose is to block unwanted signal and pass the desired signal to the AFE Input. Filters are designed with schottky diodes, capacitors, resistors and inductors. A test point was placed in the schematic in order to find failure after manufacturing the board. Schottky diodes which can rectify up to 3 ampere and 1 ampere are used in the RX filter and TX filter respectively. As seen in Figure 26, the transformer circuit is directly connected to grid. As it is stated in chapter 2, the grid exists in noisy conditions. Therefore, a metal oxide varistor, transient voltage suppression diodes, schottky diodes and a zener diode is used in order to protect the AFE chip.

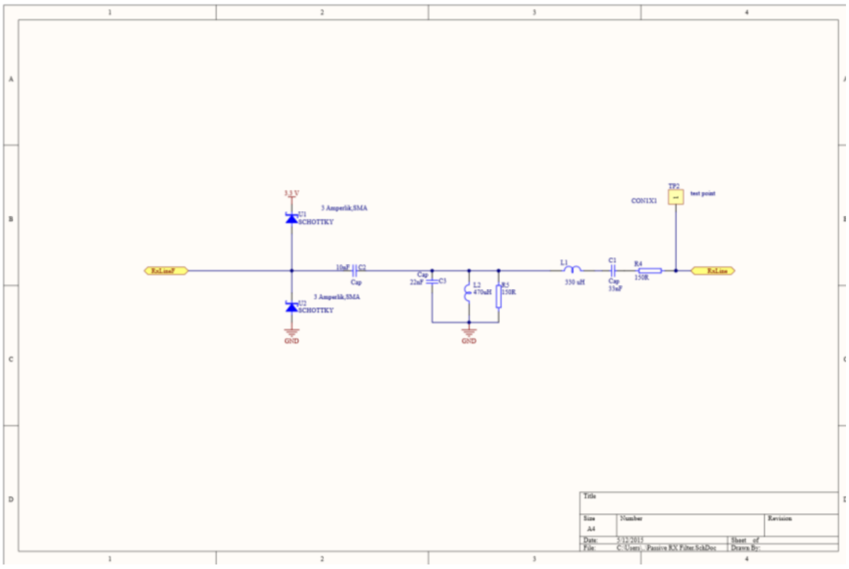

Figure 24 Passive RX Filter

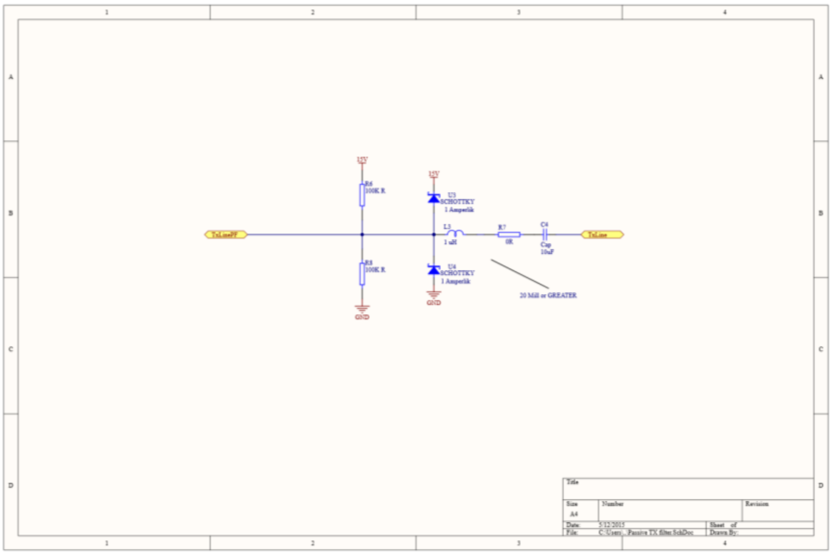

Figure 25 Passive TX Filter

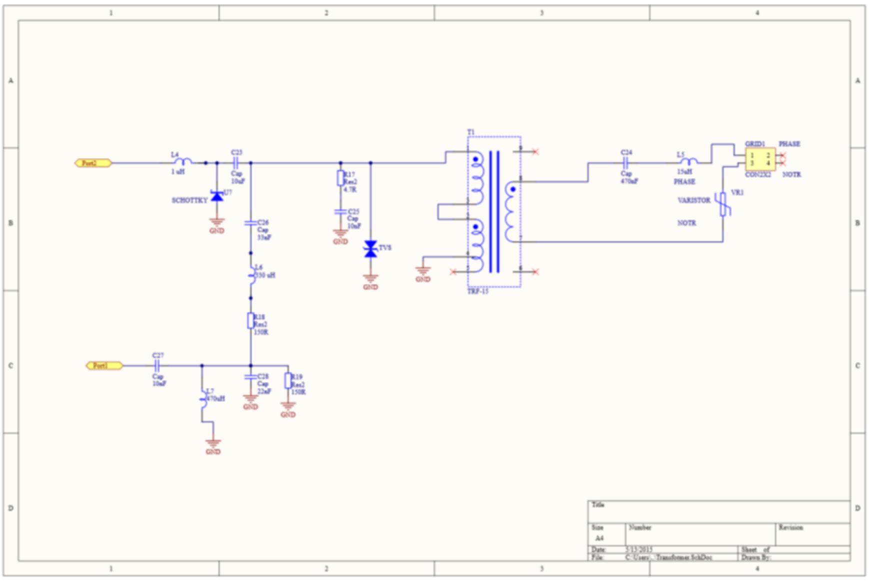

Figure 26 Transformer Circuit

In Figure 27, the layout of the transformer and AFE parts are shown. On one side of the board, there is a phase and notr connection to the grid and on the other side of the board, there are serial peripheral interface connections to the DSP Processors. The PLC modem will be completed by connecting the SPI pins to the DSP processor and connecting a 15V power supply. Any processor which support serial peripheral interface communication can be used as a PLC Modem as it can be seen in Figure 27.

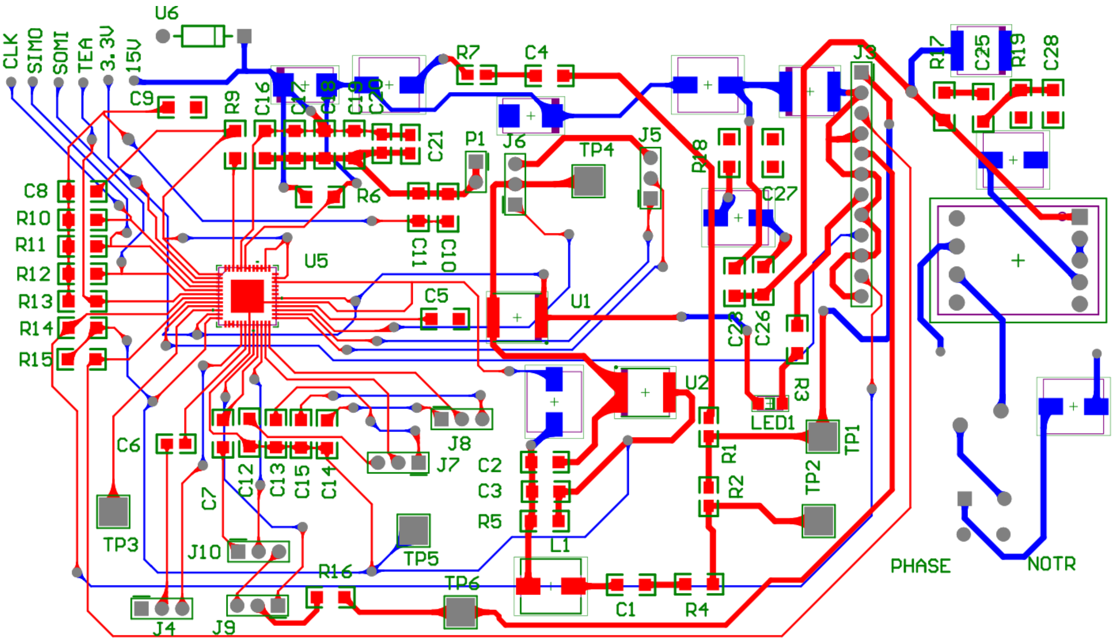

Figure 27 Layout of AFE and Transformer

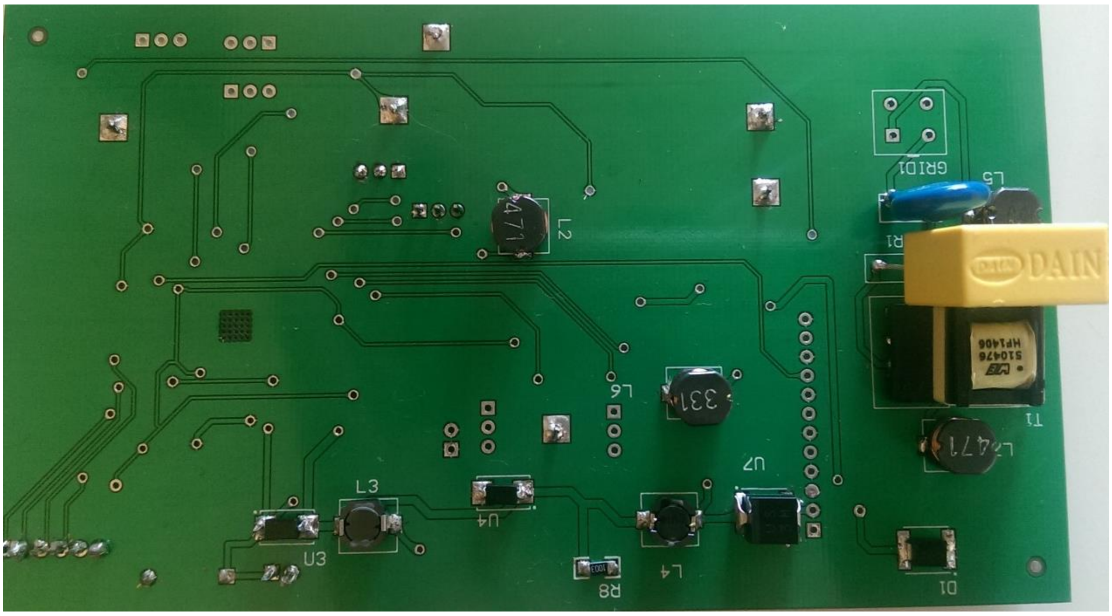

Figure 28 Bottom Side of AFE and Transformer

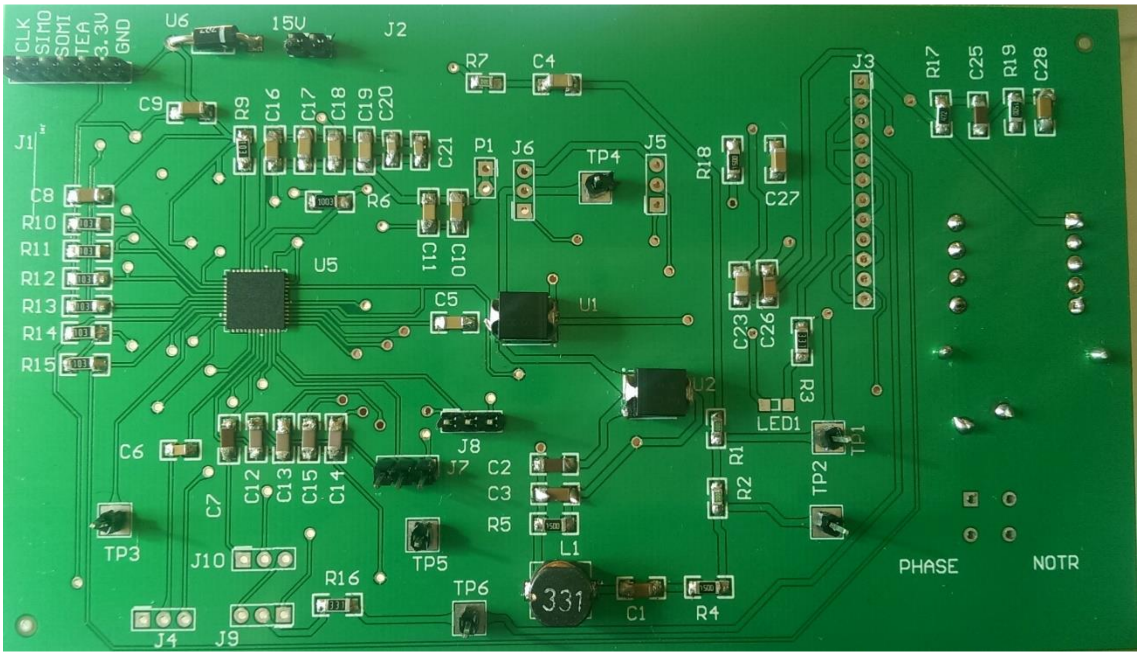

Figure 29 Top Side of AFE and Transformer

Transformer, varistor, high voltage capacitor and inductor were placed and soldered at the bottom layer as it can be seen in figure 28. Moreover, AFE chip, resistors and capacitors were placed and soldered at the top layer as it is shown in figure 29.

CHAPTER 5

RESULTS AND DISCUSSION

After testing the cables a varying impedance was found over the PLC frequencies. This impedance caused mismatch losses in the communication within the modem and these losses limit the area coverage of the communication. To decrease these losses matching the impedance of the cables to the modem transmitter should be done using adaptive matching techniques. A repeater can also be used to achieve wider coverage.

When testing the reference PLC modem in the Smart Home the objective was to better understand the point-to-point communication quality by looking at the signal-to-noise ratio, bit error rate and log bit error rate parameters. These parameters indicated that a stable communication was established in the Smart Home.

The impedance of the transformer was found not to have any resonance in the PLC Frequency band. This result is very important because any resonance caused by the transformer can abolish communication between the transmitter and receiver.

Finally, a PLC Modem was schematized and merged into one layer so the design modem was smaller than the reference original.

Further research should be done on measuring medium and high voltage cables. In terms of the PLC modem, the current DSP processor is expensive and more powerful than what is needed. A PLC Modem with a less powerful processor should be tested under different loads in order to investigate the communication quality.

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