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Bachelor Thesis

Smart metering and injection coil implementation for smart grid diagnostics

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First name and surname: **Mohamed SAIF ELDIN SALIH ABDOON**
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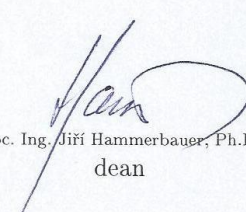
1. Analyze available injection coils.
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3. Design the injection coil compliant with CENELEC band A standard.
4. Implement the WM-BUS protocol in an embedded device.
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Tutor for dissertation: **Ing. Aleš Krutina**
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Doc. Ing. Jiří Hammerbauer, Ph.D.
dean




Doc. Dr. Ing. Vjačeslav Georgiev
Head of Department

dated: 14 October 2013

Abstract

This thesis focuses on the analysis and methods of implementing Wireless M-Bus on an embedded device. The thesis also describes the features and some of the drawbacks in the available protocols used for communications in smart grids (SG) today, and shows the procedure and the results of implementing the Wireless M-Bus protocol in an embedded device. It also analyzes some of the available injection coils used for Power Line Communications (PLC), and then it describes the design procedure of an injection coil according to the CENELEC band A standard and its features.

Key words

Wireless M-Bus, smart grid, PLC, ZigBee, communication

Declaration

I declare that this Bachelor thesis has been written only by myself using the literature provided at the references section.

I also declare that the software used for writing, preparing and simulating the tasks in this Bachelor thesis is legal.

.....

Signature

Acknowledgment

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List of abbreviations

4G	Fourth Generation of cellular networks
Access No.	Access Number
ACD	ACcess on Demand
AES	Advanced Encryption Standard
BAN	Building Area Network
Bi.	Bidirectional
CENELEC	European Committee for Electrotechnical Standardization
Conf.	Configuration
CRC	Cyclic Redundancy Check
DC	Direct Current
DES	Data Encryption Standard
DFC	Data Flow Control
DIF	Data Information Field
DIFE	Data Information Field Extension
FCB	Frame Count Bit
FCV	Frame Count Valid
FFD	Full Function Device
FIFO	First In First Out
Freq.	Frequency
GPRS	General Radio Packet Service
HAN	Home Area Network
Hex.	Hexadecimal
ID	IDentification
Ident. No.	Identification Number
IEEE	Institute of Electrical and Electronics Engineers
IEEE	Institute of Electrical and Electronics Engineers
ISM	Industrial Scientific Medical
ISO	International Organization for Standardization
Kcs	Kilo chip per second
KHz	KiloHertz

Man. ID	Manufacturer IDentification
MHz	MegaHertz
NAN	Neighborhood Area Network
OSI	Open Systems Interconnection
p.error	Permanent error
PAN	Personal Area Network
PCB	Printed Circuit Board
PLC	Power Line Communication
Post.	Postamble
Pre.	Preamble
PRM	Primary
PSpice	Software for circuit simulation
RES	Reserved
RFD	Reduced Function Device
SG	Smart Grid
Sign.	Signature
SRD	Short Range devices
t.error	Temporary error
Uni.	Unidirectional
USB	Universal Serial Bus
VIF	Value Information Field
VIFE	Value Information Field Extension
WAN	Wide Area Network
Wi-Fi	Wireless Local Area Network device
Wireless M-Bus	Wireless standard for smart grid communication
WLAN	Wireless Local Area Network
ZigBee	Wireless standard for smart grid communication
Z-Wave	Wireless standard for smart grid communication

1 Introduction

Ever since the consumption and dependency of users on the power grid started to grow, power providers needed to start billing consumers for the amount of energy they were using. In early days only mega factories and huge corporations were billed a fixed amount of money, but as the demand on electricity supply kept increasing power providers started to charge individual consumers for the use of energy. This meant that electricity meters had to be installed and power suppliers had to employ a work force to get meter readings from different users around the country.

The technological advancements in electronics and communications brought the idea of the Smart Grid (SG). The SG concept had a huge potential and many applications, it could theoretically offer bidirectional communication between all the devices which are connected to the network thus, allowing the suppliers to remotely diagnose and monitor the number of devices connected to the network. In addition they could also monitor their consumption, peak times and duration of operation. However this also means that the consumer can now monitor and adjust his power consumption, to be as efficient as possible, this eventually means that with the introduction of the SG the user has a bigger role in the determination of the amount of energy used.

The smart grid communication topology is divided into hierarchal groups which are Wide Area Network (WAN), Neighborhood Area Network (NAN), Building Area Network (BAN), and Home Area Network (HAN).

The next paragraphs will explain these communication topologies, followed by a figure to illustrate and summarize the different topologies.

- Wide Area Network (WAN): Is on the top of the hierarchy of networks, WAN allows the long distance communication between the control centers and the NAN. [1]
- Neighborhood Area Network (NAN): The NAN serves as an administrator network which monitors and gives real time readings of power consumption in a particular neighborhood or area in a city. It is also able to determine the amount of power received from different distributing stations to the area it is connected to. A NAN can be thought of as a reporter it gathers information from the several HANs connected to it and reports them to the WAN. [1]

- Home Area Network (HAN): This sits at the bottom of the hierarchy, and is defined as the user's network, it can be a group of home appliances connected together, or energy meters which enable the user to monitor and adjust his power consumption accordingly.[1]

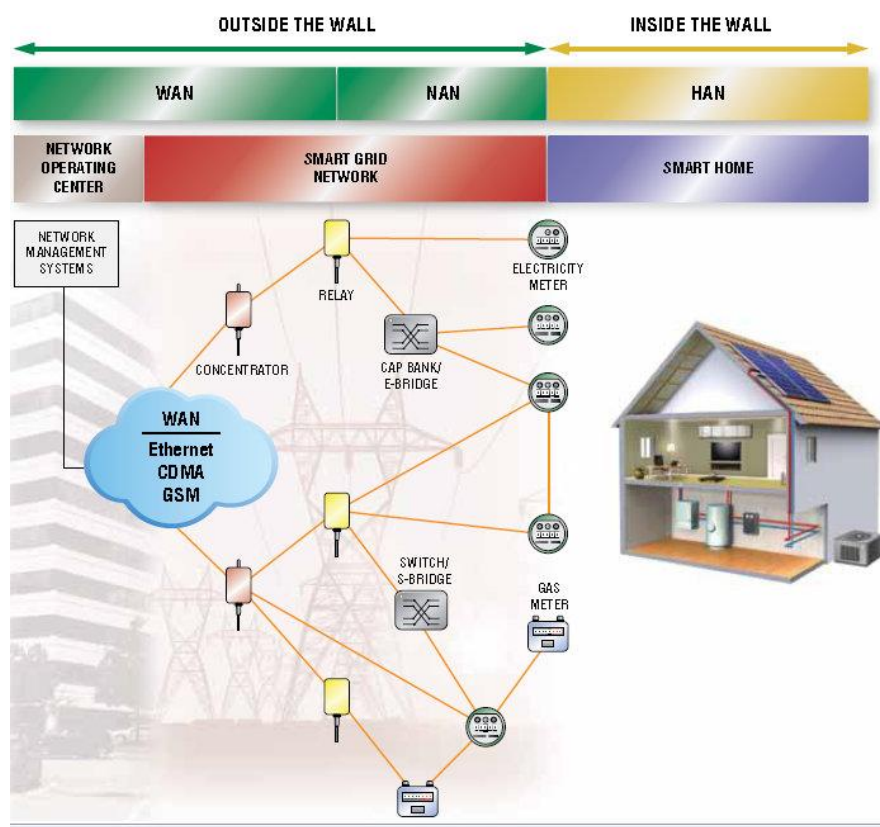


Figure 1 System topology [2]

The introduction of SG brings the need to use communication protocols, to insure the interoperability of the devices connected to the grid, these protocols should be reliable, secure, energy efficient and robust enough to suit the requirements of the devices which will be connected to the network.

It is important to properly choose communication methods that will satisfy the requirements of the smart grid. Therefore, standard communication protocols should be implemented into the grid, these communication protocols will ensure the interoperability of the grid with systems of enormous numbers, and various types that will be connected to the grid.

A grid which requires a lot of modems and concentrators along the transmission line will be impractical, because it increases the demand of its operation on the provider, meaning that it

requires more maintenance and an additional work force has to be employed in order to ensure that it is operating efficiently. In many cases there is a compromise between the cost of designing and running a communication network, and the amount of bandwidth available to handle the data sent between the devices in the grid.

In order to minimize the cost of designing and building the infrastructure for the communication in the grid, it is good to utilize some of the existing infrastructure in order to eliminate the need to construct a physical layer to connect the networks. The following chapter will introduce some of the communication protocols used in SGs today.

2 Wireless protocols used in smart grid communications

The rapid advancements in wireless technologies are slowly eliminating the need to install wired infrastructure to be used for smart grid communication purposes, wireless networks are also less prone to interference and external noises. Today, there are various protocols used in smart grid communications, this is due to the fact that the smart grid standards are not yet defined. Therefore, users usually choose a communication protocol which suits their limited application. The communication technologies range from short range technologies that span a distance of a few meters to long distance technologies. Short range technologies include EN 13757-4 (Wireless M-Bus), IEEE 802.15.4 (ZigBee), IEEE 802.11 (Wi-Fi), Z-Wave and Bluetooth. These standards could be used to establish communication between devices within the HAN. Long distance technologies include GPRS and 4G these are technologies which utilize the existence of cellular networks and their infrastructure, they can be used to connect the HAN with NAN.

In the next sections Wireless M-Bus will be introduced and explained in detail, followed by an introduction to ZigBee technology, the rest of the communication technologies namely Wi-Fi, Z-Wave, Bluetooth and Bluetooth Low Energy will be discussed just briefly.

2.1 Wireless M-Bus

M-Bus is a European standard which is specific for meter reading applications. At first communication was established and optimized for use in Power line communications (PLC) using a pair of twisted wires, this meant that it was very cost effective and easy to realize. Later the Wireless M-Bus standard was developed, which is specified to work on the Industrial, Scientific and Medical (ISM) radio bands at 169, 433 and 868 MHz.

2.1.1 Principle of operation

The M-Bus protocol simply gathers information from the energy meters and handles them to the data concentrators or data collectors. Figure 2 describes the connection between the devices when using Wireless M-Bus. Since the M-Bus protocol works on a hierarchical topology the energy meters are considered to be “slaves” and their operation is controlled by a data concentrator or data collector known as a “master”. Once the information is received by the

concentrator or collector, it could then be sent by several means for e.g. PLC, Internet, WLAN, ZigBee and many more to any party which is interested in gathering the information.

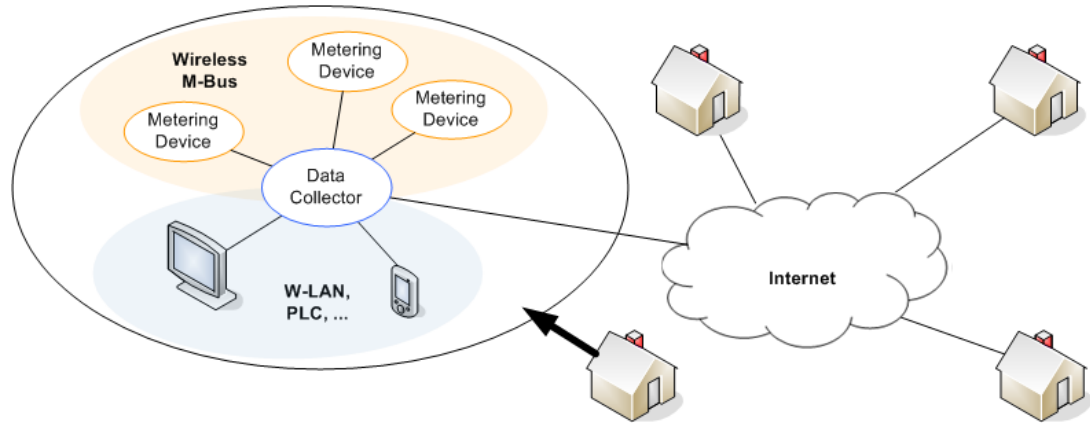


Figure 2 Wireless M-Bus connection [3]

2.1.2 Wireless M-Bus Sub-modes

Wireless M-Bus has several operation modes the most used are named S, T and R. These modes are then split into different configurations S1, S1-m, S2, T1, T2, and R2. The difference between these sub-modes is in the configuration of duty cycles, frequencies, preamble and postamble lengths. Other sub-modes also exist for example C, N and F they will be explained only briefly since they are not commonly used.

The following table describes some of the differences in configuration of these modes.

Mode	Freq.	Pre.	Post.	Sync.	Duty Cycle	Chip Rate	Direction	Notes
Unit	MHz	Chips	Chips	Hex.	%	kcs	-	-
S1	868.25-868.35	576	2-8	0x7696	1	32.768	Uni.	
S1-m	868.25-868.35	48	2-8	0x7696	1	32.768	Uni.	
S2	868.28-868.32	48	2-8	0x7696	1	32.768	Bi.	
T1	868.9-869.0	48	2-8	0x3D	0.1	100	Uni.	Meter to other
T2	868.9-869.0/868.28-868.32	48	2-8	0x3D	0.1/1	100/32.768	Bi.	Meter to other/other to meter
R2	868.330 + n×0.006	96	2-8	0x7696	1	4.8	Bi.	

Table 1 General requirements for Wireless M-Bus sub-modes [4]

2.1.2.1 S mode (Stationary mode)

- S1 (long header): Is a unidirectional way of communication from a meter to other device using Manchester encoding. Since it is unidirectional the meter has no feedback if the data has been sent or not. This mode is most suitable for battery powered receivers because of the long header.
- S1-m (short header): Is a unidirectional way of communication similar to S1, however a short header is used and that's why it requires a continuously enabled receiver.
- S2 (short or long header): Is a bidirectional way of communication using Manchester encoding. The choice between short header or long header means that the receiver can be continuously enabled or synchronized to wake up when the meter transmits its data.

2.1.2.2 T mode (Frequent transmit mode)

- T1 (short header): Unidirectional way of communication using 3 to 6 encoding. It transmits frequently several times every second, the data is transmitted in very short bursts typically < 5 ms. This makes it ideal for use in walk by or drive by read out method.
- T2 (short header): Bidirectional way of communication. Both Manchester and 3 to 6 encoding could be used. The bidirectional communication allows the receiver to be enabled only when transmission occurs.

2.1.2.3 R mode (Frequent receive mode)

R2 (medium header): Bidirectional way of communication using Manchester encoding. This mode is most optimized for battery saving receivers, therefore it requires an extended preamble before the other blocks to wake up the receiver. It uses frequency multiplexing and therefore several meters can be read at once, however the center frequency of transmitters must be spaced at 60 KHz, some transmission delays must also be taken into account to prevent the signals interfering with each other.

2.1.2.4 C,N and F modes

These modes attempt to rectify some of the drawbacks of the other modes by offering alternate operating frequencies such as 868 MHz, 433MHz and 169 MHz or faster data rates.

2.1.3 Wireless M-Bus Layers

The M-Bus follows the Open Systems Interconnection (OSI) model, which is specified by the International Organization for Standardization (ISO) which ensures the interoperability of devices made by different manufacturers. This is achieved by defining the communication functions of the devices. Table 2 describes the OSI Model [5]

7	Application Layer	
6	Presentation Layer	Application Oriented Layers
5	Session Layer	
4	Transport Layer	
3	Network Layer	Transport Oriented Layers
2	Data Link Layer	
1	Physical Layer	

Table 2 OSI model

The M-Bus protocol defines 4 of the 7 layers defined by the (OSI), one of them being an optional layer which is the network layer. The reason behind this is that the M-Bus is not a network, therefore it does not require a transport layer, session layer and presentation layer. [5] Therefore, we can reduce the previous table to be as follows in table 3. In the next sections the details of these layers will be explained in detail.

3	Application Layer
2	Data Link Layer
1	Physical Layer

Table 3 Wireless M-Bus stack

2.1.3.1 Physical Layer

The physical layer defines the physical requirements to establish communication between a meter to other or other to meter. The physical layer defines parameters such as frequency, modulation type, and chip rate. The sub-modes mentioned previously are a part of the physical layer configuration. Look into table 1.

2.1.3.2 Data Link Layer

Data link layer defines and organizes the structure and format by which the data packet is sent, and by which the data packet is recognized by the receiver. Figure 3 describes the general format used for Wireless M-Bus also known as “Frame Format A”. It is also necessary to mention that the EN 13757-4:2011 standard also specifies another frame format known as

“Frame Format B” however, this format is specified to be used optionally by modes C, N and F. The aim of introducing frame format B is to reduce the size of the sent data. In the our thesis explanation will be restricted to only frame format A, and in the following paragraphs and sections frame format A will be described in detail.

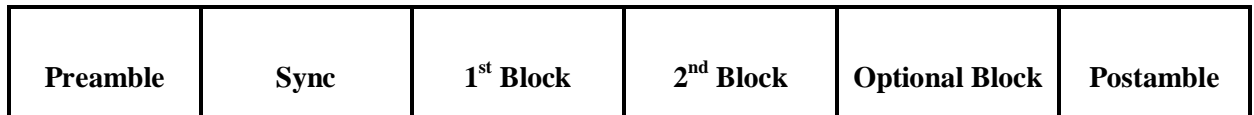


Figure 3 Wireless M-Bus frame format

Please look into table 1 for the description of Preamble, Sync and Postamble. The following figure describes the structure of the 1st Block.

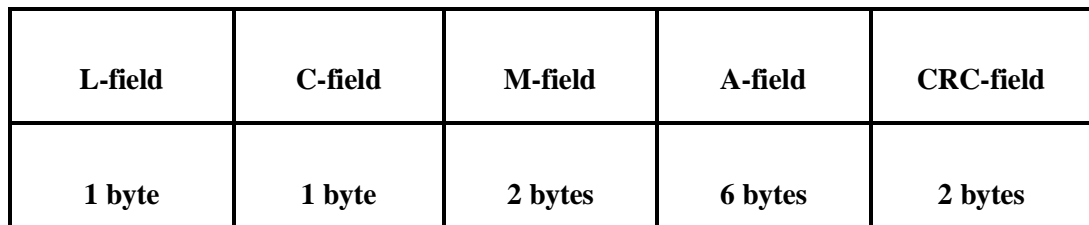


Figure 4 1st Block structure

- L-field: Is known as the Length field. Defines the total size of the user fields from (0 to 255) bytes without including the size of the L-field and the CRC-field.
- C-field: Is known as Control field. It defines the type of the sent data packet, for example (send, request, receive, acknowledge). Figure 5 describes the structure of the C-field.



Figure 5 structure of C-field [3]

The total length of this field is 8 bits or 1 byte, where the function code occupies the positions from [3:0], the FCV or DFC have position [4], FCB or ACD have position [5], PRM has position [6] and RES has position [7].

- RES: Stands for the reserved bit, and is usually set to 0.

- PRM: Stands for primary, which means that if the data packet is sent from a primary source for example a data concentrator or a meter the PRM field is set to 1. If the data packet is sent from a secondary source then the PRM field is set to 0. However, the definition of this bit should be specified by the user in order to satisfy his application requirements. If this bit is set to 1 then bits [4] and [5] are FCB and FCV, otherwise they are considered as ACD and DFC.
- FCB: Stands for Frame Count Bit. This field monitors the duplication in the sent packets from the primary station to the secondary station. The value of this field should cycle between 0 and 1.
- ACD: Stands for ACcess on Demand. When this bit is set to 1, it indicates that the secondary station (defined by user) has high priority data available. This high priority data however must be first requested by the primary station.
- FCV: Stands for Frame Count Valid. Briefly if this bit is set to 1, it means that FCB is activated or in other words is valid.
- DFC: Stands for Data Flow Control. If this bit is set to 1 it means that the secondary station cannot receive any further packets from the primary station.
- Function code: These bits define the type of the data packet (send, request, receive, acknowledge).
- M-field: Is known as the Manufacturer field and the manufacturer ID is represented here.
- A-field: Is known as the Address field. This field represents the device's unique address information. The format of the A-field is as follows:
 - ID number = 4 bytes
 - Device version = 1 byte
 - Meter type = 1 byte
- CRC field: Is known as Cyclic Redundancy Check field. The CRC polynomial used is:

$$x^{16} + x^{13} + x^{12} + x^{11} + x^{10} + x^8 + x^6 + x^5 + x^2 + 1.$$

All the information above was describing the structure of the 1st Block. The following figure describes the structure of the 2nd Block.

CI-field	Data-field	CRC-field
1 byte	15 bytes	2 bytes

Figure 6 2nd Block Structure

- **CI-field:** Is known as the Control Information field. This field gives information about the following data using predefined hexadecimal definitions. The information present here can be alarm message, data from meter, short header, long header, etc.

After the CI-field follows the data field, which can be up to 15 bytes, however if more than 15 bytes are required then multiple Optional Blocks may follow. The next figure describes the structure of the Optional Block.

Data-field	CRC-field
16 bytes	2 bytes

Figure 7 Optional Block Structure

2.1.3.3 Application Layer

Strictly speaking, a data payload could be sent as a lump of data in the Data-field of the 2nd Block. However, sending data this way does not fully satisfy the Wireless M-Bus standards especially, when the task is to integrate a network of different types of meters e.g. (water, heat gas etc).

In this final section of the description of Wireless M-Bus layers, the complete overview of the layers will be shown and their arrangement within one another will be described. In simple words the application layer organizes the structure of the Data-field. The next figure shows where the application layer plays its role, as well as showing an overview of the whole packet.

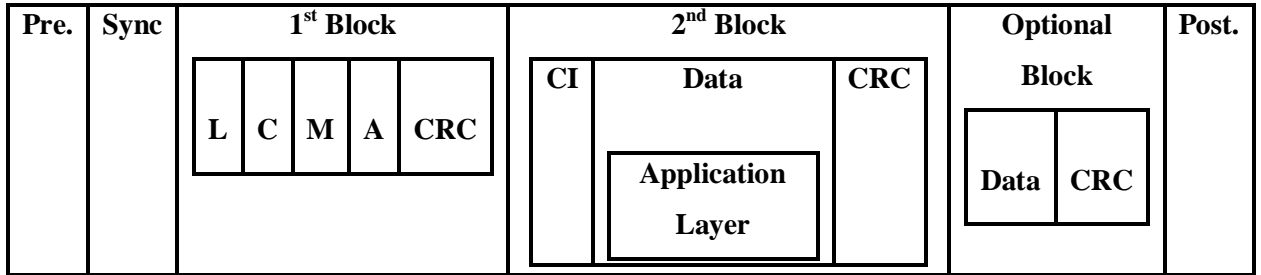


Figure 8 Wireless M-Bus layers overview

In the figure above the inner structure of every Block of the Wireless M-Bus frame format is shown. L,C,M,A and CRC represent the Length, Control, Manufacture, Address and Cyclic Redundancy Check fields respectively, all of which are present within the 1st Block itself. CI represents the Control Information field, while the application Layer's position can be seen within the Data Block inside the 2nd Block. The following figure describes the structure of the application layer.

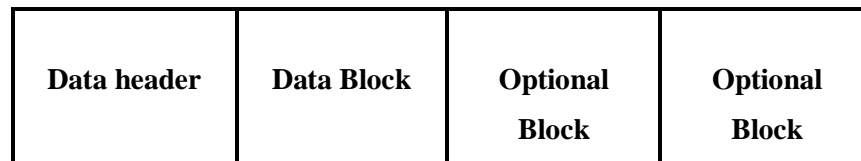


Figure 9 Structure of application layer

According to Wireless M-Bus there are three formats which can be used to configure the Data header, these formats are known as Long header, Short header and No header.

2.1.3.3.1 Short header

The short header has a total of 4 bytes and it contains three blocks Access number, Status and Configuration word or Signature. Figure 10 describes the structure of the short header.

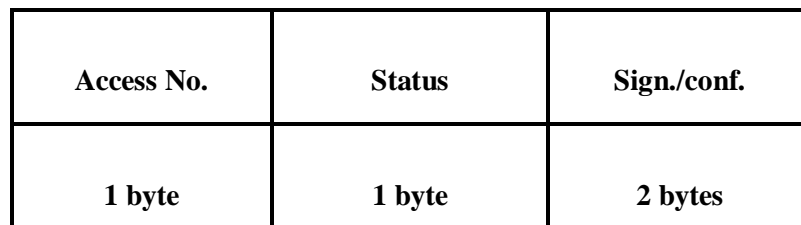


Figure 10 Structure of short header

- Access number: This field is intended to detect the repetition of data frames, or requests from other Wireless M-bus devices to read data, so if the same Access number is repeated then the data should be denied. According to the standard this field could also be used to detect any unwanted or multiple attempts to read the data of the consumer. The field uses binary coding and it is incremented by one after every request from a device. [5]
- Status: This field indicates the status of the device according to the standard. The bit positions from 0 to 8 can be configured to indicate the status as shown in figure 11.

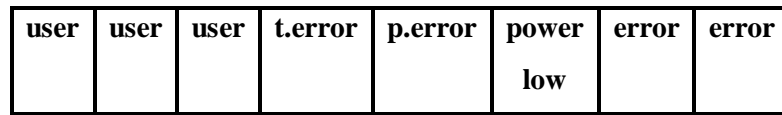


Figure 11 Structure of status-field

Bits 0 and 1 should be set together to define a specific error for example: 00 = no error, 01 = Application busy etc. Bit 2 indicates power low. Bit 3 indicates an availability of a permanent error or not. Bit 4 indicates the availability of a temporary error while bits 5, 6 and 7 can be defined by the user.

- Signature or Configuration word: This field is specific for the encryption settings. If no encryption is available then the field is set as zeros. The user can choose DES or AES encryption.

The short header is advised to be used with wireless to wireless or wired to wired devices, while the more complex long header could be used to link wired to wireless or vice versa.

2.1.3.3.2 Long header

The long header includes in its format the short header as well. It consists of 12 bytes instead of 4 bytes for the short header. The next figure describes the structure of the long header.

Ident. No.	Man. ID	Version	Device type	Access No.	Status	Sign. / conf.
4 bytes	2 bytes	1 byte	1 byte	1 byte	1 byte	2 bytes

Figure 12 Structure of Long header

- Identification number: Is a number that can be fixed by the user or can be specified during the manufacture of the device itself.
- Manufacturer Identification: Manufacturer ID according to EN 61107.
- Version: This field represents the version of the device i.e. old version or a later version of the device.
- Device type: This field indicates the type of the meter readout for example water, oil, gas, etc. look into table 4.

Type	Binary code
Oil	0000 0001
Electricity	0000 0010
Gas	0000 0011
Water	0000 0111
Compressed Air	0000 1001
Other	0000 0000

Table 4 Device types binary representations [5]

2.1.3.3.3 No header

No header simply means that no header will be available and, thus no encryption for the data will be available. It is not recommended to use this format especially when running a network of consumer devices, since this makes the consumer data vulnerable to hackers and eavesdroppers.

2.1.3.3.4 Data Block

This section shows how the data block should be structured, it is required to provide some sort of data header before transmitting the actual records acquired from the meter. The next figure shows the structure of the data block.

DIF	DIFE	VIF	VIFE	Data
1 byte	(0-10) × 1 byte	1 byte	(0-10) × 1 byte	0-n bytes

Figure 13 Structure of the data block

- **DIF:** Is known as the Data Information Field, this field shows how the upcoming data should be decoded according to predefined codes.
- **DIFE:** Is known as the Data Information Field Extension, this field is an optional field and contains information such as the tariff and the device unit.
- **VIF:** Is known as the Value Information Field. This field refers to the values of the acquired data, meaning that it contains information such as the units and range of the data for example (0.001 V to 1000 V).
- **VIFE:** Is known as the Value Information Field Extension. Similar to the DIFE field this is also an optional field, it contains additional information such as units description, tariff description, storage of the device and data and time.
- **Data:** The data acquired by the meter should be present here. The length of the data here is limited to a maximum of 234 bytes in order not to exceed the maximum size of the whole packet which is 255 bytes.

2.2 ZigBee vs. Wireless M-Bus and other technologies

The main purpose of introducing ZigBee here is to compare its features and capabilities to Wireless M-Bus, since ZigBee is considered one of the most popular and main rivals or alternatives to Wireless M-Bus. Therefore, an introduction to the ZigBee technology and IEEE 802.15.4 standard will be reviewed, while other technologies such as IEEE 802.11 (Wi-Fi),

Z-Wave and Bluetooth will be discussed just briefly.

While Wireless M-Bus was originally specified to work with energy meters, ZigBee has a more general approach, it is not only specific to energy meters but could be used in many other applications. ZigBee is based on the IEEE 802.15.4 standard. This standard defines the data rates, the operation frequencies and bandwidth of ZigBee. The ZigBee could be optimized to work on different bands, these bands are (SRD) band 868.0 - 868.6 MHz in Europe, (ISM) 902 – 928 MHz in North America and 2.4 – 2.483 GHz Worldwide.

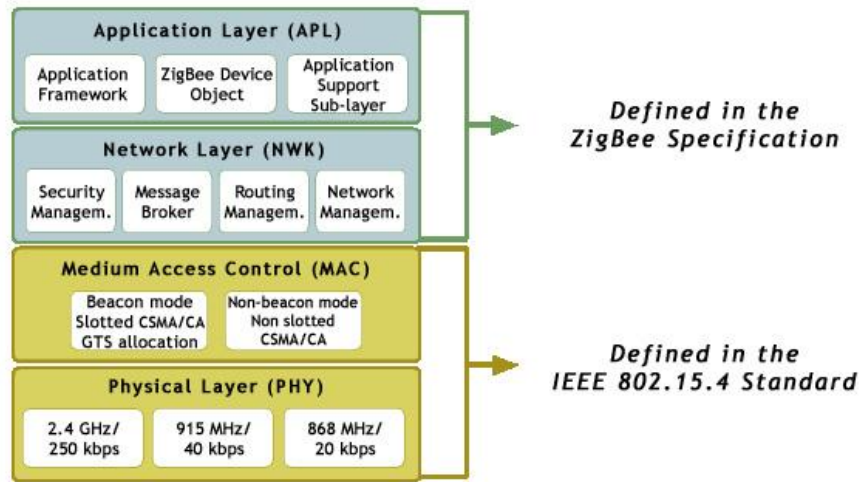


Figure 14 Structure of ZigBee [6]

2.2.1 Connection topologies

The ZigBee protocol has three possible connection topologies which are defined by the IEEE 802.15.4 standard. These topologies are star, cluster tree and peer to peer. Figure 15 shows the different ZigBee network topologies.

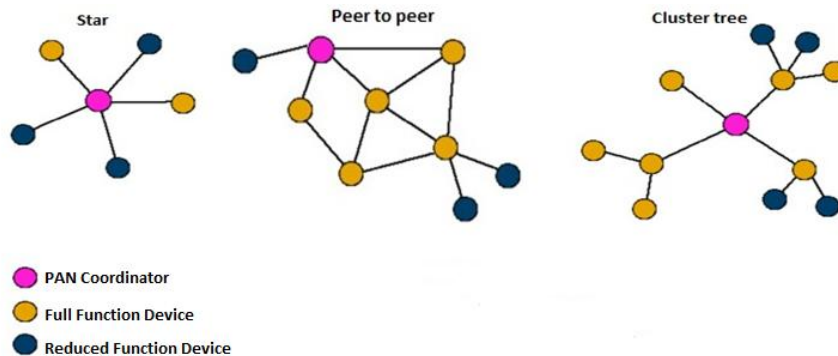


Figure 15 Network topologies [6]

In the star connection every device whether an (FFD) or and (RFD) can only communicate with the (PAN) coordinator. Star topology offers easy connectivity with the PAN coordinator, however star topology is very PAN coordinator dependant, meaning that if the PAN coordinator fails or slows down, it slows or shuts down the whole network. Peer to peer topology sometimes called mesh topology, could be thought of as an open connection because all of the devices whether FFD or RFD could connect together or independently in order to reach the PAN coordinator. This means that the devices will find the easiest and shortest way to transfer the information from the source to the end point. Tree or Cluster tree topology consists of a main PAN coordinator and FFD devices both of them act like parents which means that RFD devices in this case children could be connected to them. RFD devices cannot act as parents which means they can only send the information but they cannot act as a bridge between the coordinator and the source. Cluster tree differs from normal tree by having a unique ID for every parent and its children hence, creating a cluster. [7]

2.2.2 IEEE 802.15.4 standard

As mentioned above the ZigBee protocol is based on the IEEE 802.15.4 standard, this standard defines the physical layer which includes the data packets, operating frequencies connection topologies which were mentioned above and also the data link layer known as the MAC layer.

2.2.3 Discussion: To ZigBee or Wireless M-Bus or others

The ZigBee protocol is oriented towards being used in applications where low power, and low data rates are being used with a requirement for long battery life. ZigBee technology is used mainly in small areas as it can be an ideal solution for HAN communication and unlike Wireless M-Bus, ZigBee protocol is not only limited to being used for energy meters, but it can be used in home automation to control a variety of consumer appliances, it could also be used to control lights, doors, alarms and many more. Today there is a big movement from manufacturers to produce appliances supporting the ZigBee technology.[8]

These big movements from manufactures to provide more and more devices supporting the ZigBee technology, pushes more users and consumers to use this technology because, ZigBee devices offer quite a high degree of interoperability compared to Wireless M-Bus. However one of the biggest drawbacks of the ZigBee technology compared to Wireless M-Bus is that the

ZigBee technology has a large stack, meaning that the requirements to fulfill the ZigBee protocol are quite high in comparison to Wireless M-Bus and this means that it is also demanding on the devices. This is one of the main reasons why Wireless M-Bus finds its way easily through energy meters since these devices have generally low processing power and memories, so a less demanding protocol is always favored.

On the other hand as we previously mentioned in section 3.2.1 the ZigBee technology excels by providing the ability to connect in different topologies. The possibility of creating a mesh or peer to peer network opens huge possibilities to manipulate and use the existing devices for example sensors or meters to route the data between the devices in the network. This method might be difficult to realize using Wireless M-Bus, since it uses what is known as a bus topology where the data from the meters has to be directly sent to the data concentrator. In the end the user must choose which ever topology that proves the most efficient to transfer the data through the network as reliable and as fast as possible.

Another obvious comparison is between ZigBee and Bluetooth. There are several home automation devices today which support the Bluetooth technology mainly for communication between an electrical appliance and a portable device for example, communication between a tablet or a smartphone to a washing machine, light bulb, TV, etc. however, Bluetooth technology is much more sophisticated and advanced if compared with ZigBee. The Bluetooth technology has a higher data rate, faster respond time and has a protocol allowing it to carry various types of media formats. However the Bluetooth devices have batteries that last for days and at the best months, this is because the Bluetooth technology maintains a constant connection between the devices thus, the devices have to be working continuously all time, so it is safe to say that Bluetooth technology is less energy efficient if compared with ZigBee.

An important factor when considering which technology to use, is the availability of devices that support the technology on the market. It is apparent that the Wireless M-Bus is more common in Europe, while ZigBee being a more dominant technology in the United States. Another fact is, that users can now buy so called “single purpose devices” supporting Bluetooth, Wi-Fi or Z-wave and partly automate their living room or kitchen for example.

On the other hand, a new technology has been developed named Bluetooth Low Energy, it is aimed at being used at applications where battery life is a priority, and it succeeds at that by allowing the devices to sleep, just like ZigBee or Wireless M-Bus. All of this means that if we

compare Zigbee to Bluetooth Low Energy instead of standard Bluetooth we start to see good reasons to use Bluetooth Low Energy. [9] is a study that proves that Bluetooth Low Energy consumes less energy than ZigBee during a cyclic sleep scenario. However, Bluetooth Low Energy has a less sophisticated network topology if compared with ZigBee as mentioned above ZigBee gives us the possibility to be connected in different topologies for example star, peer to peer or cluster tree, while Bluetooth Low Energy has only the possibility to be connected only in star topology, for example a sensor connected directly to a tablet or a smartphone.

As mentioned several times in the thesis which technology to use depends solely on the type of the application, our suggestion would be to create a network composed of several protocols and technologies working together thus, making best use of the upsides of every technology to its highest potential. An example of such a network would be to use Wireless M-Bus for energy meters and data collection and then to use Zigbee or Wi-Fi for home automation.

A very short summary for the sake of comparison showing the key differences and ups and downs of every technology discussed above will be demonstrated in the following table.

Technology	Advantages	Disadvantages
Wireless M-Bus	Low processing power and Power consumption	Low data rate and simple protocol
ZigBee	Several connection topologies Low power consumption	Limitations due to ZigBee profile and overhead
Wi-Fi	High data rate	Very high power consumption relative to others
Bluetooth	High interoperability with personal devices	High power consumption and short range
Bluetooth Low Energy	Very low power consumption	Limited connection topology
Z-Wave	Huge market for single purpose devices	Restricted to home automation and high price

Table 5 Comparison between some wireless technologies

3 Practical implementation of Wireless M-Bus on an embedded device

The objective of this chapter of the thesis is to apply the theoretical knowledge and background of Wireless M-Bus on real hardware, and attempt to transmit data according to the Wireless M-Bus standard. The focus will be on properly implementing and obtaining results from configuring the physical layer of the protocol, which means that most of the work will be focused on defining radio parameters, Preamble sequences, Postamble sequences etc. for all of the different sub-modes, all of which have been explained previously in chapter 2.

3.1 Hardware

The hardware solution to implement Wireless M-Bus consists of two devices. The SPIRIT1 transceiver by STMicroelectronics, and the STM32W108 microprocessor by STMicroelectronics. These devices were chosen due to their simplicity and user friendliness in comparison with their rivals like Texas instruments or Semtech. Therefore, the STM32W108 and SPIRIT1 transceiver were teamed together on a PCB board to create the hardware for implementing the Wireless M-Bus. The next figure will show the PCB boards.

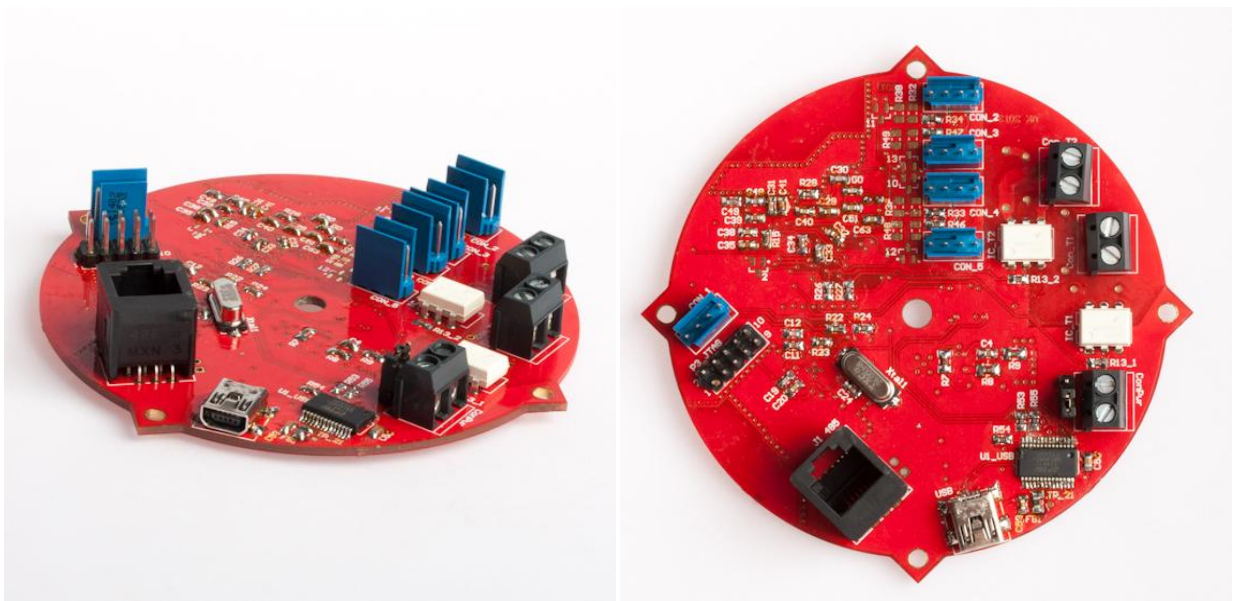


Figure 16 PCB board for implementing Wireless M-Bus

The PCB board has been designed in this shape in order to be able to fit it behind a three phase wall socket in order to perform and provide measurement results for different parameters. Its dimensions and size allow it to fit perfectly behind the socket and screw into the wall in a safe and unobtrusive way. The boards are supplied by means of a DC supply through a USB port. The boards are also prepared to connect through RS485 to perform various functionalities.

In order to simulate a real world application for example a meter and a data collector, two identical PCB boards were used, one configured as a transmitter (meter) and the other configured as a receiver (data collector).

3.1.1 STM32W108

The role of this microprocessor is to program the SPIRIT1 transceiver. This microprocessor should also be able to handle the upper layers of the Wireless M-Bus protocol i.e. the data link layer and the application layer, since the upper layers are not supported by the SPIRIT1 transceiver, instead the upper layers must be programmed and defined by the microprocessor. The microprocessor also controls the power consumption of the transceiver since the duty cycle and power on timing are determined by the microprocessor.

3.1.2 SPIRIT1

The role of the SPIRIT1 transceiver is to provide and fulfill the requirements of the physical layer of the Wireless M-Bus protocol i.e. defining the Preamble, Postamble, Sync word, sub-modes and the radio parameters, which include also the frequency band, centre frequency, channel spacing and output power. The SPIRIT1 transceiver offers an easy starting point to implement Wireless M-Bus, because it comes preprogrammed with 3 different packet structures these packet structures are Stack packet, Wireless M-Bus packet and Basic packet. The SPIRIT1 transceiver also supports several sub-modes of the Wireless M-Bus protocol, and it offers very easy and simple switching between different the sub-modes which are S1, S2, S1-m, S2, T2, R2, N1 and N2. Figure 17 shows the schematic of the connection of the SPIRIT1 transceiver.

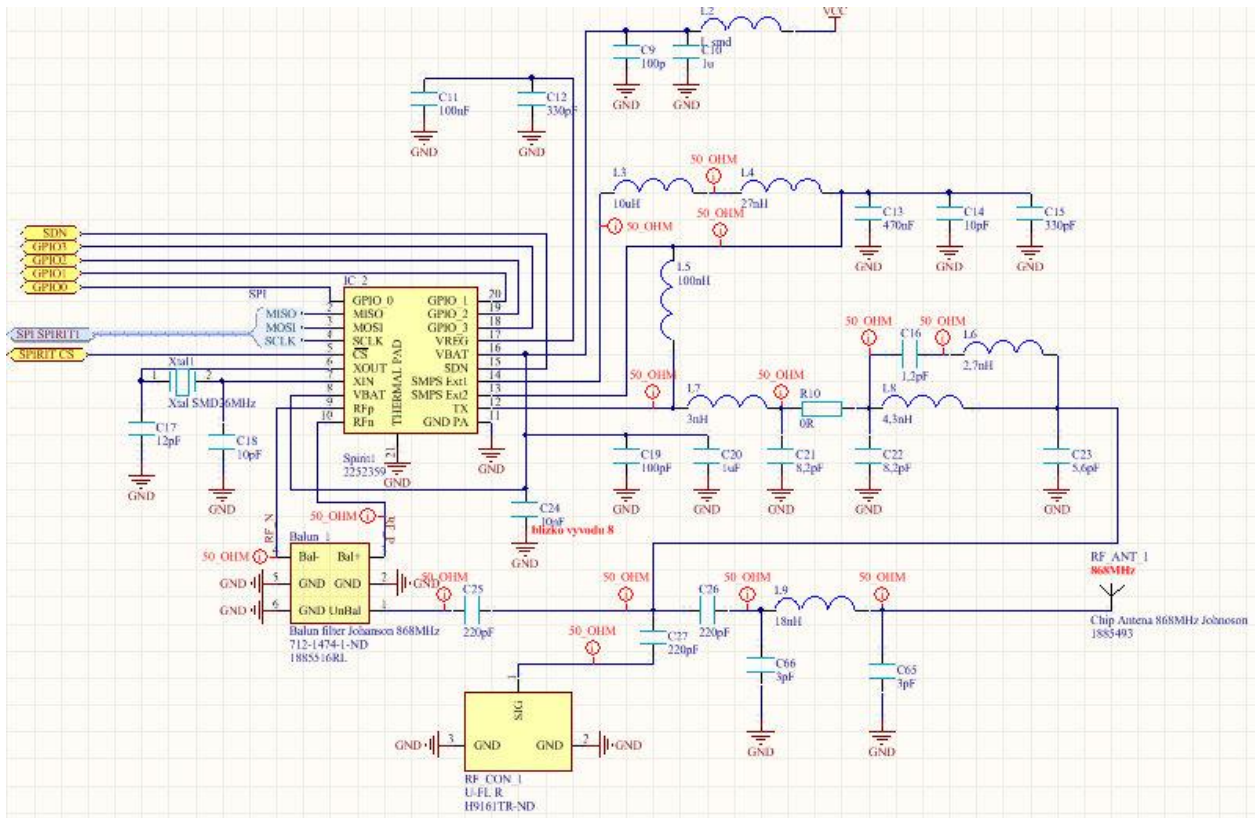


Figure 17 Schematic of the connection of SPIRIT1 transceiver

Naturally the chosen packet was the Wireless M-Bus packet which is shown in figure number 3 page number 9. After choosing the appropriate packet attention was then directed towards defining the Preamble, Postamble, Sync. words according to the standard using the information described in table 1 page number 6. The next step was to set and tune the radio parameters of the SPIRIT1 transceiver in order to transmit exactly at the defined frequencies by the standard according to the different sub-modes as mentioned in table 1.

3.2 Software and coding

Creating the software for programming the embedded devices was coded using the Atollic environment, which is intended for programming ARM devices. In the following table a list of some of the registers related to Wireless M-Bus configuration that were programmed on the SPIRIT1 chip will be shown, in addition to the original code that corresponds to a hexadecimal value intended to be programmed into the registers.

Register	Description	Value in hex.
PCKTCTRL3	Packet format, Receiver mode	0x50
MBUS_PRMBL	Preamble length	0x117
MBUS_PSTMBL	Postamble length	0x02
MBUS_CTRL	M-bus sub-modes	0x01
CHNUM	Channel number	0x04
CHSPACE	Channel space	0x1F4
FC_OFFSET[1,2]	Frequency offset	0x7D0
MOD[0,1]	Modulation type	0
SYNT	Base band	-

Table 6 Registers related to Wireless M-Bus

Theoretically the radio parameters could be programmed using 3 equations:

$$f_c = f_{base} + f_{offset} + \left(\frac{f_{xo}}{2^{15}} \cdot CHSPACE \right) \cdot CHNUM \quad (1)$$

Where: f_c is the centre frequency

f_{base} is the base frequency

f_{offset} is the frequency offset

f_{xo} is the crystal oscillator frequency

The base and offset could be calculated using the following equations:

$$f_{base} = \frac{f_{xo}}{(B \cdot D)} \frac{SYNT}{2^{18}} \quad (2)$$

$$f_{offset} = \frac{f_{xo}}{2^{18}} \cdot FC_OFFSET \quad (3)$$

Where: B represents the frequency band

D represents the internal reference divider

However, programming the result of these equations together into the registers, gives a slightly imprecise frequency. This is due to the slight tolerances present in the analogue circuitry of the antenna. Therefore, the best method to precisely set the frequency was to use a spectrum analyzer and manually tune the values of the radio Registers. Appendix A shows a part of the

actual code used to program the SPIRIT1 transceiver, while figure 18 shows the actual measured radio parameters when the theoretical result of calculating the centre frequency at 868.30 MHz is applied to the registers.

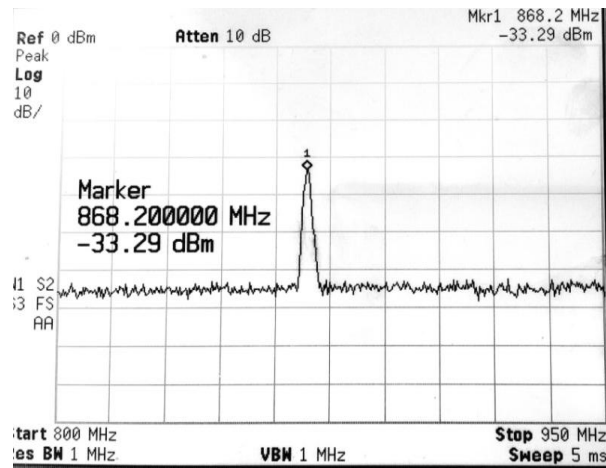


Figure 18 shows the slightly imprecise centre frequency due to tolerances in the analogue circuitry

3.3 Results

The results of the implementation will be observed using two methods. First observing the RX_FIFO register using the code to see if the data has been successfully transmitted from point A to B (transmitter to receiver) without any errors. The second method will be using a spectrum analyzer to carefully observe the spectrum of the signal and check if the radio parameters are equivalent to the Wireless M-Bus standard. However, since we attempt to only implement the physical layer, the data will be sent just as a lump of data (payload). Figure 19 shows how the packet will look like.

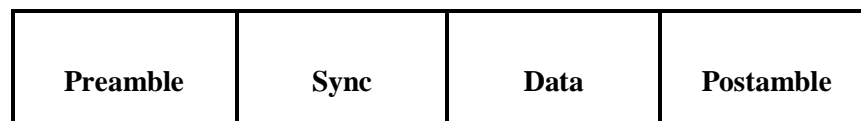


Figure 19 Test packet for physical layer implementation

3.3.1 Register values

The register values were observed while the boards were running during debug mode. Several input values were inputted for example (0x01 and 0xD0) into the SPIRIT1's FIFO data

register. The data which was inputted was in fact transmitted and received on the receiver with no errors. An array for incoming data was prepared to store these values. Therefore, we can conclude that by observing the register values we are able to successfully identify and receive the data that we intended to transmit.

3.3.2 Observing the signal using spectrum analyzer

A spectrum analyzer was used in order to verify if the signal is transmitted according to Wireless M-Bus. In our implementation we configured three different sub-modes (S, T and R) therefore, we need to make sure that the signal will match the parameters mentioned in table 1. The next figure shows the result of these measurements.

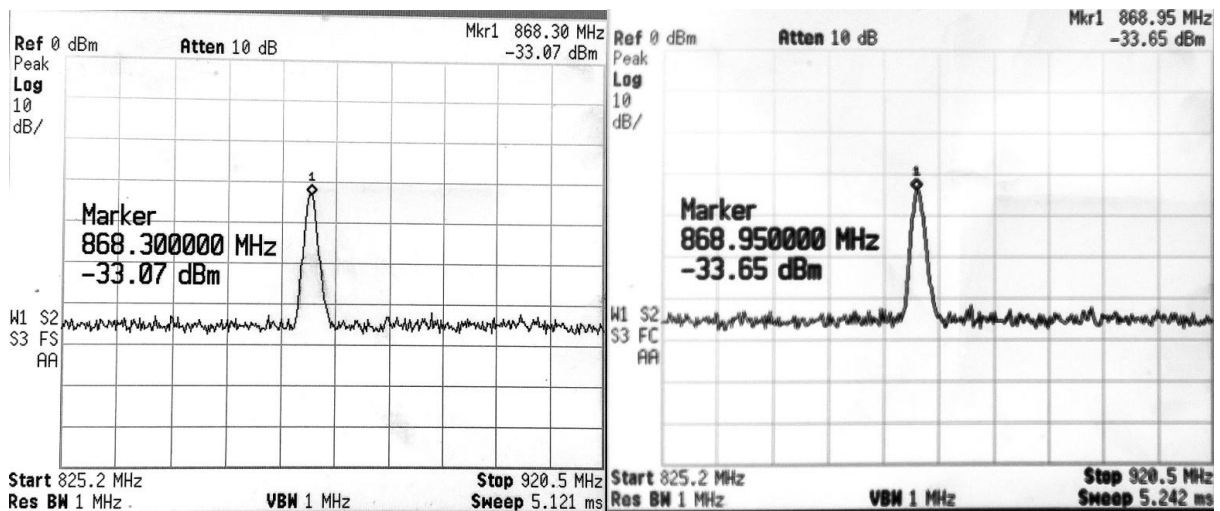


Figure 20 Results of radio parameters measurement

The unclarity in the figures above is due to the fact that they were taken by a camera. The figures show two different centre frequencies, one at 868.30 MHz and the other at 868.95 MHz. In our opinion these two frequencies are the most common and most used frequencies by the sub-modes. 868.30 MHz is used for all the S sub-modes which includes (S1, S1-m and S2), and also for T2 sub-mode in the case of other to meter. while the 868.95 MHz is used for T1 and T2 sub-mode.

4 Methods of injecting signal to power line

In the previous sections of this thesis, we focused on analyzing and implementing some of the wireless communication protocols used to establish smart grids today. In this chapter of the thesis we look into the possibilities of Power Line communication (PLC), and we attempt to design an injection coil that will comply with the CENELEC band A standard, followed by a proposal to use Rogowski coil as an injection coil.

4.1 Power Line Communication (PLC)

The idea behind PLC is to utilize the existing power line infrastructure to establish communication between the devices connected to the grid. This could be achieved by sending a modulated signal through the power line medium itself. PLC is today by far the most implemented type of smart grid communications which is due to several factors which include cost effectiveness in comparison to wireless solutions, speed and security. However, PLC is not without its disadvantages these disadvantages or challenges result from the power line medium itself, since power lines are designed with power delivery in mind instead of communications, they are noisy, unstable and are easily affected by the surrounding environment.

There are standards which govern the operation of PLC Worldwide. In Europe the standard is governed by the European Committee For Electrotechnical Standardization (CENELEC). CENELEC defines four different bands for PLC devices to operate.

- Band A: Is a band reserved for power providers and suppliers with frequencies ranging between 3 – 95 KHz.
- Band B: Is a band reserved for a consumer application with frequencies ranging from 95 - 125 KHz.
- Band C: Is also reserved for consumer applications however, the applications are restricted to networking application and the frequencies range from 125 – 140 KHz.
- Band D: Is also reserved for consumer applications but applications are restricted to alerts and reports, frequencies range from 140 – 148.5 KHz. [10]

4.2 Coupling circuits for injecting signals to power line

One of the most important things to consider with PLC is how to couple the communication signals, into the power line. There are a few techniques used for coupling PLC

signals to the power line, for example transformer coupling and inductive coupling. A coupling circuit should be able to couple the transmitted signal into the power mains and also receive a modulated PLC signal, whilst also removing low frequency signals mainly 50 Hz and 60 Hz so in other words a coupling circuit should also perform as a high pass filter to allow the communication signal to pass to the power mains. [11]

In the next sections of the thesis a brief description of the existing coupling methods will be presented, followed by a design of a solenoid to inject the signal into the power line, that will comply with CENELEC band A, then followed by a proposal to use Rogowski coil as a coupling device for injecting communication signals into the power line.

4.2.1 Transformer coupling

A widely used type of coupling is known as transformer coupling. One of the main advantages of using transformer coupling is the galvanic isolation provided by the transformer, so any low voltage circuitry or devices would not be affected by the mains voltage. The next figure shows the general schematic of transformer coupling.

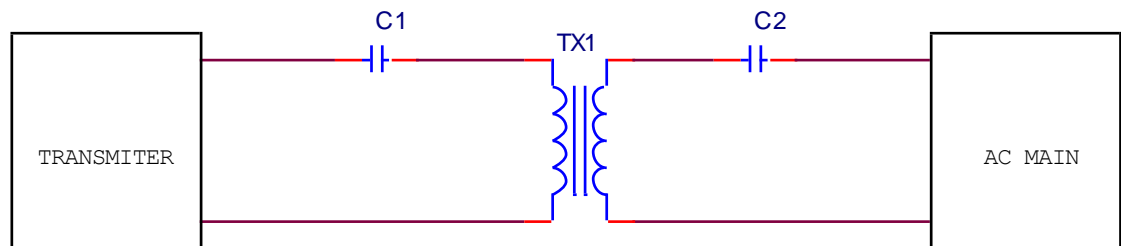


Figure 21 Schematic of transformer circuit

The capacitor C1 doesn't allow the DC offset to be shorted by the transformer. Capacitor C2 and the internal inductance of the transformer act as a high pass filter allowing the communication signal to pass and are essentially blocking the 50 Hz and 60 Hz signal, therefore the value of the capacitance has to be chosen to fulfill these requirements. It is also worth to mention that additional protection components may be added before connecting to the circuit to the main for example a fuse.

4.2.2 Inductive coupling

Is a coupling method suitable for frequencies between 2 MHz and 30 MHz. It uses a ferrite that works according to the electromagnetic induction principle, as a coupling device. The coupling device is suitable to be used when the main has a low value of impedance. The next figure shows the connection of an inductive coupled modem. The inductive coupling has several advantages over other methods of coupling these advantages include increased efficiency, and the ability to connect the ferrite easily anywhere along the power line cable, but most of all, the inductive coupling reduces the hazards related to high voltage since it is not directly connected by a physical medium to the power line. The ferrite consists of two gaps, one for accommodating the mains wire and the other for accommodating the modem wires.

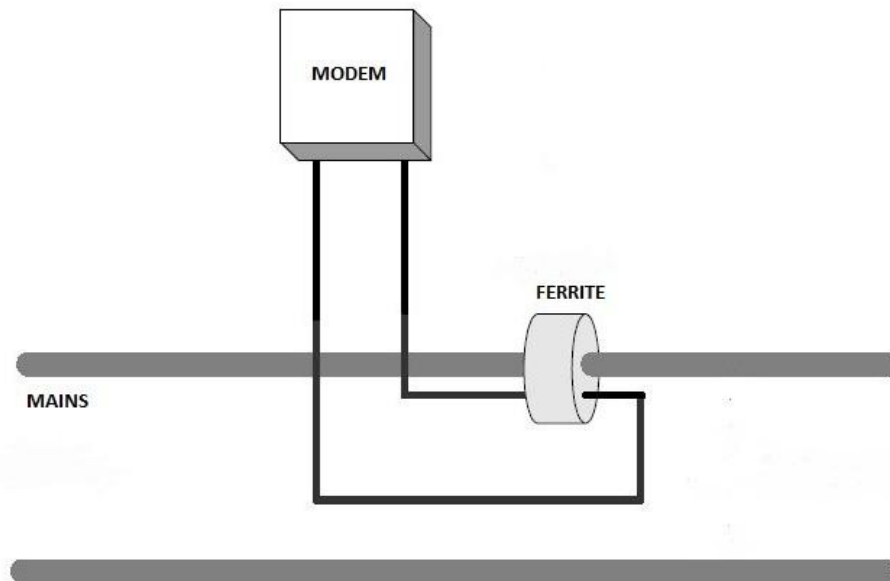


Figure 22 Inductive coupling using a single ferrite

4.3 Designing of injection coil according to CENELEC band A

In this section we will attempt to design an injection coil in order to satisfy the requirements of CENELEC band A. The general requirement of band A was previously described in section 4.1. Two types of injection coils will be introduced, the first injection method will be achieved by using a solenoid to inject the signal and the second will be using a Rogowski coil.

4.3.1 Solenoid as an injection coil

A solenoid is a coil, where the wire turns are wound around an air core. The key characteristic of our approach is that we use an air core instead of a ferromagnetic core. This gives us the possibility to avoid problems related to saturation, when the ferromagnetic core starts to lose its inductive character as the current increases.

In our case a solenoid with two windings was created, a primary winding and a secondary winding, the idea being to inject a signal between 3 – 95 KHz into the primary winding and observe an output voltage in the range of 50 – 500 mV at the secondary winding. Measurements will later be carried out to simulate the grid impedance at approximately 20 Ω .

4.3.1.1 Principle of operation and calculations

As mentioned above our solenoid, was constructed using two windings a primary and secondary. The primary winding is an uninsulated copper wire, while the secondary winding is an insulated copper wire with significantly less number of turns than the primary winding. The next figure shows the construction of the solenoid with secondary winding.

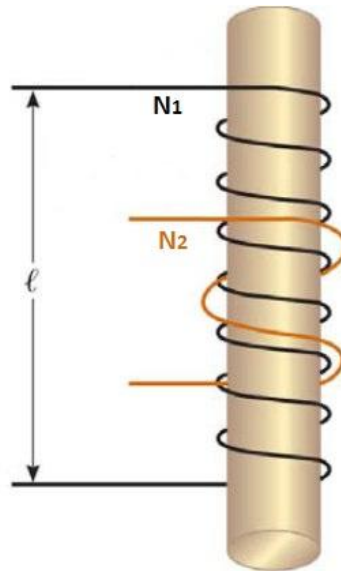


Figure 23 Construction of Solenoid with secondary winding [12]

The function of this solenoid depends on the principle of mutual inductance. Simply when varying current flows through the primary winding N_1 it creates a magnetic field around the primary winding itself, this magnetic field then encircles the secondary winding N_2 as well thus,

inducing an emf (Electromagnetic force) which can then be measured by means of a Voltmeter or an Oscilloscope for example.

The mutual inductance can be calculated using the formulae:

$$M = \frac{N_2 \phi_{12}}{I_1} \quad (4)$$

Where: M is the mutual inductance in Henry

ϕ_{12} is the flux induced by primary coil N_1 on secondary coil N_2

I_1 is the current through the primary coil N_1

Now that we know the mutual inductance M we can deduce that the emf force will be

$$\varepsilon_2 = -M \frac{\Delta I_1}{\Delta t} \quad (5)$$

Where: ε_2 is the induced emf on the secondary coil N_2

An interesting question arises which is, why is the resultant induced emf in negative value? The answer is visible in Lenz law as it states that the resultant emf will produce a current that creates a magnetic field going in an opposite direction to the direction of the flux lines.

It is then necessary to calculate the flux through the primary coil using the following formulae:

$$\phi_{12} = BA = \frac{\mu_0 N_1 I_1}{l} A \quad (6)$$

Where: μ_0 is the permeability of vacuum

l is the length of the solenoid visible in figure 23

A is the cross-sectional area of the solenoid

Using the knowledge mentioned above a solenoid with two windings was created. The inductance of the primary coil was 4.659 mH, while the inductance of the secondary coil is 8.48 μ H. Knowing these values we can compute the mutual inductance using the following formulae:

$$M = k \sqrt{L_1 L_2} \quad (7)$$

Where: k is the coupling coefficient in other words if we assume all the flux from L_1 goes to L_2 we can say that k is 1. k values range from 0 – 1.

L_1 is the inductance of the primary coil N_1

L_2 is the inductance of the secondary coil N_2

The input voltage and current into the primary winding were 10 V peak to peak and approximately 165 mA respectively. The solenoid was able to inject a peak to peak signal of 343.8 mV i.e. the amplitude was 171.9 mV with a frequency of 96 KHz when the secondary coil is not loaded. When we attempt to load the secondary coil i.e. when we try to simulate the grid impedance, we are able to inject a peak to peak signal of 115 mV in the worst case scenario as shown in figure 24.

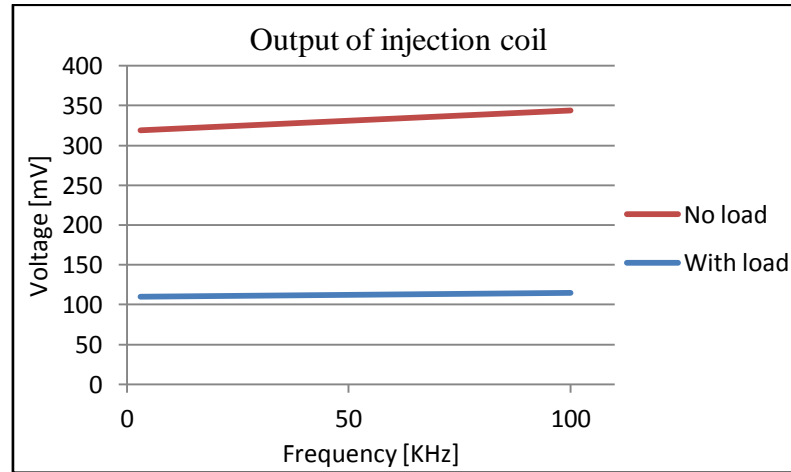


Figure 24 Output of injection coil with and without maximum expected grid impedance

The results show that the solenoid is able to inject reasonable and usable output values that could later be used for PLC and that also comply with CENELEC band A.

4.3.2 Proposal to use Rogowski coil as an injection coil

Rogowski coils offer intriguing reasons to investigate them, since unlike the traditional induction couplers which because of the use of ferromagnetic cores exhibit saturation, the Rogowski coil uses an air core. This means that we have a possibility to reduce the mass of the coupling device, whilst avoiding the ferromagnetic core related problems such as saturation. We also have the possibility to achieve galvanic isolation by using Rogowski coils for coupling.

Rogowski coils also promise us in theory a very wide range of frequencies to operate at, meaning that we are able to create one hardware and then we are able to use it to comply with CENELEC bands A, B, C and D which as mentioned previously operate between the ranges of 3 KHz to about 150 KHz. In addition we are also able to achieve Broadband Power Line Communication (BPLC) which operates in the ranges of MHz.

The principle of operation of Rogowski coil is quite similar to the principle of operation of the solenoid, the similarity exists in the fact that both Rogowski coil and a solenoid use an air core. The next figure shows how the Rogowski coil is constructed and how it is placed.

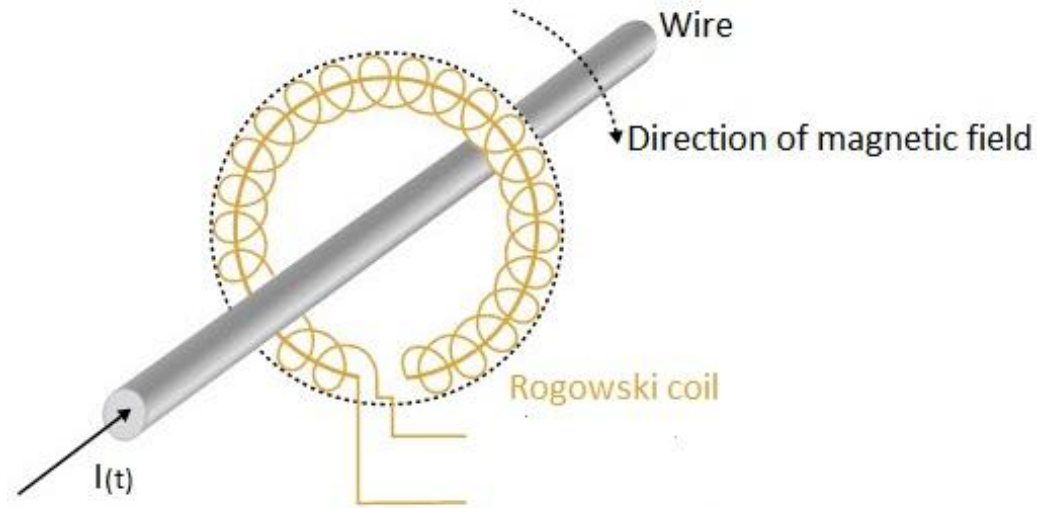


Figure 25 Rogowski coil construction and operation for measurement [13]

As seen in the figure above a wire is placed within the toroid itself and when a varying current $I(t)$ passes through a wire it creates a magnetic field that is then picked by the Rogowski coil and it then generates an emf. The general problem with Rogowski coils is that they produce weak outputs i.e. the signal that is produced as a result of the changing current through the wire needs to be amplified in order to be used for an application. Rogowski coils are mostly used to measure currents.

4.3.2.1 Simulation and modeling

In this section we attempt to investigate the possibilities of using a Rogowski coil as an injection coil. An equivalent circuit will be presented followed by a simulation for a model containing a Rogowski coil coupled to the mains.

The equivalent circuit of the Rogowski coil will be shown in the following figure.

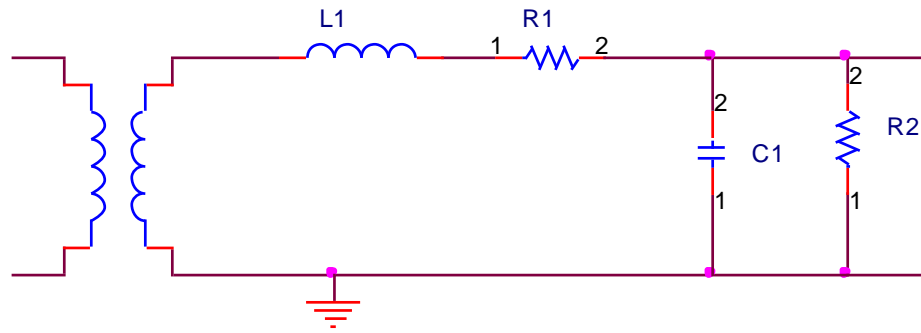


Figure 26 The equivalent circuit of Rogowski coil [14]

The components L1, R1, C1 and R2 simulate the self inductance, resistance and capacitance while R2 simulates the terminal resistance of the coil.

Our idea was simply to try to simulate what happens if we attempt to inject a signal on the terminal end of the Rogowski coil and observe the effect of the injected signal on the wire. The next figure shows the model and the simulation's circuit.

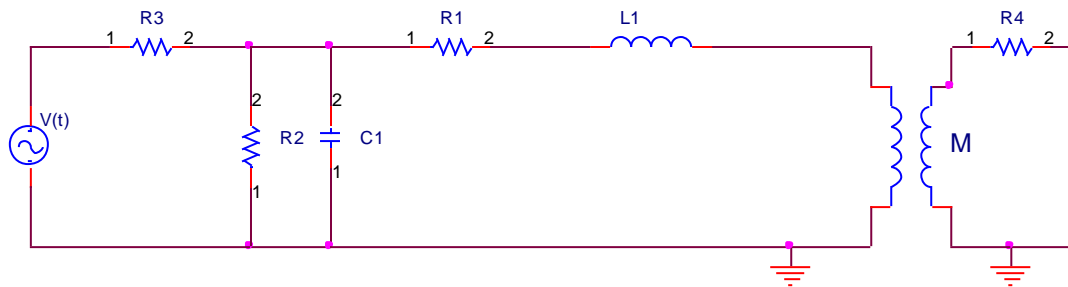


Figure 27 Model for simulating Rogowski coil as injection coil

The simulations will be carried out using the PSpice software. In the above figure the grid impedance is simulated by the resistance R4, while we inject a varying voltage on the terminal side of the Rogowski coil. The value of R4 is supposed to mimic the impedance of the grid so the chosen values were between $0.5 - 20 \Omega$, the resistor R3 represents the self resistance of the source itself, whilst M is the mutual inductance of the Rogowski coil. The next table will show the chosen values of the components that represent the Rogowski coil's parameters, these values will be fixed while values of V(t), R3 and R4 will be changed in order to simulate different operating scenarios.

Components	Value
R1	0.11 Ω
R2	2000 Ω
C1	50 pF
L1	0.6 μ H
M	1.5×10^{-7}

Table 7 Values of components used for Rogowski coil simulation [15]

The following figures will show the induced voltage on the wire when carrying out the simulation at several frequencies which are within the CENELEC band A, and with an input voltage with amplitude of 24 V while limiting the maximum current to 2 A. The simulations shown below show that in theory we are able to induce some voltage that could actually be used for PLC, while more scenarios will be shown in Appendix B at the end of the work.

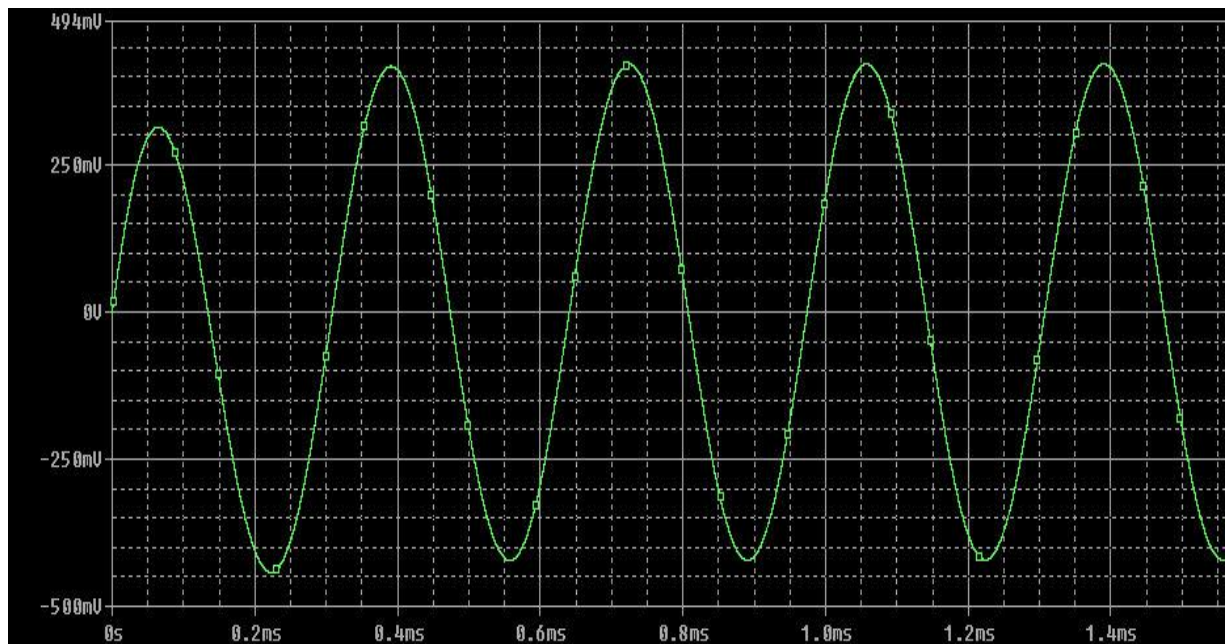


Figure 28 simulation showing induced voltage on wire at 3 KHz

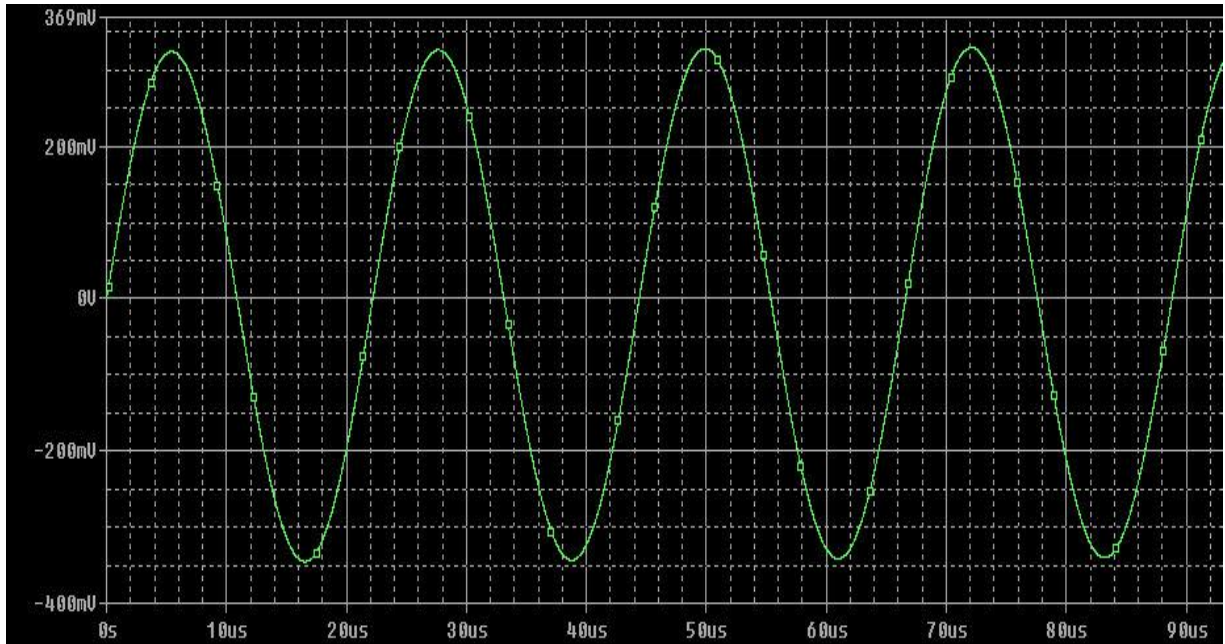


Figure 29 simulation showing induced voltage on wire at 45 KHz

5 Conclusions and future work

In this Bachelor thesis we reviewed the Wireless M-Bus protocol in detail. We attempted to create a document that could function as a simple and intuitive guide to explain Wireless M-Bus protocol.

In Chapter 1 we presented the biggest motivation towards the development of such protocols and technologies like Wireless M-Bus and ZigBee which is the Smart Grid (SG). We gave an introduction to smart grids and their problematics and demands then we explained and illustrated the different topologies and hierarchies in the smart grid communication networks.

Chapter 2 is where we introduced Wireless M-Bus and where we then compared Wireless M-Bus to rival technologies and protocols such as Zigbee and Bluetooth. We concluded chapter 2 with a comparison between the technologies used in smart grid communications and have chosen Wireless M-Bus as the preferred protocol for metering purposes while recommending using more sophisticated technologies such as ZigBee and Bluetooth for establishing communication between devices in a home network.

In chapter 3 we implemented the physical layer of Wireless M-Bus on an embedded device, and successfully transmitted a data payload according to the correct parameters stated by the Wireless M-Bus protocol. Measurements showed that the most effective way to set the radio parameters is by attempting to manually tune the values of the SPIRIT1's registers in order to obtain correct and precise operating frequencies.

Chapter 4 starts by giving an introduction to another type of smart grid communication i.e. Power Line Communication (PLC). We then described some of the methods of coupling or injecting signals to the power line in order to achieve PLC. The chapter then demonstrates the possibility of using a solenoid as an injection coil to inject the signal into the power line, followed by a simulation of Rogowski coil as an injection coil.

Results from chapter 4 show that the solenoid that was created did in fact achieve the target parameters that we were aiming at, and that it can be used to inject signals into the power line. Measurements were then carried out to simulate grid loads.

On the other hand the simulations for using Rogowski coil as an injection coil show a promising start, as the induced voltages and frequencies seem sufficient for use in PLC communications, and comply with CENELEC standards.

This bachelor thesis gives several topics for further investigation and study for example:

- Fully implementing Wireless M-Bus protocol on an embedded device and compare its energy consumption to ZigBee.
- Investigating the security of Wireless M-Bus protocol and testing the effectiveness of the used encryption algorithms against eavesdroppers.
- Implementing the Rogowski coil as an injection coil on hardware and carrying out measurements to obtain results and compare them to simulations presented in this thesis.

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Appendix A

```

#ifdef WM_WMBUS

    // Defining the sub-mode (sub-mode=0) for S1&S2.
    WM_SpiSpiritWriteReg(SP_REG_MBUS_CTRL, 0x00u<<1);

    // Defines the packet WM-BUS=2 RX_MODE&LENGTH WIDTH
    WM_SpiSpiritWriteReg(SP_REG_PCKTCTRL3, (0x02u<<7) | (0x00<<5) | (0x10u<<3));

    // According to the standard preamble must have n>278 in chip sequence
    WM_SpiSpiritWriteReg(MBUS_PRMBL, 0x117u);

    // According to standard postamble must have n=1 to 4 chip sequence
    WM_SpiSpiritWriteReg(MBUS_PSTMBL, 0x01u);

    //Radio Configuration

    // Calculated with synt register to set the frequency at 868.3
    WM_SpiSpiritWriteReg(SP_REG_CHSPACE, 0x03u);

    // Choosing FSK Modulation
    WM_SpiSpiritWriteReg(SP_REG_MOD0, 0x00u<<5);

    // Calculated to set frequency at 868.3
    WM_SpiSpiritWriteReg(SP_REG_CHNUM, 2u);

#elif WM_MBUS_T2

    // Defines the sub-mode according to spirit (sub-mode=1) for S1-m&S2,T2
    WM_SpiSpiritWriteReg(SP_REG_MBUS_CTRL, 0x01u<<1);

    // Defines the packet WM-BUS=2 RX_MODE&LENGTH WIDTH
    WM_SpiSpiritWriteReg(SP_REG_PCKTCTRL3, (0x02u<<7) | (0x00<<5) | (0x10u<<3) );

    // According to standard preamble must have n>278 in chip sequence
    WM_SpiSpiritWriteReg(MBUS_PRMBL, 0x117u);

    // According to standard postamble must have n=2 to 4 chip sequence
    WM_SpiSpiritWriteReg(MBUS_PSTMBL, 0x02u);

    //Radio Configuration

    // Choosing FSK Modulation
    WM_SpiSpiritWriteReg(SP_REG_MOD0, 0x00u<<5);

    // Calculated to set frequency at 868.995
    WM_SpiSpiritWriteReg(SP_REG_CHNUM,4u);

```

```
// Calculated to set frequency at 868.95
WM_SpiSpiritWriteReg(SP_REG_FC_OFFSET1, 0X7D0u<<11);
// Frequency offset
WM_SpiSpiritWriteReg(SP_REG_FC_OFFSET0, 0X7D0u<<7);
// Calculated to set frequency at 868.95
WM_SpiSpiritWriteReg(SP_REG_CHSPACE, 0x1F4u);
#elif WM_Mbus_R
// Defines the sub-mode according to spirit (sub-mode=5) for R
WM_SpiSpiritWriteReg(SP_REG_MBUS_CTRL, 0x05u<<1);
// Defines the packet WM-BUS=2 RX_MODE&LENGTH WIDTH
WM_SpiSpiritWriteReg(SP_REG_PCKTCTRL3, (0x02u<<7) | (0x00<<5) | (0x10u<<3) );
// Choosing variable length for payload from transmitter
WM_SpiSpiritWriteReg(SP_REG_PCKTCTRL2, 0x01u);
// According to standard preamble n=96 chips
WM_SpiSpiritWriteReg(MBUS_PRMBL, 0x192u);
// According to standard postamble must have n=1 to 4 chip sequence
WM_SpiSpiritWriteReg(MBUS_PSTMBL, 0x02u);
//Radio Configuration
// Calculated with synt to set the frequency at 868.3
WM_SpiSpiritWriteReg(SP_REG_CHSPACE, 0x03u);
// Choosing FSK Modulation
WM_SpiSpiritWriteReg(SP_REG_MOD0, 0x00u<<5);
// Calculated with synt to set the frequency at 868.3
WM_SpiSpiritWriteReg(SP_REG_CHNUM, 2u);
```

Appendix B

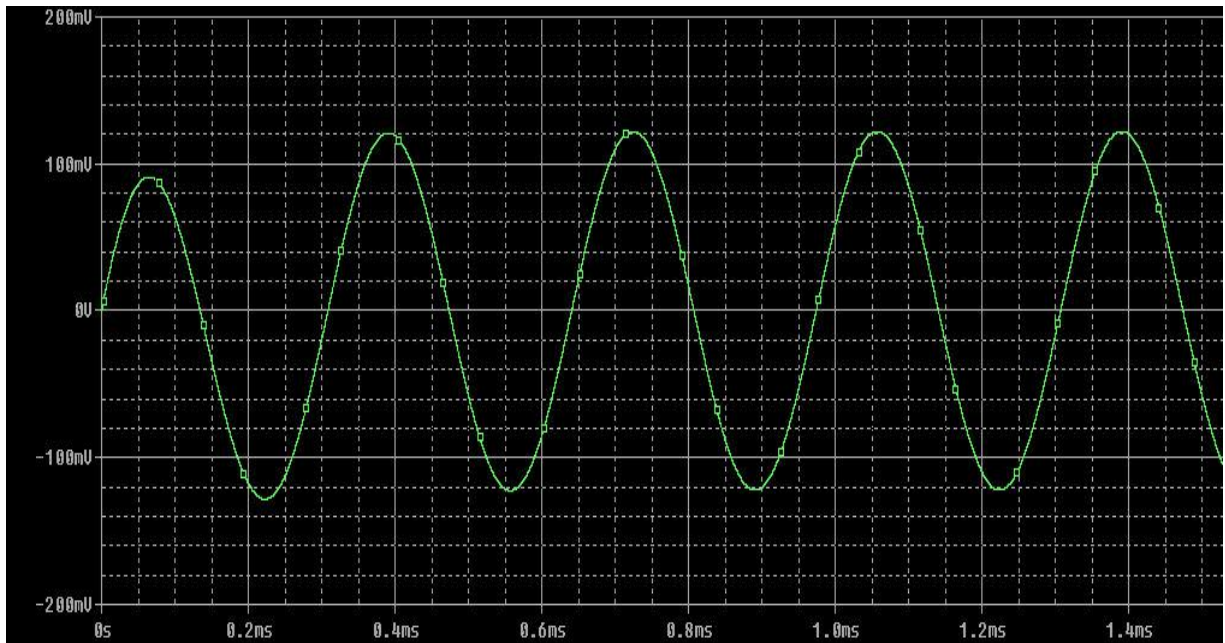


Figure B1 Parameters: input current = 5A, input voltage = 5V, frequency = 3 KHz, grid impedance = 20 Ω

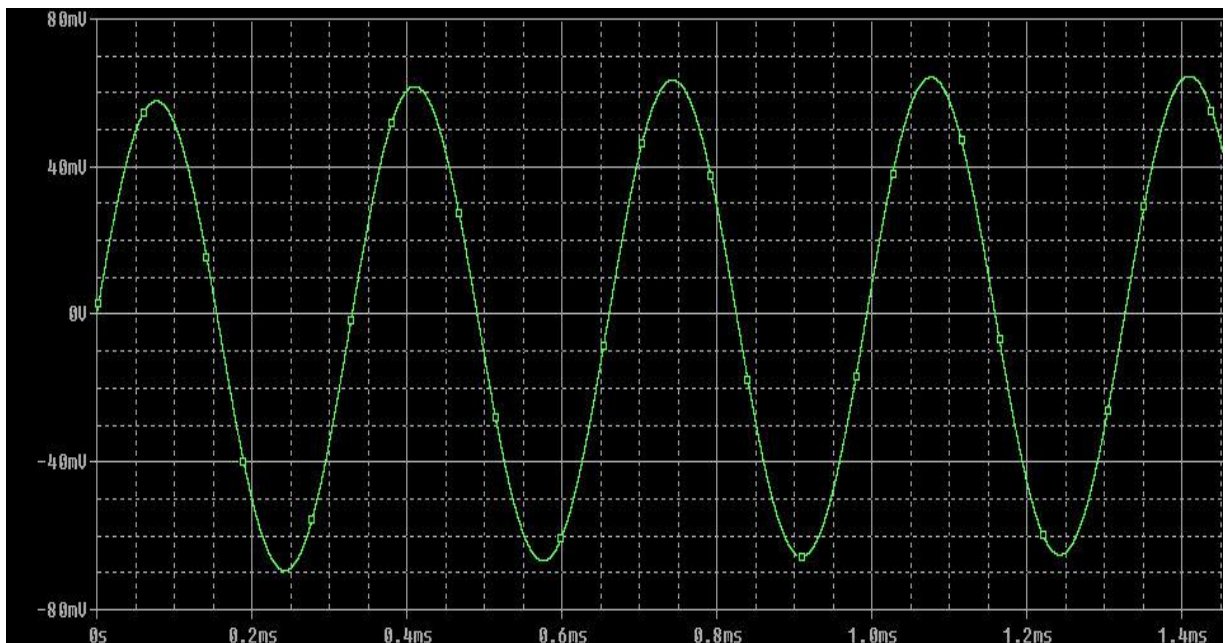


Figure B2 Parameters: input current = 2A, input voltage = 15V, frequency = 3 KHz, grid impedance = 5 Ω

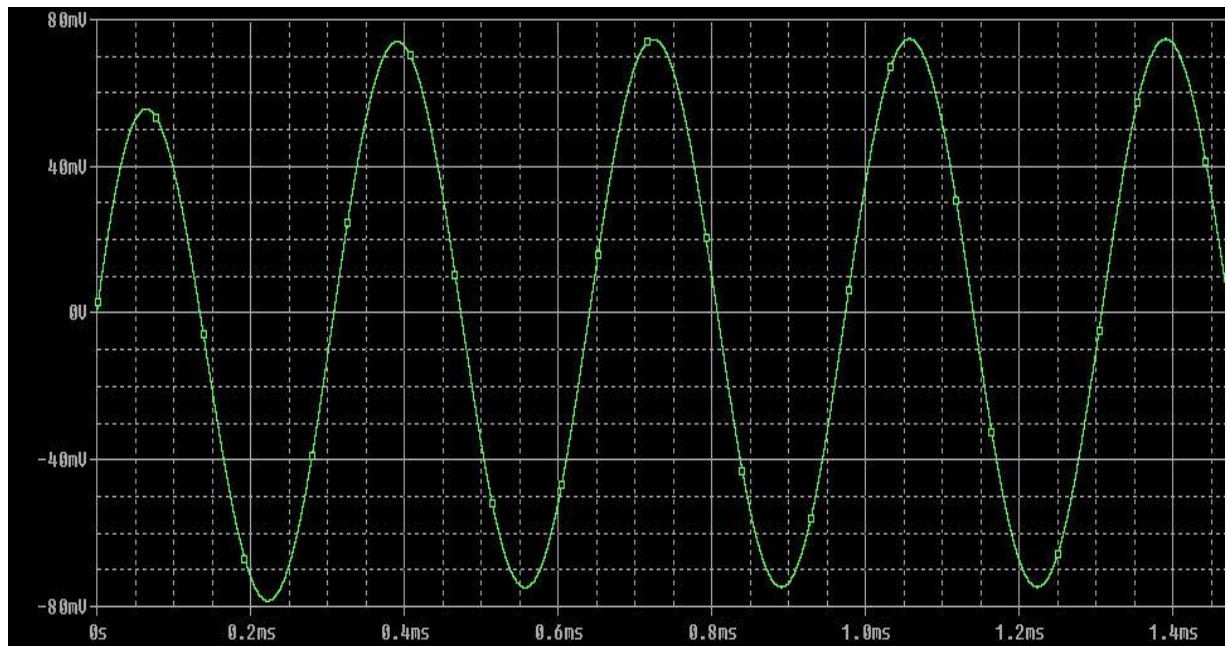


Figure B3 Parameters: input current = 0.5A, input voltage = 24V, frequency = 3 KHz, grid impedance = 20 Ω

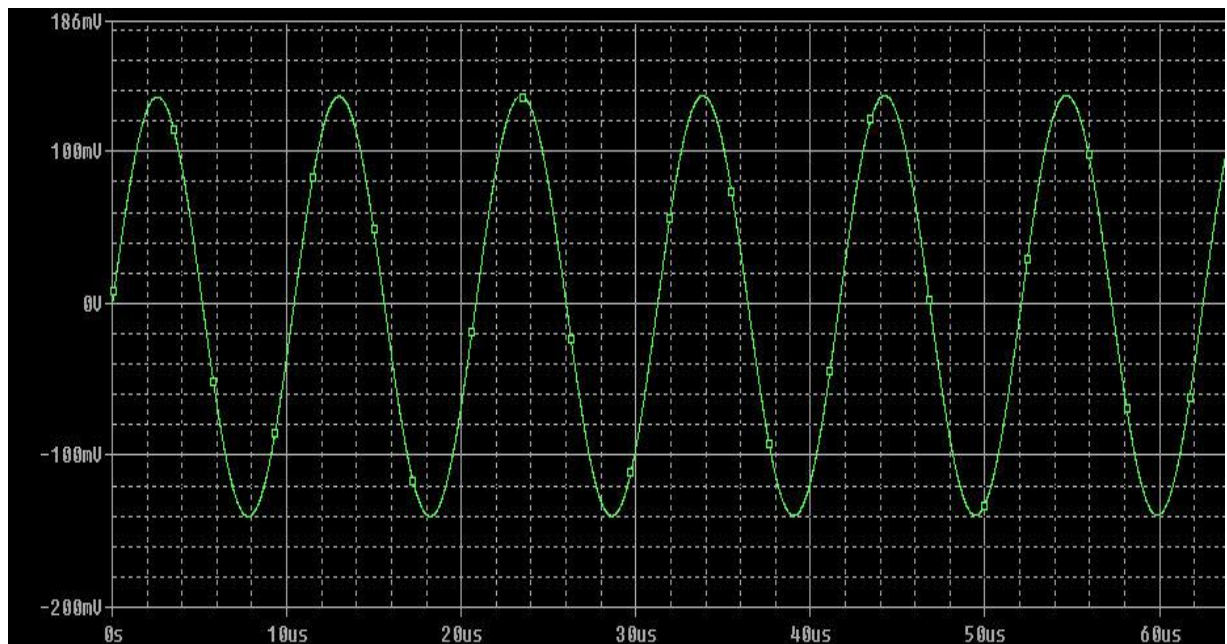


Figure B4 Parameters: input current = 5A, input voltage = 5V, frequency = 96 KHz, grid impedance = 20 Ω

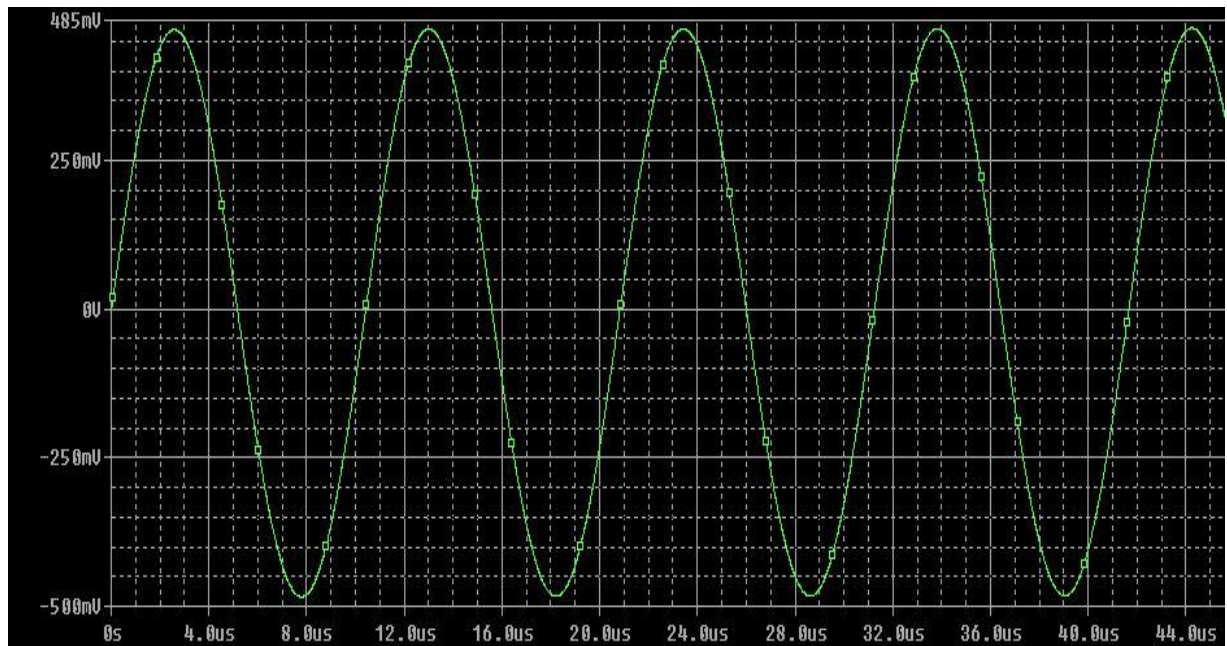


Figure B5 Parameters: input current = 2A, input voltage = 24V, frequency = 96 KHz, grid impedance = 20 Ω

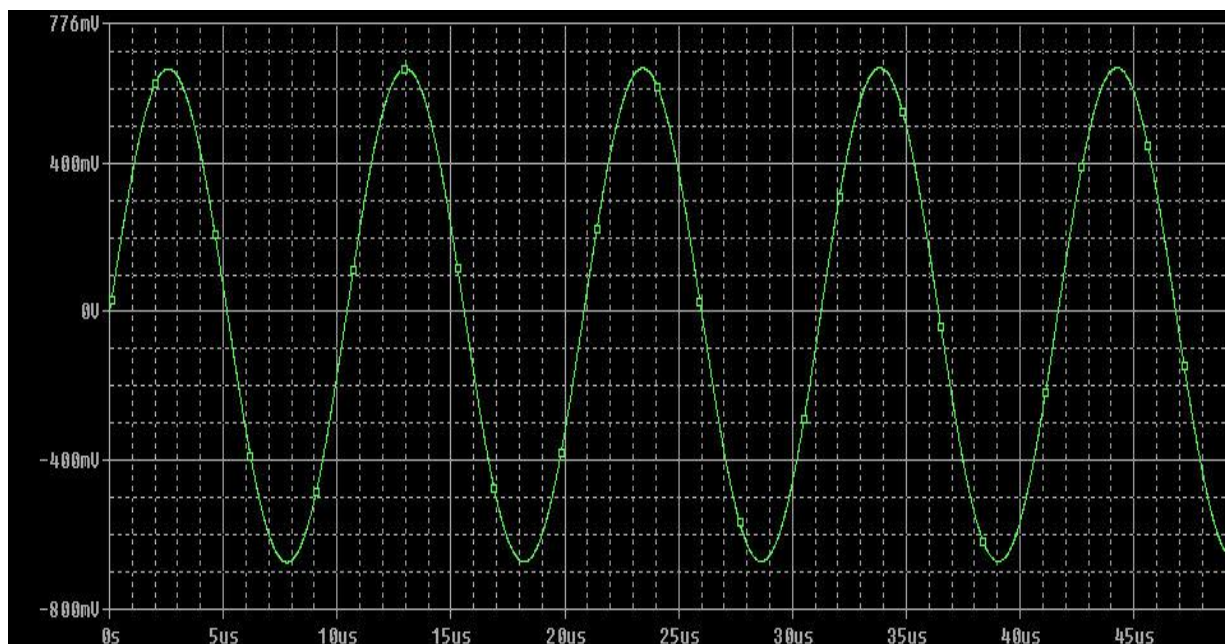


Figure B6 Parameters: input current = 5A, input voltage = 24V, frequency = 96 KHz, grid impedance = 20 Ω

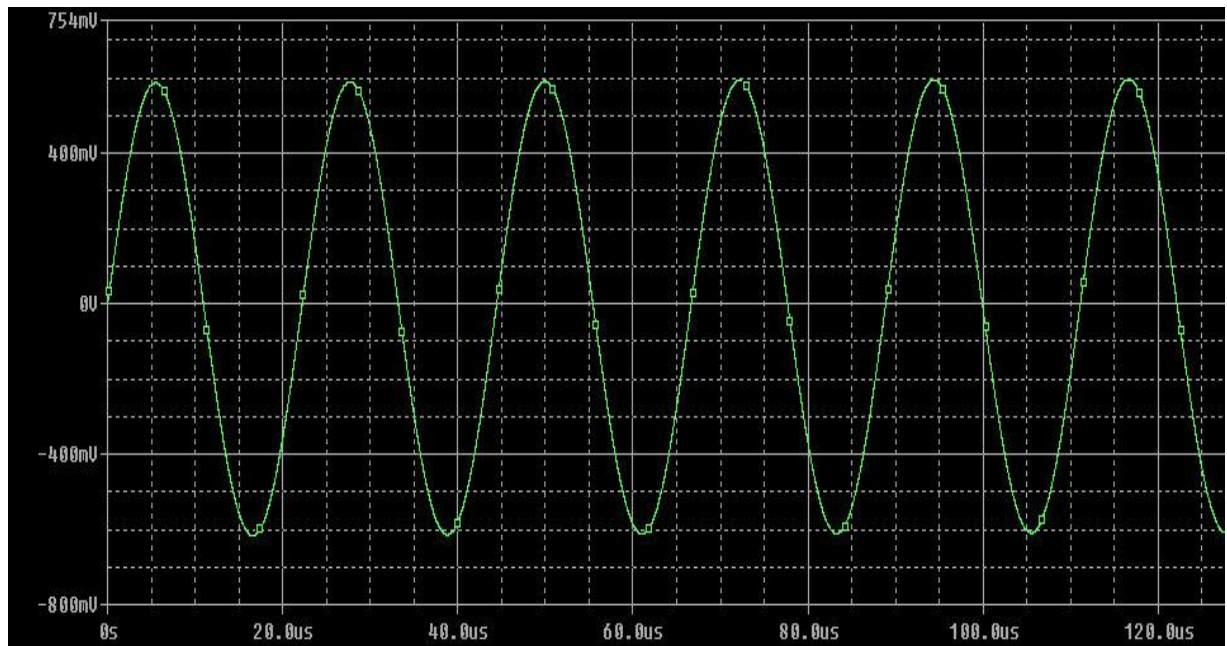


Figure B7 Parameters: input current = 10A, input voltage = 12V, frequency = 45 KHz, grid impedance = 15 Ω

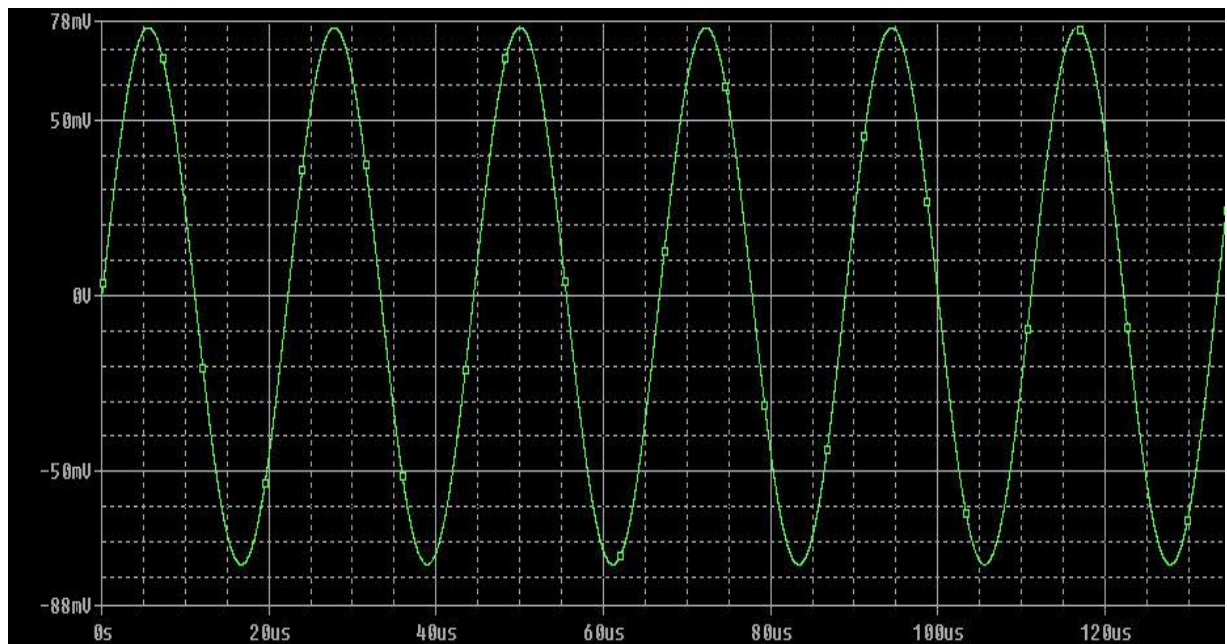


Figure B8 Parameters: input current = 10A, input voltage = 12V, frequency = 45 KHz, grid impedance = 0.9 Ω