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POWER LINE COMMUNICATIONS: AN IMPLEMENTATION OF A REAL TIME CONTROL ARCHITECTURE FOR SMART GRID

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La nostra vita è un misto di dolore e godimenti,
di affanni e di speranze, di patimenti e conforti.
Si lavora con le mani e con la testa,
si viaggia a piedi o in piroga,
si studia, si suda, si soffre, si gode:
ecco quello che vuole da noi la Provvidenza

S. Daniele Comboni

Abstract

The presence of the distributed energy resources (DERs) over the power grid has grown in recent years. The "Smart Grid" vision tries to introduce a distributed control and communication infrastructure, in order to exploit the potential of DERs and then improving and modernizing the current electric distribution grid. Applying it to the low voltage distribution network, the so called "Smart Microgrids", a testbed is developed as a proof of concept of distribution loss reduction techniques. The adopted solution balances locally the reactive power of the microgrid by controlling the local sources and thus reducing the total current needed to power the microgrid. Moreover, the advantages and benefits of the use of power lines as a transmission medium in low voltage networks are investigated and several standards and regulations are highlighted.

Abstract

Negli ultimi anni è aumentata la presenza di risorse energetiche distribuite (DERs) nella rete elettrica. La visione della "rete intelligente" (Smart Grid) cerca di introdurre un'infrastruttura di controllo e di comunicazione di tipo distribuito in modo da sfruttare le potenzialità delle DERs e quindi potenziare e modernizzare la rete di distribuzione attuale. Applicandolo alle reti a bassa tensione, la cosiddetta "Smart Microgrids", si è sviluppato un banco di prova (testbed) che permette di dimostrare tecniche di riduzione delle perdite di distribuzione. La soluzione adottata bilancia localmente la potenza reattiva della microgrid attraverso il controllo delle risorse locali ottenendo una riduzione della corrente necessaria per alimentare la rete. Inoltre, vengono analizzati i vantaggi nell'usare la linea elettrica come mezzo di comunicazione e vengono evidenziati alcuni standard di comunicazione.

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Chapter 1

Introduction

In recent years, power network has changed its structure, from a centralized approach where the energy was generated by big generation plant, to a distributed generation scenario where numerous small sources are installed. The distributed energy resources (DERs) have become widely used thanks to incentives to exploit renewable energy sources.

Hence, the old control approach does not take all the advantage of the DERs presence. The Smart Grid concept aims to improve power network "quality" by facilitating connection and operation of generators of all sizes and technologies, enabling the demand side to play an important part in optimising the operation of the system, extending power balancing into distribution and home, providing consumers with greater information and choice of supply, reducing significantly the environmental impact of the total electricity supply system, delivering the required levels of reliability, flexibility, quality and security of supply. For such purposes, a control and communication infrastructure is needed in order to implement a synergic use of DERs.

To this end, a key technology for communication techniques is power line communications (PLC). In this thesis we will study application of PLC to the control of a smart microgrid. Chapter 2 will introduce the advantages, disadvantages, issues and regulation of PLC, whereas Chapter 3 will analyse and discuss some of the recent PLC protocols for narrowband and broadband solutions. The above mentioned Smart Grid vision and design challenge will be presented in Chapter 4.

In this work, we implement a testbed that reduce the current needed in the power distribution network by locally balancing the exchanged reactive power. This approach reduces the distribution losses and allows to deliver higher active power to the user. The control and communication infrastructures are implemented in PLC modems located in the experimental lab. In Chapter 5, the modem devices and the experimental lab will be described, whereas in Chapter 6 the implemented control techniques will be presented.

Chapter 2

Power Line Communication Technology

The term Power Line Communication (PLC) is used to describe the technology devoted to carry data by the power cable used to carry electric power. Nowadays it is a prominent technology that easily allows to create a data network without deployment of new cables. In fact, it is realized transmitting high frequency signal over the normal power line signal that work at 50 Hz (in Europe) or 60 Hz (in USA).

Power lines were originally devised to transmit electric power from a small number of sources (the generators) to a large number of sinks (the consumers). It is a fact that power transmission towers and lines are some of the most robust structures ever built.

Access networks are very important for network providers because of their high cost and the possibility of the realization of direct access to the end user/subscribers [1]. However, an access network connects a limited number of individual subscribers.

Using electric powerlines as the data transmission medium in a residential contest allows high speed communication almost anywhere there is an AC outlet. In most cases, building a home network using the existing AC electrical wiring is easier than trying to run wires, more secure and more reliable than radio wireless systems like 802.11b, and relatively inexpensive as well [2]. For most small office home office (SOHO) applications, this is an excellent solution to the networking problems.

At first, single carrier narrowband solutions were used. Those operate in the audio/low frequency bands and can achieve data rates ranging from few bps to a few kbps. It was used in order to communicate between trains, to control the electrical devices using theirs own electrical network distribution, to read remotely electric meters. As technology matured and the application space widened, broadband PLC systems operating in the high frequency band (2–30 MHz) and achieving data rates up to a 200 Mb/s started to appear in the market. In the last few years, industry interest has also grown around the so-called high data rate narrowband PLC based on multicarrier schemes and operating in the band between 3–500 kHz.

Data rates and distance limits vary widely over many power line communication standards. Low-frequency (about 100-200 kHz) carriers impressed on high-voltage transmission lines may carry one or two analogue voice circuits, or telemetry and control circuits with an equivalent data rate of a few hundred bits per second. However, these circuits may be many kilometres long. Higher data rates generally imply shorter ranges; a local area network operating at millions of bits per second may only cover one floor of an office building, but eliminates the need for installation of dedicated network cabling [3].

2.1 Limits of PLC

There are some limits that slow down PLC developing and standardization process. Power supply providers try to keep actual distribution network structures in order to maintain their control. On the other hand, ICT manufacturers push to develop PLC technology applied in the Smart Grid scenario as a new promising filed. Thus, most of the efforts come from ICT rather than electric power company.

Other issues come from the field of transmission techniques. Defining and modelling PLC channel is not an easy process, it is not possible to model with the well known wired and wireless channel. Moreover, PLC highly suffers from interference of others communication channel, e.g. radio wireless communication. In this section, PLC and its limits will be illustrated.

2.1.1 Power Supply Networks

In the electrical supply system it is possible to distinguish three different network levels that are used to transport electrical power in order to dis-

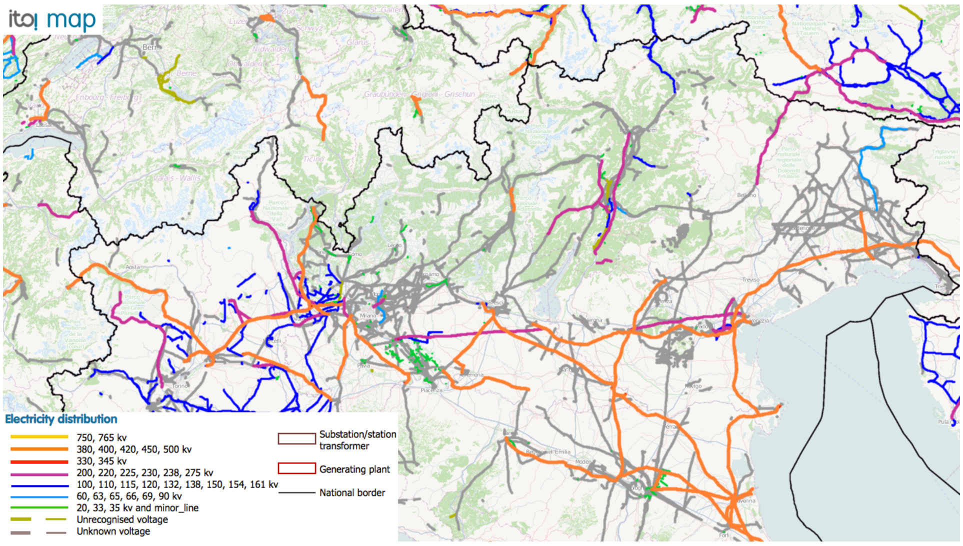

Figure 2.1: *Power electrical distribution network in north Italy from ITO World Ltd web page using OpenStreetMap data*

tribute it to home users and industries (in Figure 2.1 is shown an example of the north Italy distribution network, owned by Enel SpA).

- *High-voltage* networks goes from about 100 to 500 kV and are usually realized with overhead supply cables. They are mainly used to connect power station with large supply regions or big customers. They are also used to exchange power between different states or continents as they are suitable for very long distance link.

- *Medium-voltage* networks goes from about 10 to 30 kV and are realized as both overhead and underground networks. Spanned distance are significantly shorter than in the high-voltage networks. They are used for supply larger areas such as metropolitan and large industrial or commercial costumers.

- *Low-voltage* networks are different in each country. In Europe is distributed with 230/400 V, whereas in U.S.A. is distributed with 120 V system. The cable length is shorter, few hundred meters, due to the power loss introduced by underground connection cables. These networks are used to supply end users either as individual costumers or as single users of a bigger costumers.

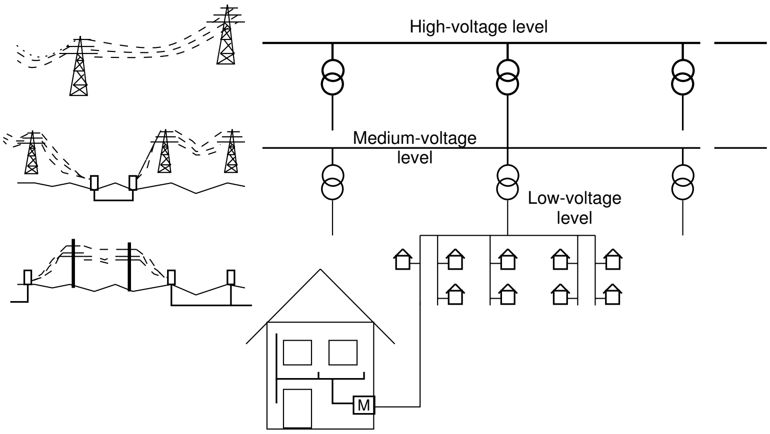

Figure 2.2: *An example of structure of electrical supply networks [4]*

As abovementioned, home electrical installations are powered with low voltage and are connected through a meter unit. This unit divides the home electrical network, owned by costumer, for the supply network, owned by electrical supply company (see Figure 2.2).

Hence, with respect to the end user prospective, low voltage supply distribution networks are the most widely spread network. Thus, low voltage PLC technology seems to have an high prospective regarding the number of connected users. On the other hand, low voltage networks cover few hundreds of meters between the transformer unit and the costumers therefore PLC offers an alternative solution of the realization of the so-called “last mile” access.

2.1.2 Interference

One of the most important issue against the use of PLC technology is often due to interferences on radio emitters.

In order to avoid interferences between the power line communication and radio transmission, a shared regulatory was developed. The power level emitted by PLC is usually few watt and the inducted electromagnetic field is comparable on ones of mobile phones, and is lower than the ones emitted by television and radio transmission.

2.2 PLC technologies

There are three main type of PLC technologies [5]:

Ultra Narrow Band (UNB): technologies operating at very low data rate (∼100 bps) in the ultralow frequency (0.3–3 kHz) band or in the upper part of the super low frequency (30–300 Hz) band.

UNB-PLC have a very large operational range (150 km or more). Although the data rate per link is low, deployed systems use various forms of parallelization and efficient addressing that support good scalability capabilities. Despite the fact that these UNB solutions are proprietary, they are very mature technologies, they have been in the field for at least two decades, and have been deployed by hundreds of utilities.

Narrowband (NB): technologies operating in the VLF/LF/MF bands (3–500 kHz), which include the European CENELEC bands, the US FCC band, the Japanese ARIB band and the Chinese band. Specifically, we have the following:

- *Low Data Rate (LDR):* single carrier technologies able of data rates of few kilobits per second. Some typical examples of LDR NB-PLC technologies are: LonWorks, IEC 61334, X10, HomePlug C&C, SITRED, etc.
- *High Data Rate (HDR)*: multicarrier technologies capable of data rates ranging between tens of kilobits per second and up to 500 kbs. Typical examples of HDR NB-PLC technologies are: ITU-T G.hnem, IEEE 1901, PRIME and G3-PLC.

Broadband (BB): technologies operating in the HF/VHF bands (1.8–250 MHz) and having a PHY rate ranging from several megabits per second to several hundred megabits per second. Typical examples of BB-PLC technologies are: HomePlug 1.0 (and following version), IEEE 1901, ITU-T G.hn, etc.

2.3 The Powerline Channel

As already mentioned, power line carrier was not designed for data transmission and provides a harsh environment for it. Time varying impedance along the line, a lot of noise that is not white and line attenuation higly dependant on frequency important issue for communications on power line [1].

Varying channel model

In order to contrast the harsh condition, the channel has to be analysed and modelled accordingly. The channel cannot be modelled as an easy Additive White Gaussian Noise (AWGN), but the transfer function is extremely complicated. Power line networks are usually made of a variety of conductor types, joined almost a random, and terminating into loads of varying impedance.

The amplitude and phase response on such transmission medium may vary widely with frequency. Moreover, the channel transfer function itself is time varying since plugging in or switching off devices connected to the network would change the network topology. Hence, the channel may be described as random and time varying with a frequency dependent signal to noise ratio (SRN) over the transmission bandwidth.

There is a lot of literature that had treated channel frequency response. A detailed discussion of modelling with mathematical treatment for power line channel and signal propagation modelling is given in [6] or [7, 8].

Highly dependence on device location

The location of the transmitter and of the receiver could have a high impact on transmission quality. For example, if the receiver is located near of the noise source and thus the signal to noise ratio (SNR) is lower than the case of the receiver located far from the noise source. The noise sources could be home devices plugged into the network.

Reflection, Multi-path fading and attenuation

As for wireless channel, the propagation of the received signal is usually not direct-line but is composed of many propagation paths that cause echos. Generally, refection are due to the various impedance mismatches in the electric network.

Noise

As above mentioned, noise in power lines is a significant issue for data transmission. The noise on power line channel is not as well studied as white gaussian noise, but is composed of different type of noises, impulsive or frequency selective in nature and, sometimes, both. Due to high attenuation over the power line, the noise is also location dependent.

Recent studies show that noise in PLC system can be classified into four categories [1]:

i. *Colored noise:* this type of noise has relatively low power spectral density which decreases with increasing frequency. It can be seen as a sum of all low power noise sources and may be time varying.

ii. *Narrowband background noise:* this noise is mainly caused by amplitude modulated signals that are emitted by broadcast radio on medium and short wave bands.

iii. *Synchronous impulse noise:* this impulse noises are periodically repeated on multiples on the power electric base frequency, i.e. 50 Hz or 60 Hz. It has a short duration and a power spectral density that decrease with increasing frequency. The noise may be caused by power supplies that operates synchronously to the main frequency.

iv. *Asynchronous impulse noise:* this is the type of noise that create most difficulties on PLC. Is very difficult to model, it vary on time duration, has a random interval time and the power spectral density can be very high (can be 50 dB above the background noise spectrum).

   Hence, is capable to wipe out blocks of data symbols during data transmission. This noise is principally caused by switching transient in the system network.

2.4 Frequency Regulations

There are no centralized standardization that universally regulate the frequency band on power cables. There are some mayor standard that actually dominate the market, but there are others standard that uses the same band. Next, regulations standard pertaining to the powerline communications are presented.

CENÉLEC BAND	*FREQUENCY BAND*	*USE*
*	3 to 9 kHz	Limited to electrical network operators for their specific needs, like remote meter reading
A	9 to 95 kHz	Limited to electrical network operators
B	95 to 125 kHz	Home automation use (baby phones, and so forth)
C	125 to 140 kHz	Home automation use (X10, and so forth)
D	140 to 148.5 kHz	Home automation use

* No "letter" description exists, due to the fact that this band was defined at a larter stage.

Table 2.1: *CENELEC frequency band for Low Bit Rate PLC*

2.4.1 European Committee for Electrotechnical Standardization (CENELEC)

CENELEC (French: Comité Européen de Normalisation Électrotechnique) is the is responsible for European Standardization in the area of electrical engineering. Together with ETSI (telecommunication) and CEN (other technical areas) CENELEC form the European system for technical standardization.

The regulations concerning Low Bit Rate PLC are described in CENELEC standard EN 50065 entitled "Signalling on low-voltage electrical installations in the frequency range 3 kHz to 148.5 kHz". The frequency range which is allowed for communications ranges from 3 to 148.5 kHz and is subdivided into five sub-bands which are shown in Table 2.1. The maximum allowed transmitter output voltage is also defined.

CENELEC norm makes possible data rates up to several thousand bits per second, which are sufficient only for some metering functions, data transmission with very low bit rates and the realization of few numbers of transmission channel for voice connections.

2.4.2 Federal Communications Commission (FCC)

The regulatory body for radiocommunications and telecommunications in the USA is the Federal Communications Commission (FCC). The FCC enforces mandatory requirements for telecommunications and radiocommunications systems.

The frequency band allowed here ranges from 0 to 530 kHz (allocated at 100 – 490 kHz) which is considerably larger than Europe. Part 15 of the FCC rules allows powerline communication outside the AM frequency band (outside 535 to 1705 kHz).

2.4.3 Association of Radio Industries and Business (ARIB)

In Japan, the Association of Radio Industries and Business (ARIB) regulates the frequency spectrum. For power line communication, the allowed frequency goes from 10 kHz to 450 kHz [9].

2.4.4 Electric Power Research Institute (EPRI)

In China, the Electric Power Research Institute (EPRI) had not regulated the frequency domain devoted to power line communication. On the other hand, practically the frequency used are 3-90 kHz or 3-500 kHz [10].

Chapter 3

Protocols for PLC

There are several protocol solutions in literature for PLC in each different field (broadband PLC, narrowband PLC, etc.). For example, IEEE has proposed several PLC standards, as IEEE P1675, IEEE P1755, IEEE P1901, but only the last one, IEEE 1901, has reached some interest. On the other hand, HomePlug Powerline Alliance Standard may be integrated into the IEEE 1901 standard.

Hence, there exists a very high competition between standard and none is now winning over the others. One of the most promising candidates for PLC broadband network (both last-mile and last-inch solution) is the HomePlug series standard, developed by HomePlug Powerline Alliance. However, there are other competitors in the medium/low voltage high-speed narrowband communication field, e.g. PRIME and G3-PLC standards. Those two standards are developed to be the base protocol for the "Smart Grid technology".

Generally, the protocols here presented are designed to work on low voltage but sometimes they can also work on both low and medium voltage power lines. In this chapter two mayor narrowband standards will be analyzed, PRIME and G3-PLC. Next, two broadband protocol are presented: HomePlug series standards are among the most interesting protocols at this time, whereas IEEE 1901 (that, at time of writing, is at draft status process) aims at unify the first and last mile broadband communications. In the last section the LonWorks protocol is presented, as today is the biggest PLC network realization in the world[11].

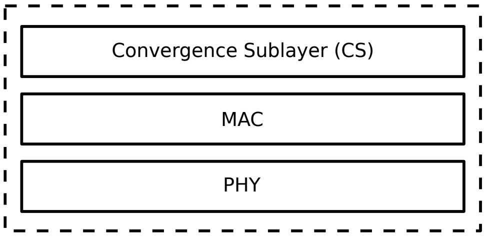

Figure 3.1: *PRIME Control and Data Plane*

3.1 PRIME

PRIME stands for *PoweRline Intelligent Metering Evolution* and was launched by Iberdola in order to meet future requirements on customer real time interfacing and smart grid evolution. The project aims to be an open, public and non-proprietary telecom solution, which will support not only smart metering functionalities but also the progress towards the Smart Grid.

It is developed by the *PRIME ALLIANCE* which provides a forum for the creation of an open, single specification standard for narrowband power lines for Smart Grid products and services. The mission of the Alliance is to accelerate the demand for products and services based on the worldwide standard and promote the broad adoption and use of the specification while promoting multi-vendor interoperability and compatibility with the global standard [12].

3.1.1 Features

PRIME defines a lower layer of a PLC narrowband data transmission system over the electric grid. The entire system has been created to be low cost and high performance. The proposed reference model is based on IEEE Std. 802.16 protocol layering and is shown in Figure 3.1 [13].

The service-specific Convergence Sublayer (CS) classifies traffic associating it with its proper Medium Access Control (MAC) connection. This layer performs the mapping of any kind of traffic to be properly included in MAC Service Data Uints (SDUs). It may also include payload header suppression functions. Multiple CSs are defined in order to accommodate different kinds of traffic into MAC SDUs.

The MAC Layer provides core MAC functionalities of system access, bandwidth allocation, connection management and topology resolution. It

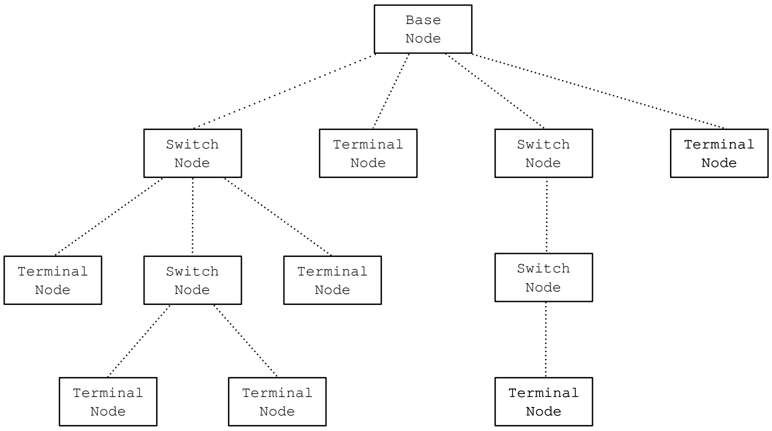

Figure 3.2: *An example of a PRIME network topology where three level are represented*

has been defined for a connection oriented Master-Slave environment, and optimized for low voltage power line environments.

The Physical (PHY) Layer transmits and receives MAC PDUs between Neighbor Nodes. It is based on Orthogonal Frequency-Division Multiplexing (OFDM) multiplexing in CENELEC-A band and reaches up to 130 kbps raw data rate. PRIME specifications take advantages of state of the art technologies and adapt them to the needed requirements, simplifying processes and overheads, to ensure performance, interoperability between devices and different system implementations [12].

In next sections, the stack level implementation used in PRIME standard will be discussed.

3.1.2 System Architecture

The PRIME system is composed of subnetworks, each of them defined in the context of a transformer station. A subnetwork is a tree with two types of nodes, the Base Node and the Service Nodes. An example of a PRIME network is shown in Figure 3.2 and will be discussed later.

Base Node

The Base Node is at the root of the tree and acts as master node that provides connectivity to the subnetwork. It manages the subnetwork resources and connections. There is only one Base Node in a subnetwork.

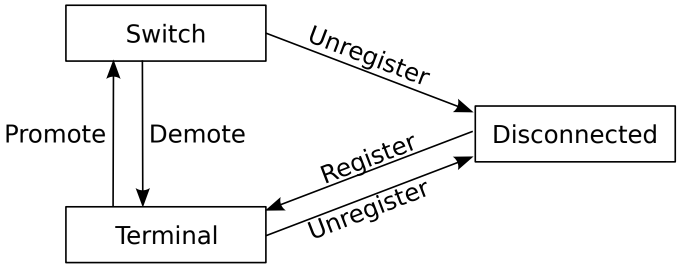

Figure 3.3: *The three status of a PRIME service node*

This Base Node is initially the subnetwork itself, and other nodes should follow a process of registering in order to enroll them to this subnetwork [12].

Service Nodes

Any other node of the subnetwork is a Service Node. Service Nodes are either leafs of the tree or branch points of the tree. These nodes start in a disconnected state and follow certain procedures to establish network connectivity. Each of these nodes is one point of the mesh of the subnetwork. These nodes have two responsibilities: connecting themselves to the subnetwork and switching the data of their neighbors in order to propagate connectivity [12].

Service Nodes change their behavior dynamically from "Terminal" functions to "Switch" functions and vice-versa (see Figure 3.3). Changing of functional states occurs based on certain predefined events in the network.

The three functional states of a Service Node are:

Disconnected: Service Nodes start in a disconnected state. In this state a node is not capable of communicating or switching the traffic of another node. The primary function of a Service Node in this state is to search for an operational network in its proximity and to try to register itself to it.

Terminal: In this state a Service Node is capable of communicating its traffic by establishing connections, but is not capable of switching the traffic of any other node.

Switch: In this state a Service Node is capable of performing all Terminal

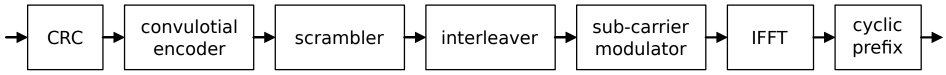

Figure 3.4: *The block diagram representation of a PRIME PHY transmitter*

functions. Additionally, it is capable of forwarding data to and from other devices in the subnetwork. It is a branch point in the tree.

3.1.3 PHY Layer

PRIME PHY Layer uses a combination of approaches that ultimately allow for robust high speed, low cost communications over power lines. As modulations is adopted scheme Orthogonal Frequency Division Multiplexing (OFDM) with an optional Forward Error Correction (FEC) and data interleaving.

In Figure 3.4, the block diagram of the PRIME PHY transmitter is shown, where the convolution encoder and the interleaver are present only if the MAC Layer decided to use the FEC algorithm. Then, the transmitter adds the CRC block and, if decided by higher layer, the resulting block is convolutionally encoded and interleaved (it will always be scrambled). Finally, the output is differentially modulated using a DBPSK, DQPSK or D8PSK scheme. The last step is OFDM, which comprises the IFFT (Inverse Fast Fourier Transform) block and the cyclic prefix generator.

The primary advantage of OFDM over single-carrier schemes is its ability to cope with severe channel conditions without complex additional mechanisms (e.g., equalization filters). Channel equalization is simplified because OFDM may be viewed as using many slowly-modulated narrowband signals rather than one rapidly-modulated wideband signal.

Additionally, a low symbol rate makes the use of a guard interval (or cyclic prefix) between symbols affordable, rendering it possible to handle time-spreading and eliminate intersymbol interference (ISI). For low frequencies like the ones PRIME uses, multipath is not a critical issue so cyclic prefixes will not waste a significant part of OFDM symbols [12].

Organization of the Spectrum

As we discussed before, in Europe the frequency spectrum for power cable is assigned by CENLEC. PRIME decided to concentrate on the CENELEC-

A band, that goes from 9 to 95 kHz, as it provides a cheap solution, a regulatory certainty solution and a extensively tested frequency for power line communications. In particular, a subset of the frequencies is used: between approximately 45 kHz and 90 kHz, channel characteristics are better than the other part of the CENELEC-A frequencies.

The final frequency usage of PRIME OFDM signal is from 41992.1875 Hz (that correspond to the first subcarrier central frequency) to 88867.1875 Hz (that correspond to the last subcarrier central frequency) [13]. In total, PRIME uses more than 47 kHz of bandwidth and still comfortably fits inside the "best" part of CENELEC-A band.

PRIME OFDM signal presents these features:

- The subcarrier spacing is 488.28125 Hz.
- With the available bandwidth this implies 97 subcarriers. 96 of them will be used for data.
- The IFFT interval length is 2.048 ms plus a cyclic prefix of 0.192 ms.

In order to cope with electromagnetic limits, PRIME defines a Transmit PSD (Power Signal Density) measurement setup: the power amplifier shall be capable of injecting a final signal level in the transmission node of 120 dBμVrms (1 Vrms) when connected to a certain artificial mains network.

Error Correction and Coding

The Forward Error Correction (FEC) is optionally used and the decision will be taken by upper layers that will adaptively decide on whether to use it or not. The selected encoder is a half rate binary non-recursive, non-systematic convolutional encoder with constraint length $k = 7$ and free distance 10.

Additionally to convolutional encoding it is necessary to perform interleaving: because of the frequency fading (narrowband interference) of typical power line channels, OFDM subcarriers at the receiver generally show different amplitudes. Interleaving is applied along with convolutional encoding to randomize the occurrence of bit errors prior to decoding. PRIME uses three different interleaving schemes depending on the constellation itself.

An additive scrambler is always used to avoid the occurrence of long sequences of identical bits. By randomizing the bit stream, the crest factor at the output of the IFFT is reduced. This is a cheap but helpful mechanism

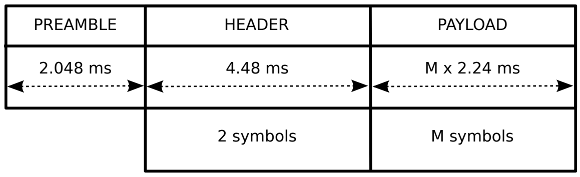

Figure 3.5: *Structure of the PRIME frame*

to decrease the Peak to Average Power Ratio (PAPR) of the OFDM signal, which could otherwise reach dangerous values.

Modulation and Frame Format

The adopted modulation scheme are from the differential PSK family; this family provides the simplest and cheapest design compared to the QAM family. Is was seen that 16-QAM benefits over 8-PSK were negligible. Then, the adopted modulation is DBPSK, DQPSK and D8PSK with or without FEC.

The unmodulated payload is modulated as a multicarrier differential phase shift keying signal with one pilot subcarrier and 96 data subcarriers that comprise 96, 192 or 288 bits per symbol. The pilot subcarrier is used inside each OFDM symbol to provide phase reference for the frequency domain differential modulation.

Each transmission starts with a fixed preamble (see Figure 3.5 for reference). This is a crucial element for synchronization purposes. The use of OFDM symbols for the preamble is not appropriate.

In order to get a robust synchronization, well-known chirp signals are chosen: they give a constant envelope signal (in order send a maximum of signal energy) and excellent autocorrelation properties.

Just after the preamble, 13 pilot subcarriers are inserted in each of the first 2 OFDM symbols to provide enough information to estimate the sampling start error and the sampling frequency offset. These two symbols form the header. The header is modulated DBPSK with 84 data subcarriers that comprise 84 bits per symbol. The header is always sent using FEC (convolutional coding) “On”.

However the payload is DBPSK, DQPSK or D8PSK encoded, depending on the SNR available to achieve the desired BER. The MAC Layer will select the best modulation scheme using information from errors in the last

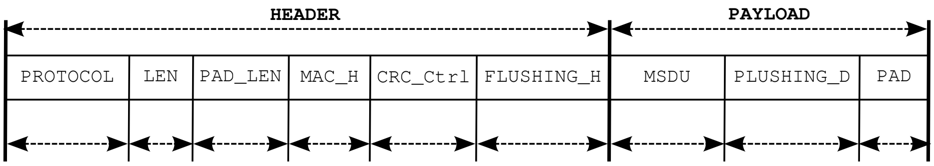

Figure 3.6: *Structure of the PRIME PHY packet*

frames. The system will then configure itself dynamically to provide the best compromise between throughput and efficiency in the communication. This includes deciding whether or not FEC (convolutional coding) is used. Each OFDM symbol in the payload carries 96 data subcarriers and one pilot subcarrier. Each data subcarrier will have a bit-load of 1, 2 or 3 bits.

The fields that form the header and payload, represented in Figure 3.6, are:

HEADER: it is composed of the following fields:

- PROTOCOL: contains the transmission scheme of the payload.
- LEN: defines the length of the payload in OFDM symbols. Thus a maximum of 63 OFDM symbols will be transmitted in one payload.
- PAD_LEN: defines the length of the PAD field in bytes.
- MAC_H: MAC Layer Header. It is included inside the HEADER symbols to protect the contained information.
- CRC_Ctrl: the CRC_Ctrl(m), $m = 0 \ldots 7$, contains the CRC checksum over PROTOCOL, LEN, PAD_LEN and MAC_H field (PD_Ctrl).
- FLUSHING_H: flushing bits needed for convolutional decoding. All bits in this field are set to zero to reset the convolutional encoder.

PAYLOAD: is composed of the following fields:

- MSDU: Uncoded MAC Layer Service Data Unit.
- FLUSHING_D: flushing bits needed for convolutional decoding. All bits in this field are set to zero to reset the convolutional encoder. This field only exists when FEC is 'On'.

- PAD: Padding field. If the last OFDM symbol is not completed, the padding data must be inserted.

3.1.4 MAC Layer

The Medium Access Control (MAC) layer provides the addressing and channel access control mechanism that makes it possible for several nodes to communicate. In this section, the particular solution adopted by PRIME solution will be analyzed.

Addressing

In a PRIME network, each connection can be univocally identified over all the PRIME network. Each nodes as its universal MAC address, i.e. EUI-48[1]. Each manufacturer assigns this address during manufacturing process and it is used to universally identify a node during network registration process.

The Base Node of the subnetwork use its EUI-48 as the Subnetwork Address (SNA) identifier (exist only one Base Node per subnetwork). Then, the Base Node assigns an Switch Identifier (SID) to each switch node during the promotion process. This SID is a unique identifier of 10 bits for each Switch Node inside a subnetwork. A Switch Node is universally identified by the pair of SNA and SID. SID = 0 is reserved for the Base Node.

Every switch has the authority to assign an ID to each terminal that is added in its network trunk. The switch assigns a Local Node Identifier (LNID) (which is 16 bits long) to each Terminal Node during the registration process. The LNID = 0 is reserved for the Switch Node. LNID uniquely identifies a node within the nodes served by a Switch. Hence, a node can be univocally identified by a pair of SID and LNID. The combination of SID and LNID is called Node Identifier (NID).

During connection establishment a local connection identifier (LCID) is reserved. This field, which is 6 bits long, identifies specific connection in a node. The combination of NID and LCID is called Connection Identifier (CID). CIDs uniquely identify connections in a subnetwork.

Any node (or connection) can be universally identified by a pair of SNA and NID (or CID). The representation of the addressing structure is shown in Figure 3.7.

[1] Extended Unique Identifier (EUI) is standardized by IEEE and is a way of identify (and represent) a node in a network using 48 bits, for EUI-48, and 64 bits, for EUI-64.

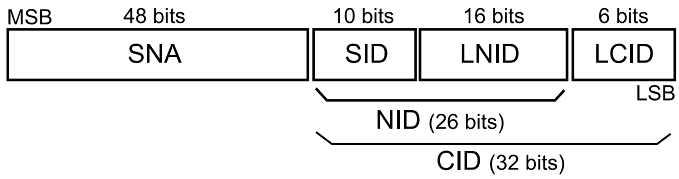

Figure 3.7: *Representation of the full addressing structure and length of PRIME MAC Layer*

Additionally, multicast and broadcast addresses are used for transmission of data and control information. There are several broadcast and multicast address types, depending on the context associated with traffic flow.

Each Service Node has a level in the topology. The nodes that are connected directly to the Base Node have level 0. The level of any Service Node not directly connected to Base Node is the level of its Switch Node plus one.

Network Management

A Base Node is primarily responsible for setting up and maintaining a subnetwork. In order to execute its task, the Base Node performs the following:

- *Beacon transmission:* it transmits its own beacon and coordinate the beacon transmission among the Switch Nodes.

- *Promotion and demotion of terminals and switches:* Manage all promotion requests, generated by Terminal Nodes, and maintains a table of all Switch Nodes in the subnetwork and allocates a unique SID to new incoming requests. Likewise, the Base Node is responsible for demoting any registered Switch Nodes (initiated by the Base or by the Switch Node itself).

- *Device registration management:* The Base Node receives registration requests and assigns an unique NID. As before, also de-registration is managed by the Base Node.

- *Connection setup and management:* As the MAC Layer is connection oriented, data exchange is necessarily preceded by a connection establishment and the Base Node has to be informed.

- *Channel access arbitration:* Channel access can be contention-free or contention-based. The Base Node prescribes which usage mechanism shall be in force at what time and for what duration.

- *Distribution of random sequence for deriving encryption keys:* In order to encrypt all MAC control packets[2], the encryption key is derived from a 128 bit random sequence. The Base Node periodically generates a new random sequence and distributes it to the entire subnetwork.

- *Multicast group management:* The Base Node maintains all multicast groups in the subnetwork.

Channel Access

Channel Access and multiplexing in PRIME subnetwork is implemented by Carrier Sense Multiple Access (CSMA/CA) and Time Division Multiplex (TDM). Time is divided into composite units of abstraction for channel usage, called frames (see Figure 3.8). Base Node and Service Nodes in a subnetwork can access channel in either the Shared Contention Period (SCP) or they may request for dedicated Contention-Free Period (CFP).

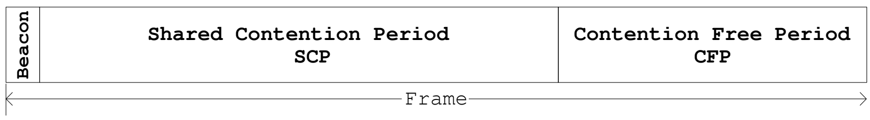

Figure 3.8: *Representation of a frame of PRIME network*

A frame is comprised of one or more Beacons, one Shared Contention Period and zero or one CFP. When present, the length of CFP is indicated in the Beacon PDU.

The channel access in CFP needs devices to make allocation requests to the Base Node. The Base Node, depending on the present status of channel usage, may grant access to the requesting devices for a specific duration or may deny the request. The channel access in SCP does not require any arbitration. The transmitting devices however need to respect the timing boundaries of the SCP within a frame. The composition of a frame in terms of SCP and CFP is communicated in every frame as a part of a beacon.

[2]MAC control packet always has to be encrypted, whereas data packet can optionally be encrypted.

Switching

In order to extend network coverage, switching function is defined as an integral part of MAC Layer. As mentioned earlier, devices that forward traffic are called Switch Nodes.

Switch Nodes do not necessarily need to connect directly to the Base Node, they may be attached to another Switch nodes and form a cascade chain. There is no limitation to the number of Switch Nodes that may connect to a Switch Node down the cascaded chain, thus contributing significantly to range extension and scalability.

Switch Nodes are primarily responsible for:

- Transmitting Beacon PDUs at fixed intervals. It helps the synchronization of Service Nodes and transmit control information to connected devices.

- Relaying data and control packets to/from the devices in their domain from/to the Base Node.

Switch nodes do not perform any control functions except for transmitting Beacons. All control functions including initial registration and subsequent connection setups are centralized in the Base Node. This allow to make cheap Service Node and give to the Base Node the full control and vision of the status of the overall subnetwork.

Each Switch Node maintains a table of other Switch Nodes that are connected to the subnetwork through it. Maintaining this information is sufficient for switching purposes because traffic to/from Terminal Nodes will also contain identifiers of their respective Switch Nodes.

Retransmissions

The power line channel at PHY operational frequencies can experience impulsive noise. While the duration of this noise is very short, it is bound to cause problems for any data on the channel. For this reason, to enable better application layer efficiency, a retransmission scheme is specified within the MAC. A "Selective Repeat" ARQ mechanism adopted.

The implementation of ARQ functions into the MAC Layer is not mandatory. Hence, Switch Nodes that does not implement ARQ are required to operate as transparently bridge.

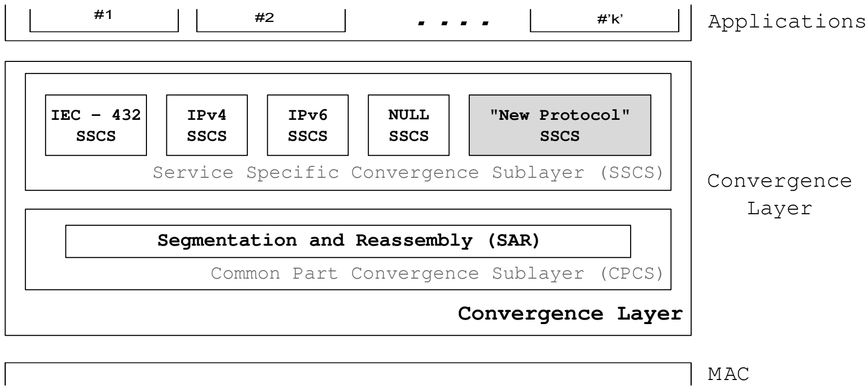

Figure 3.9: *Structure of PRIME Convergence Layer*

Security

In the PRIME standard, it is mandatory to implement some security mechanism to provide privacy, authentication and data integrity to the MAC Layer through a secure connection method and a key management policy.

While the use of encryption on data packet is optional, it is mandatory for all MAC control messages to be encrypted with a specific security profile (128 bit AES encryption method is used). Additionally, the Beacon PDU and Promotion Needed PDU are also transmitted without encryption. The 128 AES encryption method is used.

3.1.5 Convergence Layer

The Convergence Layer (CL) is divided into two different sub-layers, the Common Part Convergence Sublayer (CPCS), that provides a set of generic services, and the Service Specific Convergence Sublayer (SSCS), that contains services that are specific to one application layer. As shown in Figure 3.9, there are a number of SSCS, typically one per application, but only one common part.

In particular, the Convergence Layer (CL) classifies traffic associating it with its proper MAC connection. This layer performs the mapping of any kind of traffic to be properly included in MAC SDUs, providing access to the core MAC functionalities of system access, bandwidth allocation, connection management and mesh topology resolution. It may also include payload header suppression functions.

Common Part Convergence Sublayer

Currently there is only one such service. It is segmentation and reassembly (SAR). The SAR segments convergence layer SDUs that are larger than a specific size into fixed size segments. The segmented data is reassembled at the destination SAR before being forwarded to applications.

PRIME specifies a uniform segment size for all convergence layers, thus making it possible to have low complexity implementations.

Service Specific Convergence Sublayer

The last revision of the protocol (v1.3.6) defines three application protocol supported by the CL:

IEC 61224-4-32 LLC: This convergence layer supports the same primitives as the IEC 61334-4-32 standard. Additionally, PRIME IEC 61334-4-32 SSCS provides some extra services that help to map this connectionless protocol to the connection oriented nature of PRIME MAC.

In this SSCS, a Service Node can only exchange data with the Base Node and not to other Service Nodes.

IPv4 and **IPv6:** The IPv4 (IPv6) convergence layer provides an method of transferring IPv4 (IPv6) packets over the PRIME network.

A Service Node can pass IP packets to either the base, or to other Service Nodes. In particular, the Base Node acts as a router between the PRIME subnet and the backbone network. Moreover, the current implementation supports only a single route but both static and dynamic configured IP address can be used (via DHCP service). Also, the convergence layer performs the routing of IP packets.

IPv4 (IPv6) convergence layer in PRIME is connection oriented. Once address resolution has been performed (on a separated and dedicated connection), a connection is established between the source and destination Service Node for the transfer of IP packets. This connection is maintained while there is traffic being transferred and may be removed after an inactive period.

Optionally TCP/IP headers may be compressed. Compression is negotiated as part of the connection establishment phase. Finally, Broadcasting and multicasting of IP packets is supported in PRIME.

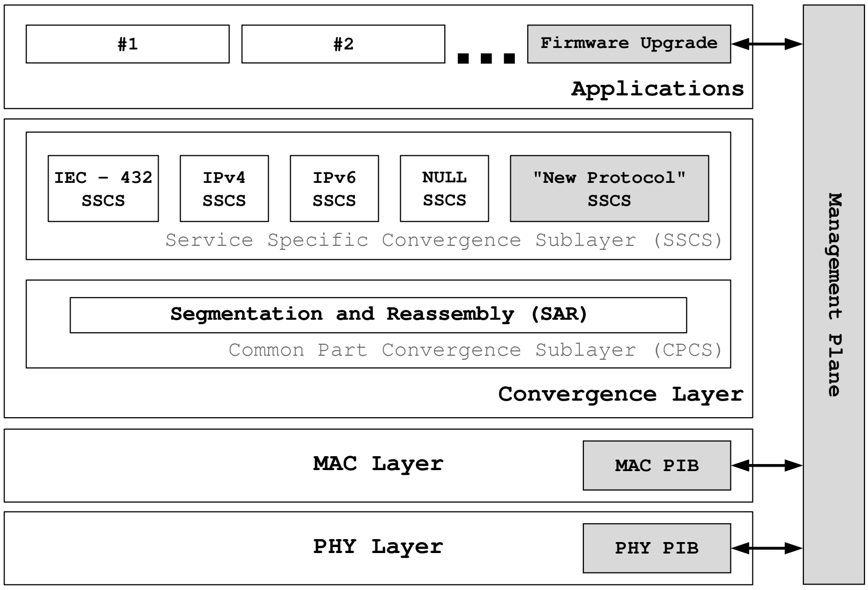

Figure 3.10: *Structure of PRIME Management Plane*

NULL: It provides a transparent layer to the upper layers. It should be as simple as possible and minimizing overhead. It is intended for applications that do not need any special convergence capability.

3.1.6 Management Plane

The last protocol block, Management Plane, is developed on the side of PRIME layers (see Figure 3.10). It is devoted to enable a local or remote control entity to perform actions on PRIME devices.

The current version of the protocol specifies device management and firmware upgrade, but other services may be added in future specifications of the protocol. Moreover, management plane functions shall use NULL Convergence Layer.

Remote operation shall be started by Base Node using management connection in order to enable access to management functions on a Service Node. Such connection could be done only on registered nodes (Terminal or Switch Nodes) but not on Disconnected nodes. Multicast management connections can also exist and, up to the last specification, multicast management connection shall only be used for firmware upgrade purposes. Obviously there is no possibility to use broadcast messages for management connection: this overcomes possibility incompatibility problems of networks composed of nodes of different vendors.

Device Management

It is accomplished through a set of attributes: both PHY and MAC layers. Some of them are called PRIME Attribute Base (PIB) and are described with a 16 bit value. The first half of them are open to be standardized and the others are open to vendor specific usage.

Attributes are divided in groups: PHY PIB attributes, MAC PIB attributes and Application PIB attributes. Each group is divided into subgroups, like: Statistical attributes, Implementation attributes, Variable attributes, Functional attributes, List attributes, etc.

Firmware Upgrade

The firmware download functionality is mandatory for PRIME devices. It is able to work in unicast and multicast modes where control messages are all sent using unicast connections and the data can be sent via unicast (by default) or multicast (if supported). The reply is only sent in unicast.

As already mentioned, broadcast is not supported in order to ensure firmware upgrade of Service Node from different vendors. The multicast and unicast connections are set up by the Base Node.

Firmware upgrade is implemented via a status machine. In particular, a "open back-door" mechanism is implemented to ensure that on all the states is possible to recover the node on the last working firmware. Moreover, Service Nodes are not allowed to discard any of the stored firmware versions until the final confirmation from the Base Node arrives or until the safety time period expires.

3.2 G3-PLC

G3-PLC is developed in order to fulfill industrial market requirements to have a power line standard that is devote for Smart Grid applications. G3-PLC is is an high speed narrowband protocol, capable of long distance communications. This protocol has the ability to cross transformer in order to reduce infrastructure cost and it is yet capable of transport IPv6 pack-

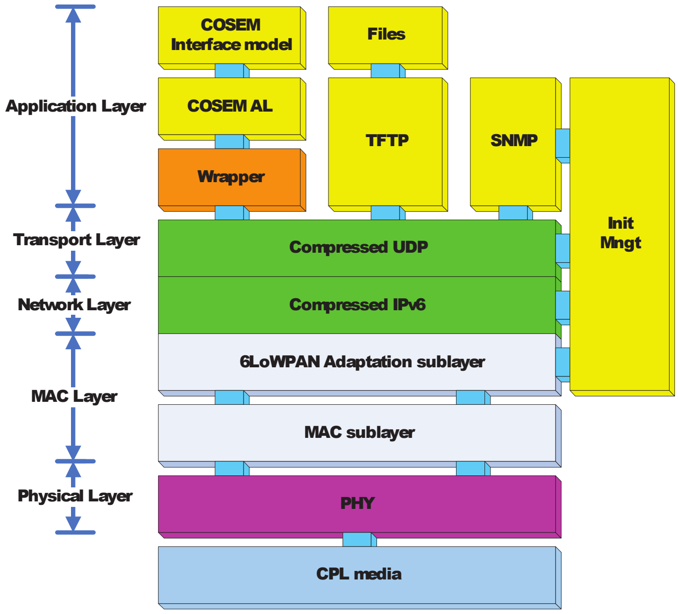

Figure 3.11: *Structure of G3-PLC protocol stack [14]*

ets using the 6LoWPAN technology. The protocol stack is represented in Figure 3.11.

The application layer comprises standards as ANSI C12.19/C12.22, IEC 62056-61/62 (DLMS/COSEM). Transport and network layers are based on UDP and IPv6 respectively.

G3-PLC implements both PHY and MAC layers. PHY layer uses frequency from 10 kHz to 490 kHz, thus is compatible with CENELEC, ARIB and FCC frequency regulations. It is based on OFDM schemes with DBPSK or DQPSK carrier modulation with a maximum data rate of 33.4 kbps on CENELEC band, and 250 kbps on FCC bands. In this chapter only use on CENELEC frequencies will be considered.

3.2.1 PHY Layer

When G3-PLC uses the CENELEC-A frequency band, as other protocols, it uses only a portion of the spectrum, between 35.9 kHz to 90.6 kHz. There is also an option that extends the upper frequency to 180 kHz.

As already mentioned above, the adopted modulation schemes uses OFDM with DBPSK and DQPSK to support up to 34.1 kbps data rate in normal mode of operation (on CENELEC band). To achieve best per-

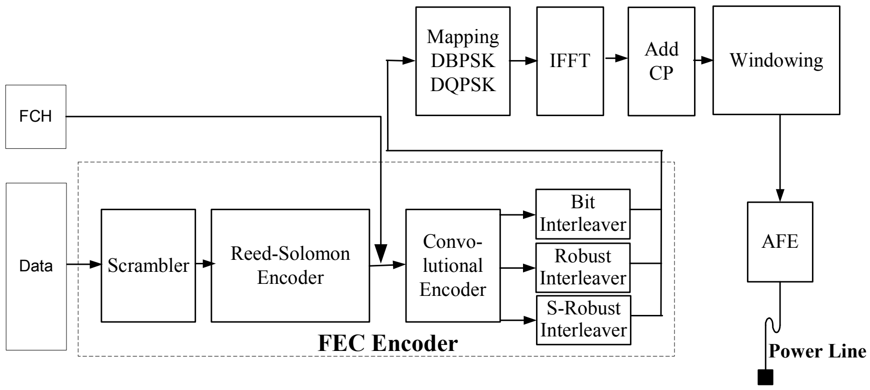

Figure 3.12: *Block diagram of the G3-PLC System [15]*

formance, 36 subcarriers with frequency spacing of 1.56 kHz are used (IFFT size is 256).

A block diagram of the system is shown in Figure 3.12. There are three modes for the that PHY layer work: normal DBPSK mode, normal DQPSK mode, and ROBUST mode. In normal modes, the forward error correction (FEC) is applied using a Reed Solomon encoder followed by an half rate convolutional encoder with an octal generator polynomial and a constraint length of 7. In ROBUST mode, the FEC is composed as normal mode but, on last phase, a Repetition Coder is added. This repetition coder introduces three bits of redundancy for each data bit. There is also an option for a super ROBUST mode which is used to transmit the Frame Control Header (FCH). It uses convolutional code combined with RC that introduces five bits of redundancy for each data bits.

In order to correct for errors from both sources, following the convolutional encoder, a two-dimensional interleaving scheme is applied, with the first bit interleaved in the time domain, and the second is interleaved in the frequency domain. This technique prevents frequency-dependent fading and impulsive noise from disrupting the data. At the end, an IFFT is applied to the data with 256-point IFFT of the data and generates 256 time-domain samples that are then pre-pended by 30 samples of cyclic prefix. Finally, Raised Cosine shaping is applied to both data and frame control symbols in order to reduce the out-of-band emission and the spectral side lobes.

The PHY supports two types of frames: Data frame and ACK frame, where the ACK frame is similar as the Data frame but without the data section. An example of a G3-PLC PHY layer packet is shown in Figure 3.13. A typical frame starts with a preamble used for synchronization purposes and then followed by symbols allocated for Frame Control Header (FCH). FCH has important control information (type, length, tone map index, etc.) required to demodulate the data frame that follows. The FCH data integrity is protected with a 5-bit CRC. Following FCH, a data frame consisting of a maximum of 252 data symbols is transmitted.

PHY layer also implements functions like fragmentation, SNR monitoring and channel estimation.

3.2.2 MAC Layer

There are two devices type that compose the G3-PLC network:

Full-Functional Device (FFD): there are three modes for a FFD: coordinator of the Personal Area Network (PAN), coordinator or simple device. An FDD can communicate with other FDDs, and implements all functions of MAC layer and of IEEE 802.15.4 protocol.

Reduced-Function Device (RFD): this device differs from FDD as it implements a reduced functionality of MAC layer. RFD devices have limited resources in terms of memory, computation capacity and thus can't be a coordinator. Moreover, RFD can't communicate with other RFDs but only with FFDs.

Two type of network topology implemented are in G3-PLC protocol, as represented Figure 3.14:

Star Topology: consists on a central coordinator node of the networks surrounded by other nodes. Other nodes can communicate only with the coordinator; hence two nodes exchange messages only routing packet through the coordinator node. The coordinator node then forwards the message to the destination node.

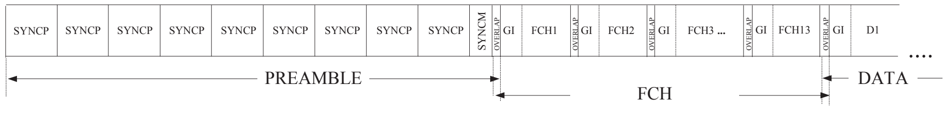

Figure 3.13: *Structure of G3-PLC PHY layer packet*

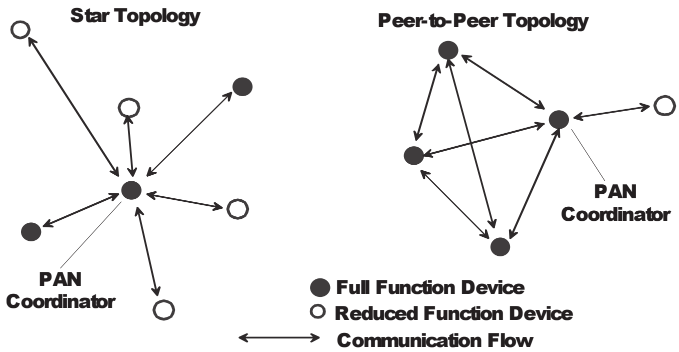

Figure 3.14: *Structure of the two G3-PLC MAC layer topology, star topology and peer-to-peer topology*

This topology has some drawbacks: there is no alternative route and it suffers of fall out in case of a bad communication channel between the coordinator and the node. Next, the coordinator node may be a bottleneck for the system.

Peer-to-Peer Topology: also in this structure there exists a coordinator node but, differently by star topology, each node can communicate with other nodes, in its "coverage range", without assistance by the coordinator.

The system enables a multi-hop option that allows to reach all nodes of the network. Hence, there could be multiple alternative route between two nodes, avoiding system blocks due to deterioration of the communication channel. A peer-to-peer network automate organizing operation and link recovery.

At MAC layer, each node shall have a Neighbor Table of information of all devices on its coverage. This table has the information needed by MAC and PHY layer to initiate the communication link between neighbor nodes. It is updated each time that a packet is received by neighbor nodes.

As previously mentioned, G3-PLC MAC layer is divided into two sublayers: MAC Sublayer and 6LoWPAN Adaptation Sublayer.

MAC Sublayer

The MAC Sublayer is based on IEEE 802.15.4 and then its functionalities are derived by this protocol. In G3-PLC, beacon packets are not transmitted periodically, as PRIME, but a request is needed. Hence, non beacon techniques is used.

Those involve a reduced traffic congestion due to cyclic beacon transmission. Next, G3-PLC does not have a contention free period frame, but only a contention period.

The functions carried out by MAC Sublayer are:

- *MAC Protocol Data Unit (MAC PDU) generation*: There are three types of MAC PDU: MAC Data Frame, that adds some header field to packet coming from the 6LoWPAN sublayer (like sequential number, source and destination node address, etc); MAC Check Frame that carries control information (like channel status); Beacon Frame that sends active node characteristic of the network, MAC address and node role (coordinator or device simple).

- *Channel Access Method*: G3-PLC implements Unslotted CSMA/CA in order to avoid collisions on channel access.

- *Reliable neighbor data transfer*: The MAC Sublayer uses ACK/NACK techniques to check communication status and prevent packet loss.

- *Security*: Data encryption based on AES-128 CCM is optionally added.

- *Network identification and node addressing*: The MAC Sublayer assign two different ID to each devices: a "long address" with EUI-64 format that is extracted by univocal node id (EUI-48), and a "short address" 16 bit long, dynamically assigned by 6LoWPAN Bootstrap Protocol (LBP). PAN network id is derived by coordination configuration.

- *Neighbor active scan*: This functionality is enabled when a node is on a disconnected status. This device sends an active scan MAC packet and all neighbor nodes will respond with a Beacon Frame. After answers are received, the node reorders the packets based on a parameter (like MAC address, network id, signal quality, etc.) and classifies nodes.

  Other communications occur on 6LoWPAN level with the use of LBP. Those include authentication, encryption key distribution, configuration initialization. LBP communications are activated with node at the first position on the list and, when communication fails, the next node in the list will be considered.

6LoWPAN Adaptation Sublayer

This sublayer is composed by a Routing Table that has information on the destination node (short address), the next hop address (short address), route status and time to live.

6LoWPAN Adaptation Sublayer functionalities are:

- *Internet and Transpoprt Layer Header compression*: 6LoWPAN can compress header from packet of Internet and Transport layer.
- *Fragmentation*: it is possible to fragment IPv6 packets to smaller segments, better adapted to PLC.
- *6LoWPAN PDU Generation*: there are two types of PDU packet, the 6LoWPAN Data Frame that adds some other header field to IPv6 packet, and the Check Frame that is used to implement LBP and LOAD (Ad Hoc On Demand Distance Vector Routing) protocols.
- *Packet ordering.*
- *Reliable end-to-end data transmission*: using ACK/NACK mechanism.
- *Retransmission of MAC packet*: this functionality is based on the Routing Table.
- *Routing on Mesh topology*: 6LoWPAN sublayer elaborates the optimal route between two nodes using LOAD routing protocol (see example in Figure 3.15):
  - the node sends on broadcast a RREQ message with null total cost;
  - all nodes of the networks able of propagating the message (`C`, `D`, `E` and `F` of the figure), add the short address to the packet and increase the link cost between nodes `A` and x, where x is `C`, `D`, `E` or `F`. If the node has a route to `B`, it will forward the message over this route, otherwise it sends the message on broadcast.
  - node `B` receives more RREQ messages coming from different routes, that are saved in the message body. `B` chooses the route with minimum cost and sends a RREP answer message to `A` though this minimum cost route.

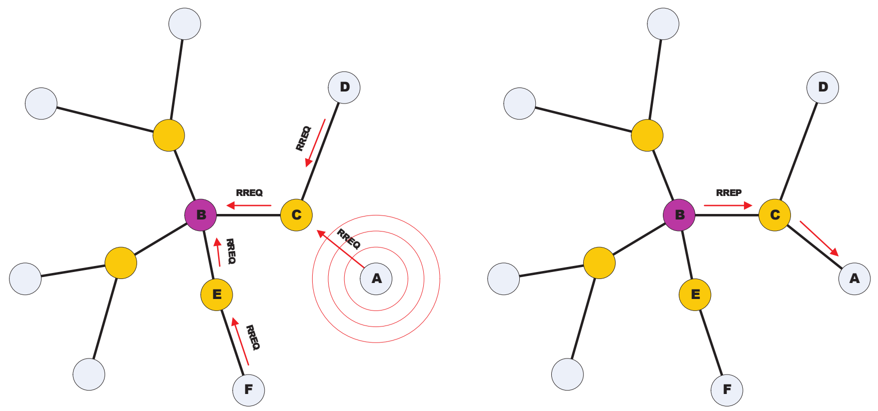

Figure 3.15: *An example of LOAD routing protocol on a G3-PLC network*

 – Each node, when receiving RREP message, updates the Routing Table of node `B`

- *Security and channel initialization*: here function devoted on security are implemented: access control, authentication, message integrity, anti-replay and Denial of Service (DoS) prevention, key generation and distribution, short message allocation. In addition, this sublayer manages the first configuration of devices.

3.3 HomePlug Standards Series

The HomePlug™Powerline Alliance's mission is to enable and promote rapid availability, adoption and implementation of cost effective, interoperable and standards-based home powerline networks and products.

The alliance developed standards for applications such as in-home distribution of TV, gaming and Internet access. It also developed a specification for smart power meters and in-home communications between electric systems and appliances. The alliance tests for interoperability and certifies products based on HomePlug specifications and IEEE 1901 standards.

3.3.1 HomePlug History and Variants

HomePlug is the family name for various power line communications specifications that support networking over existing home electrical wiring. Several specifications are inspired under HomePlug, with each offering unique performance capabilities and coexistence or compatibility with other HomePlug specifications [16].

HomePlug 1.0 was first introduced in June, 2001 and it was the first HomePlug specification. It provides a peak PHY-rate of 14 Mbps.

There are also HomePlug 1.0 with Turbo adapters that still may be found on the market. These comply with the HomePlug 1.0 specification but feature a faster, proprietary mode that increases the peak PHY-rate to 85 Mbps.

HomePlug AV was introduced in August 2005 and provides sufficient bandwidth for applications such as HDTV and VoIP. HomePlug AV offers a peak data rate of 200 Mbps at the physical layer, and about 80 Mbps at the MAC layer. HomePlug AV devices are required to coexist, and optionally to interoperate with HomePlug 1.0 devices.

Utilizing adaptive modulation on up to 1155 OFDM sub-carriers, turbo convolution codes for error correction, two-level MAC framing with ARQ, and other techniques, HomePlug AV can achieve near the theoretical maximum bandwidth across a given transmission path. For security reasons, the specification includes key distribution techniques and the use of 128 bit AES encryption. Furthermore, the specification's adaptive techniques present inherent obstacles to eavesdropping and cyber attacks.

HomePlug AV2 is currently under development and is the next generation for the HomePlug line. Current specification offers 500 Mbit/s on powerline and 700 Mbit/s on coax wiring. That translates into 350 Mbps on MAC interface in case of powerline wiring.

HomePlug AV2 is fully interoperable with HomePlug AV and will be brought into the IEEE 1901 standard once the specification is completed. HomePlug AV2 offers Gigabit speed at the physical layer and 500Mbs at the MAC layer.

HomePlug Green PHY is a new specification and a subset of HomePlug AV. It is specifically designed for the requirements of the smart grid market. It has peak rates of 10 Mbit/s and is designed to go into smart meters and smaller appliances such as HVAC/thermostats, home appliances and plug-in electric hybrid vehicles so that data can be shared over a Home Area Network (HAN) and back to the utility.

For these applications, there's not a great need for high capacity broadband; the most important requirements are for lower power, robust, reliable coverage throughout the home, smaller size and cheaper. GreenPHY uses up to 75% less energy than AV.

HomePlug Green PHY-based products will be fully interoperable with products based on HomePlug AV, IEEE 1901 or the upcoming HomePlug AV2 specification.

HomePlug Access BPL Access Broadband Power Line (BPL) refers to a to-the-home broadband access technology. The HomePlug Alliance formed the HomePlug Access BPL Working Group, whose first charter was to develop the Market Requirements Document (MRD) for a HomePlug Access BPL specification. The Alliance made an open invitation to the BPL industry to participate in the development of or provide input for consideration in the MRD. After several months of collaboration between utilities, ISPs and other BPL industry groups, the MRD was completed in June 2005. HomePlug's work on the Access BPL was subsequently contributed and merged into the IEEE 1901 standard.

3.3.2 HomePlug Structure

The HomePlug AV protocol uses a Physical layer (PHY) which operates in the frequency range of 2-28 MHz and provides a 200 Mbps PHY channel rate and a 150 Mbps information rate. It uses windowed OFDM and a powerful Turbo Convolutional Code (TCC), which provides robust performance within 0.5 dB of Shannon Capacity. Long OFDM symbols with 917 usable carriers (tones) are used in conjunction with a flexible guard interval. Modulation densities from BPSK to 1024 QAM are independently applied to each carrier based on the channel characteristics between the transmitter and the receiver [17].

HomePlug AV provides connection-oriented Contention Free (CF) service to support the QoS requirements of demanding AV and IP applications. This Contention Free service is based on periodic Time Division Multiple

Access (TDMA) allocations of adequate duration to support the QoS requirements of a connection. HomePlug AV also provides a connectionless, prioritized Contention based service to support both best-effort applications and applications that rely on prioritized QoS. This service is based on Collision Sense Multiple Access/Collision Avoidance (CSMA/CA) technology.

HomePlug AV implements a flexible, centrally-managed architecture. The central manager is called a Central Coordinator (CCo). The CCo establishes a Beacon Period and a schedule which accommodates both the Contention Free allocations and the time allotted for Contention-based traffic. The Beacon Period is divided into 3 regions:

- Beacon Region
- CSMA Region
- Contention-Free Region

The CCo broadcasts a beacon at the beginning of each Beacon Period; it uses the beacon to communicate the scheduling within the beacon period. The beacons are extremely robust and reliable.

The MAC layer provides both Contention (CSMA) and Contention Free (CF) services through the respective regions in the Beacon Period. The CCo-managed Persistent Contention Free (PCF) Region enables HomePlug AV to guarantee on Higher Layer Entity (HLE) QoS requirements. An HLE uses the Connection Specification (CSPEC) to specify its QoS requirements. The Connection Manager (CM) in the station evaluates the CSPEC and, if appropriate, communicates the pertinent requirements to the CCo and asks the CCo for a suitable Contention Free allocation.

If the CCo is able to accommodate the connection request, it will ask the stations to “sound” the channel. This allows the stations to perform the initial channel estimation. The Tone Map is communicated from the receiver to the transmitter; the channel estimation is also communicated in abbreviated form to the CCo to help it determine how much time should be allocated to the connection.

More details of the working can be found in the technical white papers from the vendor [17].

3.4 IEEE 1901

As already mentioned, one of drawback of widespread adoption of broadband PLC technology is the current lack of an international technical standard issued by a credible and globally recognized standards-setting body. Elimination of this barrier is the major work of the IEEE P1901 Corporate Standards Working Group. It has started in 2005 to unify PLC technologies in order to develop a high speed protocol (hundreds of megabits) for home networks and access networks using the spectrum below 100 MHz.

IEEE P1901 would use transmission frequencies below 100 MHz for all classes of PLC devices, including devices used for the first-mile/last-mile connection (up to 1.500 m to the premise) to broadband services, as well as devices used in buildings for local area networks (LANs) and other data distribution (up to 100 m between devices) applications. The efforts of the P1901 WG are limited to the physical (PHY) layer and the medium access (MAC) sub-layer of the data link layer.

In the last years, the WG has focused on three mayor functional and technical requirements:

- *In-home (IH)* try to enable communication in a residence or office using low-voltage power line cable.

- *Access (AC)* try to bring multimedia services to residences via power lines and communication for developing electric power utility applications.

- *Coexistence (CX)* this cluster focuses on requirements that will make PLC devices compatible even if based on different technologies. A coexistence protocol is being defined that will allow non-IEEE 1901 devices to share the channel with each other and with IEEE 1901 devices.

Multiple PHY layer solutions are commonly used in standards (802.11, for example). In fact, a baseline of the standard defines tree PLC technologies for PHY/MAC layer: an FFT-OFDM based, a Wavelet-OFDM based and a G.9960 Compatible version. The FFT-OFDM 1901 PHY specification facilitates backward compatibility with devices based on the HomePlug AV specification, whereas Wavelet-OFDM 1901 PHY specification facilitates backward compatibility with device on HD-PLC Alliance industry specification.

However, when devices with different PHY layers are in proximity and connected to the same shared medium, them shows auto-interference problem and impose the necessity of handling the case. The Inter-PHY Protocol (IPP) is designed to cope with this particular issue and its scope is to enable fair sharing of resources among devices equipped with IEEE 1901 PHY layers.

Inclusion of IPP in the protocol is a small price to pay in terms of complexity if a longer product life can be offered to PLC technologies based on the IEEE 1901 standard.

The fundamental architecture used to coordinate the IEEE P1901 network is master/slave. The master, that is the quality of service (QoS) controller, authorizes and authenticates the slave stations in the network and may assign time slots for transmissions using either CSMA-based or TDM-based access. Direct communication between stations is allowed in order to increase the efficiency of the network and reduce the load on the master.

The MAC layer employs a hybrid access control based on TDMA and CSMA/CA by defining a contention-free period (CFP) and a contention period (CP) to accommodate data with different transmission requirements. Intelligent TDMA is also defined in the proposal. Intelligent TDMA is a dynamic bandwidth allocation mechanism that exploits information about the amount of traffic queued in each transmission station.

Frequency division multiplexing (FDM) can also be supported to allow for coexistence between in-home and access networks. Other important features of the current proposal are: fragmentation support, data bursting, group acknowledgment (ACK), and selective repeat automatic repeat-request (ARQ).

3.5 LonWorks Protocol

The LonWorks protocol provides services at each layer of the OSI seven layer reference model.

The protocol is open for anyone to implement[3]. Since its invention, the

[3]Exist also a reference implementation in the C programming language which can be

protocol has become an ANSI standard, an IEC standard, a Chinese national standard, and recently has achieved ISO standardization.

This protocol is implemented into the Italian power electric network, owned by the Italian electric company ENEL, as metering solution for electrical energy.

The layer structure of LonWorks protocol can be resumed into the seven layer of ISO/OSI model:

Layer 1: Physical Layer At this layer, multiple physical links are supported such as RS-485; our free-topology (FT) and power line (PLC) transceivers; and third-party wired, wireless, and fiber transceivers.

Layer 2: Link Layer – MAC Algorithm At the Link Layer, Layer 2 of the OSI model, the LonWorks protocol provides an innovative independent media access control (MAC) layer based on improvements made to the Carrier Sense Multiple Access (CSMA) family after Ethernet was standardized. The MAC layer combines two concepts: p-persistent CSMA and non-persistent CSMA to "create" the predictive p-persistent CSMA. The maximun advance is the support of prioritized access to the link when the network is congested, some number of randomizing slots may be assigned to individual stations for their exclusive use.

Layer 2: Link Layer – Bit Encoding Beside the MAC algorithm, Layer 2 provides bit encoding and a 16-bit cyclic redundancy check (CRC) whereas bit encoding is bi-phase space encoding. This bit encoding does not need to differentiate the two wire as normal differential Manchester do.

Layer 3: Network Layer It provides addressing. In the LonWorks protocol, addressing is hierarchical, starting with the node's domain and followed by its subnet and identification number, each expressed in eight bits. Alternatively, a node may have membership in multiple multicast groups, with each group address encoded as a single byte (up to 256 multicast groups) each having a maximum of 127 nodes.

To save bandwidth, a domain's address may be encoded as zero in length, as a single byte, three bytes, or to ensure uniqueness, six bytes.

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obtained from CEA.

This simple addressing design permits very simple routing of packets across multiple links.

Layer 4: Transport Layer In this layer, packet retransmission and duplicate detection are handled. It is possible to use unreliable or reliable transport services. The protocol supports reliable unicast as well as multicast with a configurable number of retries. This allows transactions to either fail or succeed within a bounded time, meeting the application response time requirements.

Layer 5: Session Layer It handles request response services. Besides sending a response, the protocol saves it, so that if a retry comes along, the response can be resent without the application needing to re-compute and retransmit.

Layer 6: Presentation Layer It is used with Echelon's publisher-subscriber data model. The Presentation Layer header encodes the semantics of data passed in the Application Layer. It also carries the identifier of data items.

Layer 7: Application Layer It provides data called network variables. Network variables are application specific data types that contain semantics beyond float, integer, and Boolean.

In Layer 7, the protocol also provides for node discovery, and even more importantly, their logical interfaces, their possible provisioning and other information to allow each node to be easily integrated into a control system. Finally, Layer 7 supports a standard way to upgrade node software.

Chapter 4

Smart Grid Technology

4.1 Introduction

In recent years, the concept of "Smart Grid" become one of most attractive research topics. Recent evolution of renewable energy sources has triggered the need for developing of a smarter grid.

Old energy production was normally centralized in large power plants using synchronous generators and electric power delivered to the end user within a rigid top-down structure, with a fully centralized control by the utility companies and unidirectional power flow. Power grids are designed to be managed through a rather old-fashioned centralized cyber-infrastructure model, referred to as Supervisory Control and Data Acquisition (SCADA).

One of factors that stimulates research and developing of smart grid technology is its intrinsic potential of reducing the loss of electricity distribution networks. In fact, the sensibility toward the need of preserving the environment and uses more efficient by the available resources are measured, also considering the limited availability of fossil fuels and their negative impact on the quality of life.

The growth of energy demand has outpaced the rate at witch energy generation can grow by traditional means. The necessity of modernizing the electric grid infrastructure around the world in order to take the full advance of the small power sources, usually distributed in residential contest, is one of the primary objectives of smart grid research [5]. The coordinated uses of all the new power devices are advocated as sustainable solutions to our energy crisis. Those device are Distributed Energy Resources (DERs) feeding into the distribution system or home, decentralized storage to compensate for the time varying nature of wind and photovoltaic sources, Plug-in (Hybrid) Electric Vehicles (PHEV) that may cause large load increases on sections of the grid, microgrids, and in allowing active participation of consumers via Demand Side Management (DSM) and Demand Response (DR) programs [18].

Starting from the assumption that direct and complete definition of Smart Grid is still far to come, in this chapter will be presented a general introduction to the Smart Grid vision and future possible applications.

4.2 The Smart Grid Vision

Smart Grid involves innovative products and services together with intelligent monitoring, control, communication and self-healing technologies to:

1. Facilitate connection and operation of generators of all sizes and technologies
2. Enable the demand side to play a important part in optimizing the operation of the system
3. Extend power balancing into distribution and home
4. Provide consumers with greater information and choice of supply
5. Significantly reduce the environmental impact of the total electricity supply system
6. Deliver the required levels of reliability, flexibility, quality and security of supply

The vision sets out how smart grids may, directly or indirectly: maintain or enhance the quality and security of electricity supply; facilitate the connection of new low and zero carbon generating plants from industrial to domestic scale; enable innovative demand side technologies and strategies; facilitate a new range of energy products and tariffs to empower consumers to reduce their energy consumption and carbon output; feature a holistic communications system that will allow the complete power system to operate in a coherent way.

In Figure 4.1 an example of how a smarter power grid may be realized in future is shown. The most important points are:

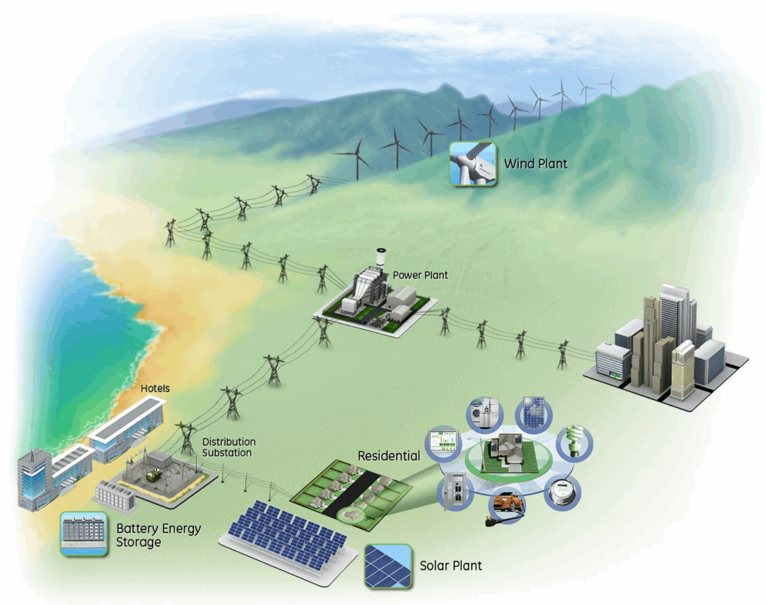


Figure 4.1: *Example of the smarter power grid in the future [19]*

- *Traditional Generation:* Over time, traditional generation asset such as coal-fired generation plants will be offset by renewable energy sources in providing energy to the distribution grid.

- *Renewables Sources:* Renewable energy sources, such as wind turbines and solar panels, are more readily integrated into the smart grid compared to a traditional power grid.

- *Plug-In Hybrid Vehicles:* Plug-in hybrid vehicles can store energy in their batteries. When they are connected to the distribution grid, plug-in vehicles can serve as an additional source of energy, providing power back to the grid during times of peak demand.

- *Smart House:* A Smart House tracks usage information through smart meters installed in home. Customers will have a variety of options through which they can interface with to learn about the most cost-efficient energy usage patterns. Increased information empowers consumers to reduce their energy use.

- *Sensors:* Advanced communication equipment on the grid, including sensors, enables utilities to monitor, identify and quickly correct problems. Increased reliability of power is the result.

A series of common challenges are driving toward a global smart grid investment [20]:

- *Carbon reduction:* Enable and accelerate power system carbon reduction, e.g. demand-side responses effectively integrate inflexible low-carbon generation.
- *Energy security:* Increasing the network's capacity to manage a potentially diverse set of new requirements, e.g. manage the technical risk of connecting new generation, and of changing demand patterns.
- *Economic competitiveness and affordability:* Cost-effectively transition to a low-carbon energy system, increasing affordability, e.g. reduce the need for grid reinforcement to handle new loads.

As already anticipated above, the vision of Smart Grid from the point of view of power systems is intended as an upgrade of the existing infrastructure, increasing the measurements, communication and control capabilities. This increases the reliability of grid state estimation and guarantees improvements in control and healing after faults, as well as fault prevention thank to the increased available information from the grid [21].

Another relevant topic is the communication strategies that Smart Grid infrastructure will be based on. There is a debate on what is the actual role of PLC in the Smart Grid. E.g. some advocate that it is a good candidate whereas others expreses concern and look at wireless as a more estabilished alternative. Most probably multiple types of communication technologies, wireless and wired, will be used.

As we analyzed on Chapter 3, PLC standardization is far to be completed and does not help PLC integration in the Smart Grid project. More, PLC modems are still too expensive, offer a small data rate and electromagnetic compatibility (EMC)and these issues have to be deeper analyzed before PLC technology becames widely adopted.

4.3 Applications

There are many examples of application where PLC can be used for utility applications. In low voltage Smart Grid side, most of them are in the

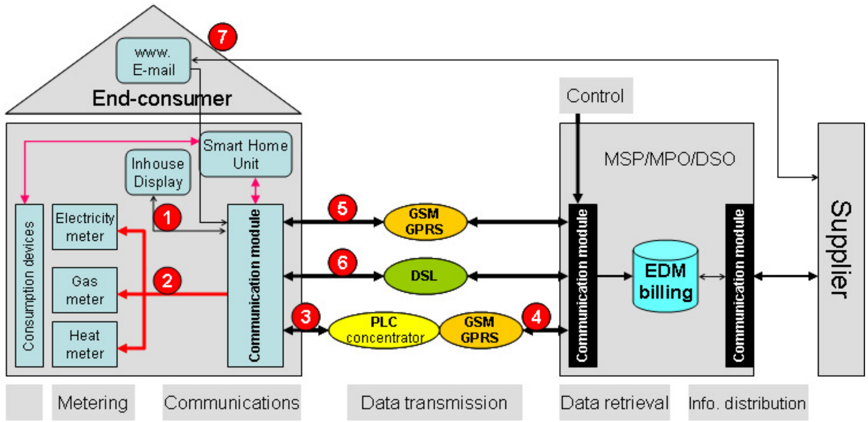


Figure 4.2: *General Architecture and communications interfaces of AMI [14]*

area of Advanced Metering Infrastructure (AMI), Vehicle-to-Grid (V2G) communications, Demand Side Management (DSM) and in-home energy management. Next sections will present these applications.

4.3.1 Advanced Metering Infrastructures

Remote metering infrastructure is implemented using the so called Automatic Meter Reading (AMR). This technology allows one-way communication, where the supplier can automatically collect consumption, diagnostic, and status data from water meter or energy metering devices (gas, electric) and transferring those data to a central database for billing, troubleshooting, and analyzing.

On the other hand, Advanced Metering Infrastructures (AMI) systems provide two-way communications allowing information exchange between customer devices and systems. This allows companies to have feedback by customer devices and then quickly respond to potential problems and then improving reliability. The AMI architecture, shown in Figure 4.2, builds the bridge between power utility's premises and its costumer, and several communication tasks are required at different levels.

In addition, electric companies can send price signals to "smart" customers devices (like thermostats and so on) and then providing consumers the ability to use electricity more efficiently. Energy-use feedback can help to reduced the amount of wasted energy, save money and reduce electricity consumption by 4 to 12 % [14]. Moreover, the platform provides the utility with the opportunity to make substantial gains from efficiency of power transmission and distribution.

Key AMI attributes can be summarized as follows:

- Two way communications to the electric meter to enable time stamping of meter data, outage reporting, communication into the customer premise, service connect/disconnect, on-request reads and other functions
- Ability of the AMI network to self register meter points
- Ability of the AMI network to reconfigure due to a failure in communications
- AMI system interconnection to utility billing, outage management systems and other applications

4.3.2 Vehicle-to-Grid communications

Vehicle-to-Grid (V2G) communication introduce the opportunity to increase the reliability and efficiency of electric power system using the electric storage and/or generation capacity of battery of Plug-in (Hybrid) Electric Vehicles (PHEV) [22].

The key enabler for V2G applications is the availability of a communication link between the car and the Electric Vehicle Supply Equipment (EVSE). The physical connection between the veichle and a specific EVSE shows a distinctive advantage when associated with PLC for V2G communications. This physical association has its advantages, especially in terms of security and authentication [5].

Narrowband PLC technology seems to be the best solution also in this scenario, although the PLC channel in this scenario is impaired by several harmonics present due to the inverter. Narrowband PLC is also an excellent choice for meters and appliances, so the availability of a single class of PLC technologies for the internetworking of different actors is of course tempting.

4.3.3 Demand Side Management

One of the primary Demand Side Management (DSM) applications on the LV side is Demand Response (DR). DR refers to the ability to make demand able to respond to the varying supply of generation that cannot be scheduled

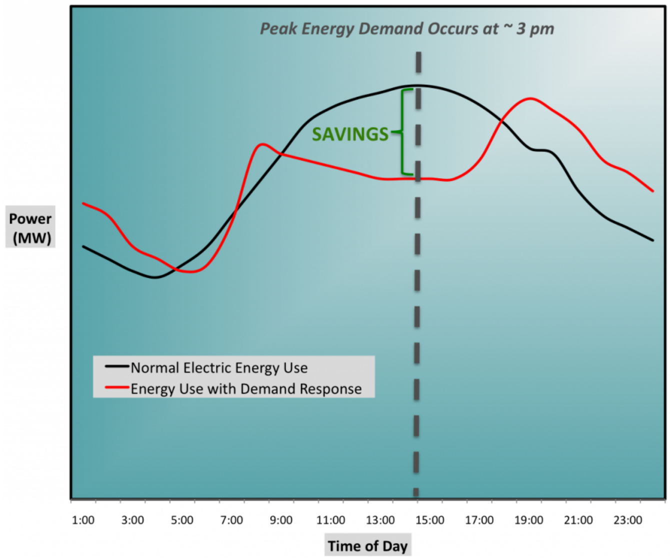


Figure 4.3: *Demand Response graph where both normal operation mode (black) and with DR operation mode (red) are plotted [23]*

deterministically, e.g., solar and wind. Thus, DR is a means to alleviate peak demand and to bring more awareness on energy usage to the consumer as shown in Figure 4.3.

It is believed that DR will allow a better control of peak power conditions, maximize the use of available power, increase power system efficiency through dynamic pricing models and allow customers to participate more actively to energy efficiency [24]. Implementation of DR requires establishing a link (either direct or indirect, e.g., via gateway) between the utility and household appliances.

Due to the much lower path loss at lower frequencies, narrowband PLC solutions are also good candidates for DR applications for both direct (without a gateway) and indirect load control (with a gateway called Home/Building Energy Management System)

4.3.4 In-Home Energy Management

There are intriguing possibilities of tying Smart Grid applications with Home Energy Management System (HEMS) and there is a strong belief that these applications will help foster a behavioral change in how consumers address energy consumption [5]. The HEMS is the system providing the electricity

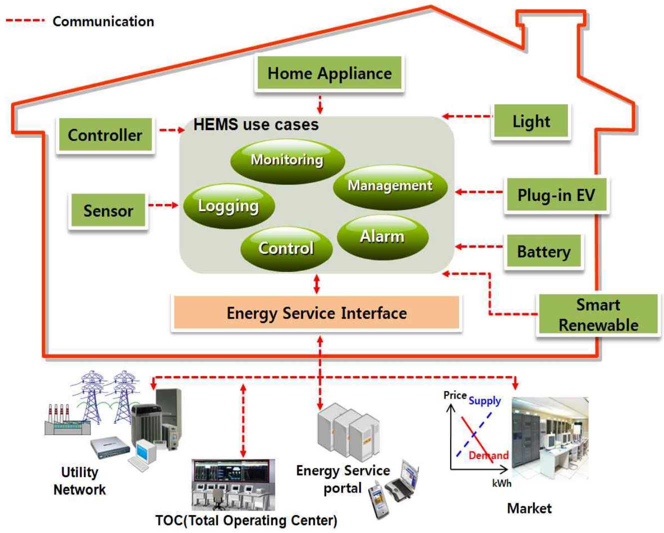


Figure 4.4: *The function of HEMS[25]*

and monitoring for the use of energy about home appliances and energy management services.

The HEMS provides automatic control, measurement of the smart meter for the amount used of the energy and information collection of home devices through the energy service interface and energy Man-Machine Interface (MMI) device and others [25]. It also provides energy storage management service by instruction of distributed energy resources (DER) and renewable energy.

Figure 4.4 shows a typical example of application of HEMS technology. If devices behave abnormal, HEMS is shown the status of devices and warns through the personal digital device like an alarm. In addition, it provides the function of monitoring by the remote and control. It provides the status of monitor and management about the various operation modes of the home devices and also information by using the personal computer and the mobile phone [25].

Home is a natural multiprotocol and multivendor environment and it is realistic that this will not change anytime soon even though there is a lot of pressure by some industry segments to reduce the number of allowed networking choices. Segregating Smart Grid applications in one band (CENELEC/FCC/ARIB) and separating them from traditional entertainment and Internet access running on broadband PLC (but also with the

Figure 4.5: *Microgrid Example [19]*

capability of linking these applications securely via the HEMS) seems a good engineering solution that balances efficiently the various requirements of these different applications. However, the use of narrowband PLC in the in-home environment may require special attention to cope with reduced cross-phase connectivity since the capacitive nature of cross-phase coupling yields higher attenuation at lower frequencies than at the higher ones used in the upper part of the FCC/ARIB band or in BB-PLC [26].

4.4 Smart Microgrids

A microgrid is a collection of distributed generation systems deployed in a residential contest to provide an independent and self-sufficient small scale power grid system, together with connected and disconnected capability to the main grid depending on usage and requirements [19].

Moreover, it can be observed that “low voltage” is always coupled with “microgrid”. This is somehow natural, because low voltage distribution is the most peripheral part of the power network [21].

From the main grid point of view, the microgrid, with its own distributed control, generation and energy storage can be seen by the rest of the grid as an equivalent active load. This load is able to interact with the main grid, and therefore is a subsystem, a sub-network similar to the different connected networks composing the transmission system.

The microgrid can operate in two different modes: grid-connected mode, where the microgrid is connected to the main distribution network, and autonomous (islanded) mode, where it works independently. The islanded modes is fundamental to guarantee supply reliability in case of faults of the main grid, and also to relax the stability limits of the whole power network: in case of overload, the network operator could request a number of microgrids to disconnect from the network, or in case to support the power generation making available the storage resources. This two modes provide a high quality and almost fail-proof electricity supply to the location.

On the one hand, the microgrid itself provides a high quality distributed power generation solution. On the other hand, it also provides valuable energy resources to the main grid with valuable contributions such as supplying peak load supply and reactive power correction, etc.

Smart microgrids represent a new arena where several branches of information technology are merging together to allow full exploitation of distributed generation (DG), reduced power consumption from the mains, better power quality and higher distribution efficiency.

4.5 Loss Minimization Techniques

The aim of this section is to give an introduction to loss minimization algorithms. At first, an introduction is given and then, two interesting minimization techniques for smart grid will be presented.

The analysis is based on a number of assumptions, required to reduce the complexity of the system, being thus able to obtain an analytically derivation of distribution loss [21]:

- Low voltage distribution, with radial distribution feeders. This the normal topology for LV distribution systems and the resulting network graph is a tree.
- The microgrid nodes are either leads (passive nodes) or distributed generators (active nodes), both modelled as AC current sources (the current is considered absorbed both for loads and generators), named i_a and i_p respectively.
- All the voltages and currents in the microgrid are sinusoidal in steady

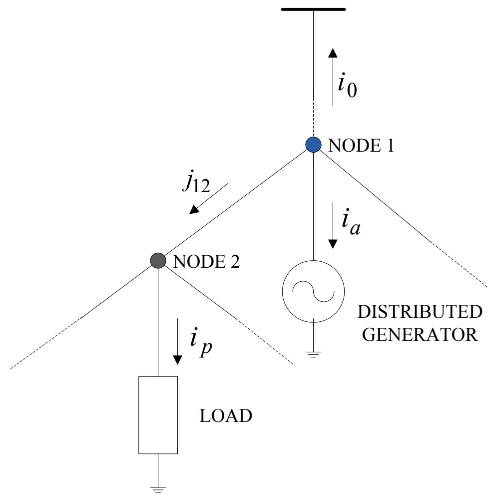


Figure 4.6: *Microgrid section with currents definition and direction [21]*

state. This means that all transients related to power converters and loads control loops are here neglected.

- The microgrid is single phase. Thus, all the derivations are valid for three phase balanced systems, while the case of unbalances is nod treated here.

Further, there are some conventions used over the tree. An origin of the tree is named "node 0" and this node connects the microgrid to the rest of the distribution network (grid-connected mode). The current flowing from a node N to a node M trough a distribution line is oriented from the closest node to node 0 to the farthest node to node 0. This notation has the consequence that the network graph is oriented (see example shown in Figure 4.6).

In this situation, node 0 guarantees the power balance between loads and generation. Mathematical this is traduced into:

$$i_0 = -\sum_{n=1}^{N} i_n \tag{4.1}$$

where N is the total number of active and passive nodes in the microgrid, excluding node 0, and i_n is the current absorbed by each node and i_0 is the current absorbed by node 0.

4.5.1 Minimum Loss Plug & Play Control

In [27] a Plug & Play approach is presented, which allows independent operation of each Electronic Power Processor (EPP) while ensuring efficient utilization of the grid. In this section is an extracted of [21], where a simplified presentation is done.

This solution tries to exploit the advances of residential microgrid structures, where the number of Distributed Energy Resources (DERs) end, then generated power is changing during the time and a communication infrastructure is not available [28].

Given a single phase low voltage microgrid with a number of distributed generators interfaced with the microgrid through power converters, the idea is to understand the possible improvement in the distribution loss if the generators are not equipped with communication infrastructure and can only perform local measurements on the network. The current regulations on the grid connected energy sources allow a pure active power injection, without any coordination and control among the different units, especially in the case of low power sources. In this technological background, the first step could be the introduction of a degree of local reactive power control, without the need for communication and with minimum updates to the converters control systems [21].

The first requirement is that all the sources have to be interfaced with the microgrid through a power converter, i.e. a power conversion topology whose final stage is an inverter, to have a fully controllable power injection. Moreover, the inverter is current controlled. From now on, the energy source and its conversion system will be named Energy Gateway (EG).

Focusing now on the Plug and Play technique, consider the generic node equipped with EG in the microgrid in Figure 4.7. From the figure, the active node N has access to a limited amount of information, represented by the measure of all the currents departing from the connection point. Moreover, node N measures its voltage. In these conditions any knowledge about the microgrid topology and about the other generation units is excluded. Consider first the case where node N is fully controllable, meaning that the EG can inject both controlled active and reactive current.

In this first case, the driver for the definition of current references is the distribution loss. Only a qualitative approach can be implemented considering the limited information: from the restricted point of view of node N,

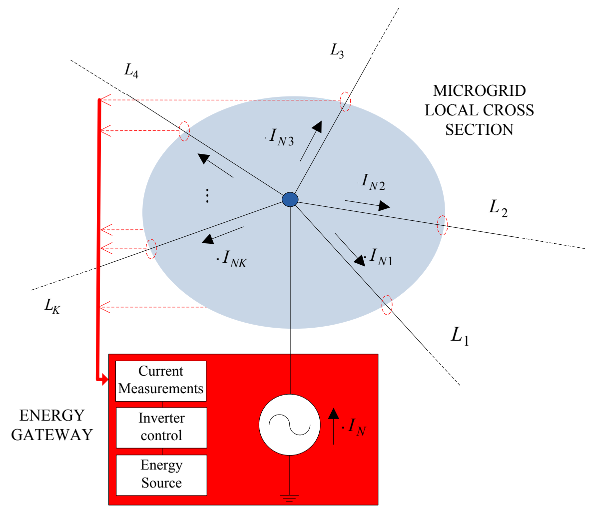


Figure 4.7: *Simplified representation of an EG and correspondent interface with the microgrid in case of Plug and Play control [21]*

the distribution loss tends to be minimized if the sum of the modules of currents $\dot{I}_{N1} \dots \dot{I}_{NK}$ in the K surrounding branches is minimum. Defining the cost function φ:

$$\varphi = \sum_{k=1}^{K} I_{Nk}^2 \tag{4.2}$$

the distribution loss is minimized when the cost function is minimized.

The function could also include more information, for example can integrate the impedance of each departing branch, if is possible to know the local topology of the microgrid. Considering that this additional information is generally not available, the analysis is limited to the base case expressed by (4.2).

To minimize (4.2), consider the application of a small perturbation $d\dot{I}_N$ to node current $\dot{I}_N$ and measure the corresponding current variations $d\dot{I}_{Nk}$ in each branch L_k. Define now the sharing coefficients $\dot{\chi}_{Nk}$ as:

$$\dot{\chi}_{Nk} = \left[\frac{d\dot{I}_{Nk}}{d\dot{I}_N} \right]_Q \tag{4.3}$$

where Q is the node status $(\dot{U}_N^0, \dot{I}_N^0)$ before the perturbation is applied. Assuming that the network is linear, the coefficients $\dot{\chi}_{Nk}$ can be used to determine the current variations $\Delta\dot{I}_{Nk}$ corresponding to a larger perturbation

$\Delta\dot{I}_N$ of the node current:

$$\Delta\dot{I}_{Nk} = \dot{\chi}_{Nk}\,\Delta\dot{I}_N \tag{4.4}$$

In other words, $\dot{\chi}_{Nk}$ are the current dividers that indicate how the amount of current injected in node N is divided among the neighbour branches. Substituting in the objective function, and naming $\dot{I}^{\circ}_{Nk}$ the current in the k-th surrounding branch before the control action, results:

$$\varphi = \sum_{k=1}^{K} I^2_{Nk} = \sum_{k=1}^{K} (\dot{I}^{\circ}_{Nk} + \Delta\dot{I}_{Nk}) \cdot (\dot{I}^{\circ}_{Nk} + \Delta\dot{I}_{Nk})^* \tag{4.5}$$

Substituting (4.4) in (4.5):

$$\varphi = \sum_{k=1}^{K} I^2_{Nk} = \sum_{k=1}^{K} (\dot{I}^{\circ}_{Nk} + \dot{\chi}_{Nk}\,\Delta\dot{I}_N) \cdot (\dot{I}^{\circ}_{Nk} + \dot{\chi}_{Nk}\,\Delta\dot{I}_N)^* \tag{4.6}$$

In (4.6), all the terms are known, and the only unknown is the current variation $\Delta\dot{I}_N$.

The goal is to find the $\Delta\dot{I}_N$ that minimizes the cost function φ. The minimum is found setting to zero the derivatives of the function, calculated for the real and the imaginary part of $\Delta\dot{I}_N$. In particular, considering a generic element of the sum

$$\Phi = (\dot{I}^{\circ} + \dot{\chi}\,\Delta\dot{I}) \cdot (\dot{I}^{\circ} + \dot{\chi}\,\Delta\dot{I})^* \tag{4.7}$$

and naming $\dot{I}^{\circ} = I_x + jI_y$, $\dot{\chi} = \chi_x + j\chi_y$, $\Delta\dot{I}^{\circ} = \Delta I_x + j\Delta I_y$ results:

$$\begin{cases} \dfrac{\partial\Phi}{\partial\Delta I_x} = \left(\chi_x^2 + \chi_y^2\right)\,\Delta I_x + I_x\chi_x + I_y\chi_y = 0 \\ \dfrac{\partial\Phi}{\partial\Delta I_y} = \left(\chi_x^2 + \chi_y^2\right)\,\Delta I_y + I_y\chi_x + I_x\chi_y = 0 \end{cases} \tag{4.8}$$

Solving the equation gives:

$$\left(\chi_x^2 + \chi_y^2\right)\,\Delta\dot{I} = -\dot{I}^{\circ}\dot{\chi}^* \tag{4.9}$$

Extending to the whole function φ:

$$\Delta \dot{I}_N = -\frac{\sum_{k=1}^{K} \dot{I}^{\circ}_{Nk} \cdot \dot{\chi}^{*}_{Nk}}{\sum_{k=1}^{K} \chi_{Nk}} \tag{4.10}$$

The node current which optimizes the cost function is finally given by:

$$\dot{I}_N = \dot{I}^{\circ}_N + \Delta \dot{N}_N \tag{4.11}$$

Of course, application of the solution (4.11) is possible only within the current capability of the EG connected at node N. In addition, it requires independent control of active and reactive current. If the active current is constrained to regulate the power flow from the energy source into the grid, solution (4.11) can be applied to determine reactive currents only. Clearly, controlling both active and reactive current performs better than controlling reactive current only, but this requires energy storage capability at node N. Moreover, observe that applying the above approach to a peripheral node, (4.11) gives necessarily $\dot{I}_N = 0$. This means that the energy source located at node N should support only the local loads, without injecting power in the distribution grid.

When only the reactive current is taken into account, this means than node N and its surrounding nodes will appear to the PCC an equivalent active load with unity power factor. The technique is therefore reduced to a simple power factor correction.

4.5.2 Token Ring Control

The Plug & Play Control algorithm can be further improved extending it with a distributed approach. In [29, 30] is proposed a distributed control approach, called Token Ring Control, where each electronic devices in the microgrid is equipped with power processing and with PLC capability.

In smart microgrids, the grid nodes may coincide with the power meters. In a realistic scenario, it is also assumed that every power meter is equipped with voltage, current and power measurement capability in addition to PLC, which provides synchronization and communication capabilities as well. Thus, grid nodes can exchange voltage and current data in the form of synchronized phasors.

The token ring control approach is proposed in order to avoid instabilities due to concurrent control of all active nodes that may cause interaction of the EPPs via the small distribution line impedances.

The token ring technique, used to implement distributed sequential control, operates as follows [29]:

- Cyclically, each reference node in the grid (PCC or other selected nodes) sends a token to one of the surrounding nodes. The destination node is selected for the longest hold time or is chosen randomly. Accordingly, all surrounding nodes are activated in sequence by the reference node.

- When an active node receives the token it enters the control phase and performs all needed control actions (ranging, dynamic grid mapping, optimum reference calculation).

- When the control phase ends, the active node resets its clock and enters the hold phase. The token is sent to another node (but not the node from which the token came from), selected for the longest hold time or chosen randomly.

With this technique, all nodes in the grid receive sequentially the token and progressively contribute to improve grid operation.

The control approach require some extra features in order to be implemented. It is required that:

- Each grid node is univocal identified and is equipped with sufficient data processing and PLC capability;

- all nodes have a synchronized clock;

- PLC neighbor communication is applicable in the grid in order to exchange data on voltage, current and power measurements in the form of phasors;

- surrounding nodes can be identified in real time (dynamic grid mapping) and their distances can be measured (ranging).

The requirement here listed introduced some advance feature not required by Plug & Play approach. Contrary to Plug & Play, voltage and current phasor are fundamental in this control. A further analysis of distance measurement and dynamic grid mapping over PLC can be found in [31].

The main goal of the proposed distributed control solutions is to converge to a set of current references for the EGs that achieves a distribution loss in the microgrid as closed as possible to the ideal loss minimization, without the need for a central controller.

Chapter 5

PLC development kit and Experimental Lab

In this chapter we firstly will be present the TI solution for smart grid, the power line modem developer's kit, and next a short introduction to the software tool used to develop the software for the modem. At the end, we will present the smart microgrid experimental lab, where the architecture developed will be tested.

5.1 TI PLC modems

Texas Instruments (TI) offers a wide variety of products for Smart Grids, from hardware solution trough to software implementation. One of the most active research area are PLC modems, and the development kit.

TI offers a robust Low Frequency Narrowband PLC technology ensuring data integrity while lowering power consumption and reducing system cost. Developers also speed design, tuning, and testing with the TI plcSUITE, a comprehensive development platform offering programmable modulation and protocol libraries within a complete software framework. TI's PLC roadmap will provide developers with PLC solutions for every stage of the Smart Grid from utility substations to the entire home area network [32].

TI's Power Line Communications (PLC) technology is based on TI's C2000 microcontroller architecture. Developers can select the right blend of processing capacity and peripherals for adding PLC to an existing design or implementing a complete application with PLC communications.

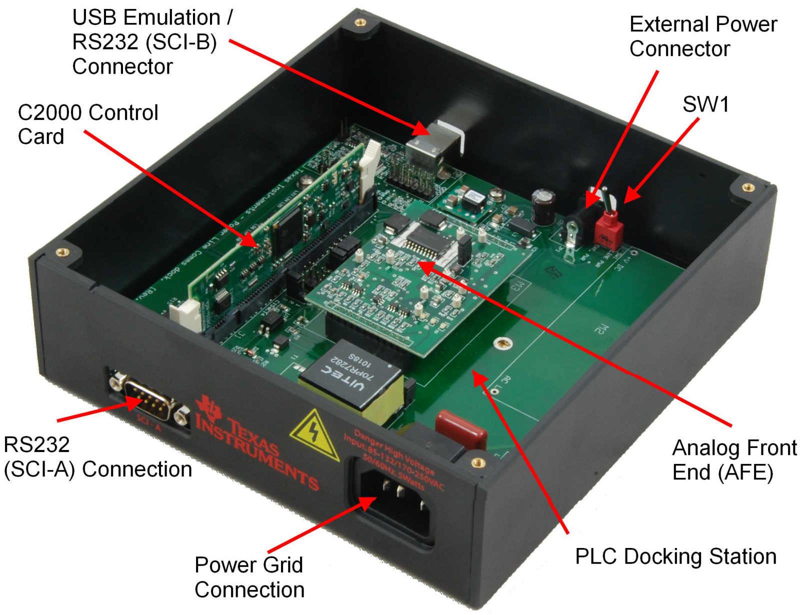


Figure 5.1: *C2000 Power Line Modem Developer's Kit [32]*

The development kit used in the laboratory is "C2000 Power Line Modem Developer's Kit V2" (TMDSPLCKIT-V2), shown in Figure 5.1. The development kit includes two sets of development board. Each set contains:

- one F28335 MCU control card
- one docking station
- one AFE board

The C2000 Power Line Modem Developer's Kit enables easy development of software based Power Line Communication (PLC) modems. The kit includes two PLC modems based on the C2000 TMS320F28335 controlCARD and TI's advanced PLC analog front end AFE031. The included PLC SUITE software supports PRIME protocol. The kit includes onboard USB JTAG emulation and Code Composer Studio [32].

The TI PLC Development Kit for PRIME contains the following main components and supported features [33]:

- DSP control card with Texas Instruments F28335 microcontroller
- AFE daughter card with Texas Instrument operational amplifier OPA564 and programmable gain amplifier PGA112

- Docking board and AFE board
- RS-232 interface for diagnostic port interface
- Serial interface for host data port interface: UART, SPI, etc.
- LEDs and test points for firmware and hardware debug
- USB/JTAG for custom firmware download

The main characteristic of the system are:

- Operating frequency range 40-90 kHz (CENELEC A band)
- Data rates from 21 kbps to 128 kbps
- Transmission with OFDM and FEC
- Number of used data carriers is 96
- Differential Phase modulation (DBPSK/DQPSK/D8PSK)
- PRIME-ROBO mode provides Reed Solomon encode/decode and Repetition code with DBPSK
- Convolutional encoder/Viterbi decoder
- Bit interleaving for noise effect reduction
- CRC8 in headers and CRC32 in data for error detection
- Data randomization for uniform power distribution
- Automatic gain control
- Zero-crossing detection
- Supports PRIME PHY, MAC, IEC61334 -4-32 LLC and IPv4 Convergence layer

5.1.1 TMS320F28335 DSP

The F2833x (C28x+FPU)/F2823x (C28x) family is a member of the TMS320C2000TM digital signal controller (DSC) platform. The C28x+FPU based controllers have the same 32-bit fixed-point architecture as TI's existing C28x DSCs, but also include a single-precision (32-bit) IEEE 754 floating-point unit (FPU).

It is an C/C++ engine and also enables math algorithms to be developed using C/C++. The 32x32-bit MAC 64-bit processing capabilities enable the

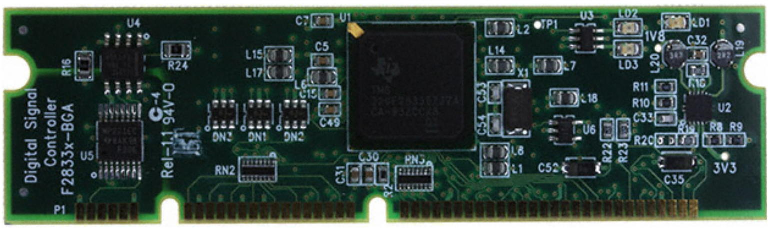


Figure 5.2: *TMS320F28335 ControlCARD (TMDSCNCD28335) [32]*

controller to handle higher numerical resolution problems. Add to this the fast interrupt response with automatic context save of critical registers, and you have a device that is capable of servicing many asynchronous events with minimal latency. The device has an 8-level-deep protected pipeline with pipelined memory accesses. This pipelining enables it to operate at high speeds without resorting to expensive high-speed memories. Special branch-look-ahead hardware minimizes the latency for conditional discontinuities. Special store conditional operations further improve performance [34]. A block diagram of the F28335 DSP is shown in Figure 5.3.

Features

The TMS320F28335 DSP developed by TI has the following important features [34]

- High-Performance Static CMOS Technology
  - Up to 150 MHz (6.67-ns Cycle Time)
  - 1.9-V/1.8-V Core, 3.3-V I/O Design
- High-Performance 32-Bit CPU (TMS320C28x)
  - IEEE-754 Single-Precision Floating-Point Unit (FPU)
  - 16x16 and 32x32 MAC Operations
  - 16x16 Dual MAC
  - Harvard Bus Architecture
  - Fast Interrupt Response and Processing
  - Unified Memory Programming Model
  - Code-Efficient (in C/C++ and Assembly)
- Six Channel DMA Controller (for ADC, McBSP, ePWM, XINTF, and SARAM)

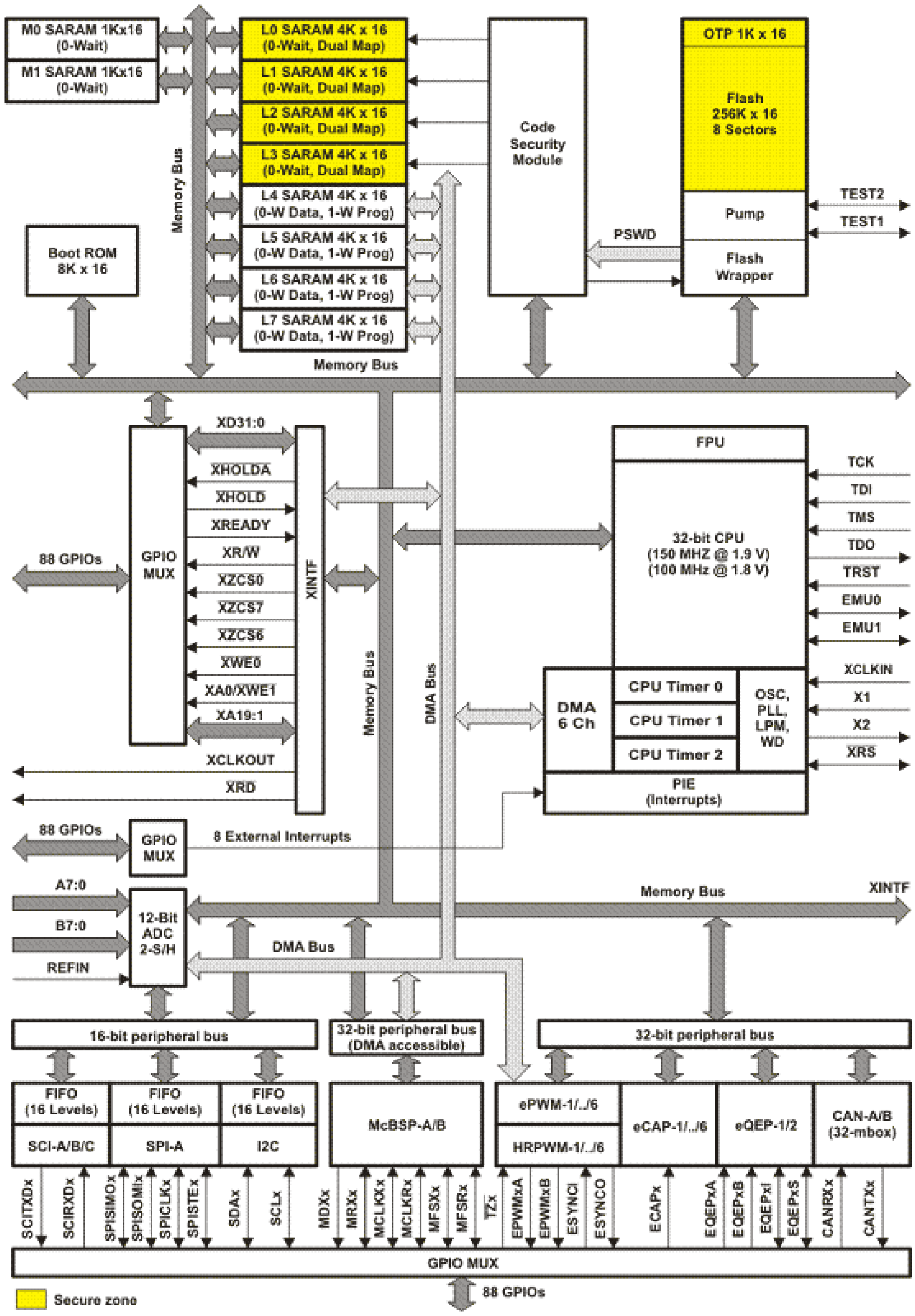


Figure 5.3: *Functional Block Diagram of the F28335 DSP [34]*

- 16-bit or 32-bit External Interface (XINTF)
  - Over $2Mx16$ Address Reach
- On-Chip Memory
  - $256Kx16$ Flash, $34Kx16$ SARAM
  - $1Kx16$ OTP ROM
- Boot ROM ($8Kx16$)

Memories

The F28335 DSP has three type of memories, a flash, a SARAM and a ROM memory. All memory blocks on C28x devices are mapped to both program and data space.

The flash memory is $256Kx16$ in size, segregated into eight $32Kx16$ sectors. The DSP also contains a single $1Kx16$ block of OTP memory. The user can individually erase, program, and validate a flash sector while leaving other sectors untouched. However, it is not possible to use one sector of the flash or the OTP to execute flash algorithms that erase/program other sectors.

F28335 contains M0 and M1 blocks of single-access RAM (SARAM), each $1Kx16$ in size. The C28x device presents a unified memory map to the programmer. Hence, the user can use M0 and M1 to execute code or for data variables. It also contain $32Kx16$ of SARAN, divided into 8 blocks (L0–L7 with 4K each).

The Boot ROM is factory-programmed with boot-loading software. Boot-mode signals are provided to tell the bootloader software what boot mode to use on power up. The user can select to boot normally or to download new software from an external connection or to select boot software that is programmed in the internal Flash/ROM (see Table 5.1). The Boot ROM also contains standard tables, such as SIN/COS waveforms, for use in math related algorithms.

Peripheral

The JTAG (Joint Test Action Group) interfaces emulates a serial communication, that is connected to DSP via its SCI-B port. It can be used to download the firmware on the modem, debugging and as a standard serial

GPIO84	GPIO85	GPIO86	GPIO87	Modalità
1	1	1	1	Jump to Flash
1	1	1	0	SCI-A boot
1	1	0	1	SPI-A boot
1	1	0	0	I2C-A boot
1	0	1	1	eCAN boot
1	0	1	0	McBSP-A boot
1	0	0	1	Jump to XINT x16
1	0	0	0	Jump to XINT x32
0	1	1	1	Jump to OTP
0	1	1	0	Parallel GPIO I/O boot
0	1	0	0	Jump to SARAM
0	0	1	1	Branch to check boot mode
0	0	1	0	Branch to Flash, skip ADC calibration
0	0	0	1	Branch to SARAM, skip ADC calibration
0	0	0	0	Branch to SCI, skip ADC calibration

Table 5.1: *Boot mode selection*

interface. There are also another serial interface, the SCI-A, that is RS-232 compliant interface and can be used to connect other external serial devices.

All the integrated peripherals in the DSP are:

- 6-channel Direct Memory Access (DMA)
- Three 32-bit CPU-Timers
- Up to six enhanced PWM modules (ePWM1, ePWM2, ePWM3, ePWM4, ePWM5, ePWM6)
- Up to six enhanced capture modules (eCAP1, eCAP2, eCAP3, eCAP4, eCAP5, eCAP6)
- Up to two enhanced QEP modules (eQEP1, eQEP2)
- Enhanced analog-to-digital converter (ADC) module
- Up to two enhanced controller area network (eCAN) modules (eCAN-A, eCAN-B)
- Up to three serial communications interface modules (SCI-A, SCI-B, SCI-C)
- One serial peripheral interface (SPI) module (SPI-A)
- Inter-integrated circuit module (I2C)
- Up to two multichannel buffered serial port (McBSP-A, McBSP-B) modules
- Digital I/O and shared pin functions
- External Interface (XINTF)

5.2 Code Composer Studio

Code Composer Studio (CCStudio) is an integrated development environment (IDE) for Texas Instruments' (TI) embedded processor families [32]. CCStudio comprises a suite of tools used to develop and debug embedded applications. It includes compilers for each of TI's device families, source code editor, project build environment, debugger, profiler, simulators, real-time operating system and other features.

Code Composer Studio is based on the Eclipse open source software framework. The Eclipse software framework was originally developed as an open framework for creating development tools. Eclipse offers a software framework for building software development environments.

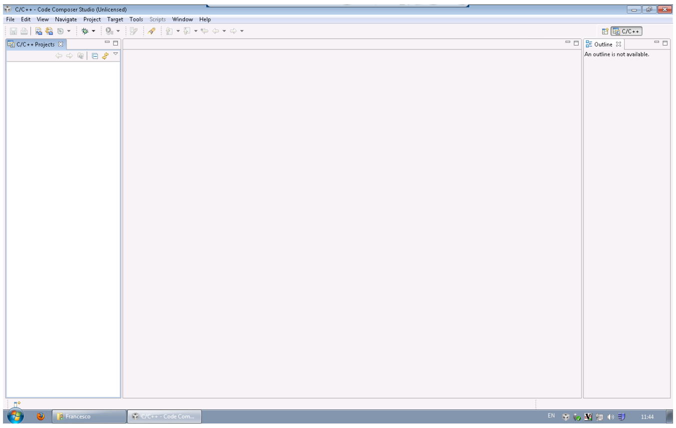
The release used in the current work is the lastest release available, version 4.2.4. In the current work CCStudio was used to programming F28335 DSP included in the PLC development kit described before.

In the following, two point are presented which are relevant in order to create and develop a firmware for the modems. The former group (from Figures 5.4 to Figures 5.6) shows the procedure to create a new CCStudio project for a F28335 DSP device and some key points to know in order to use the IDE. The latter group (Figures 5.7 and Figures 5.8) shows how to import the base project, called "test_tx_rx", given with the kit. In particular, this project was modified in order to put all the libraries in a suitable folder that allows to use the "global" folder in different computers. For further details, refer to [35].

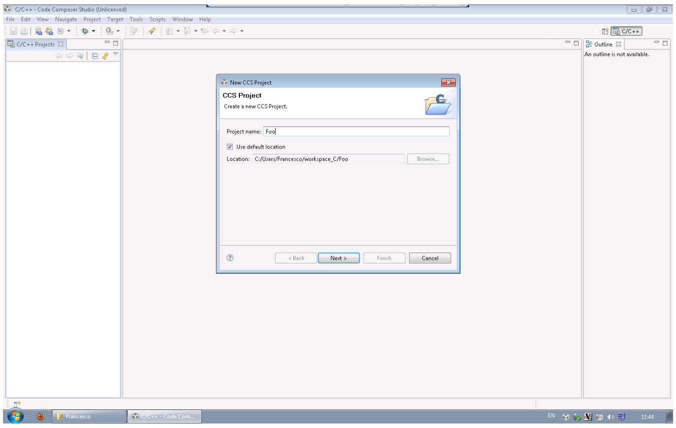
5.3 Experimental Lab

The team at the University of Padova is a Telecommunications team based at DEI, Department of Information Engineering, which gathers people with different expertise, from physical to network aspects, to guarantee valuable contributes on all layers of the ISO/OSI model. This team is part of a wider interdisciplinary team of researchers at DEI working on all relevant subjects related to SmartGrids. This group gathers together people from control, telecommunications, measurement, power electronics, and power systems, and has developed a deep scientific and technical background which will be instrumental to the project.

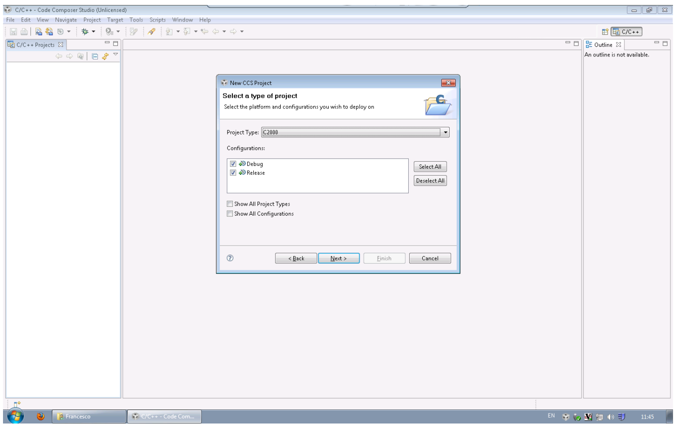
The DEI has realized an experimental lab represented in Figure 5.9 in or-



5.4.1: *Initial Screen of the IDE*

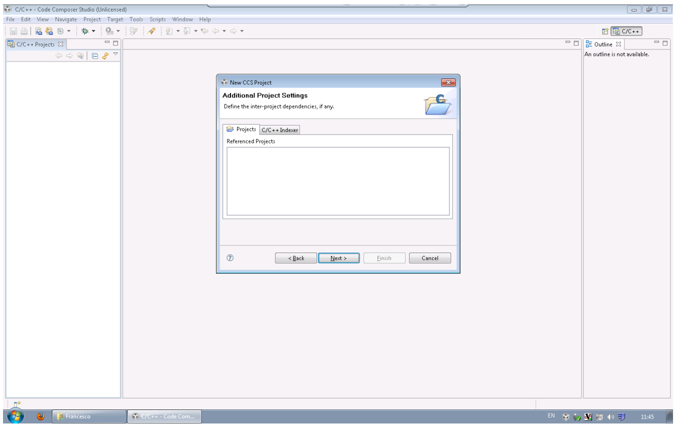


5.4.2: *Creation of a new CCStudio project*

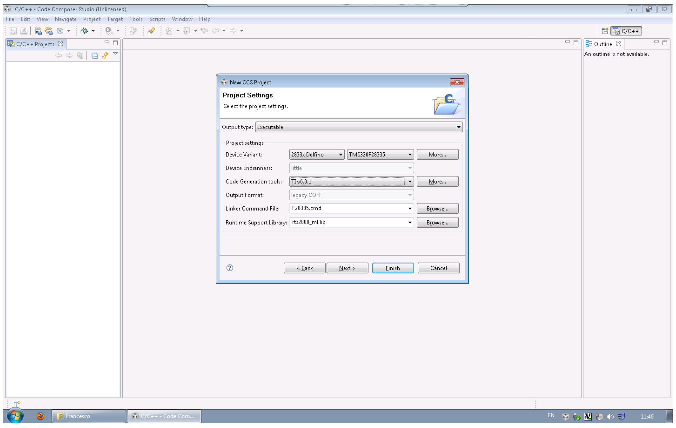


5.4.3: *Selection of a type of project: the family of DSP device*

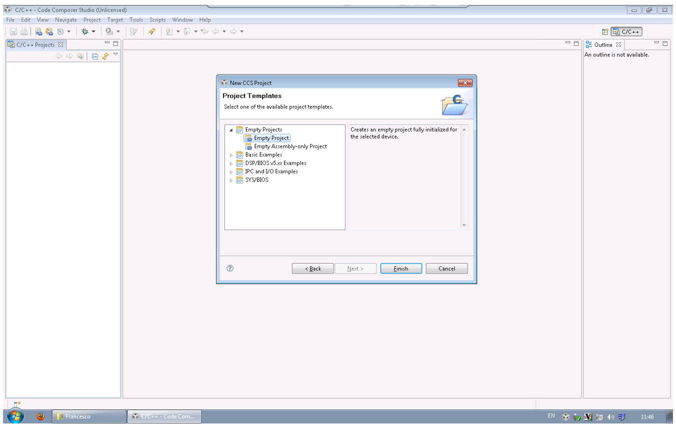
Figure 5.4: *Creation of a new empty project (Part 1-3)*



5.5.1: *Additional Project Settings*

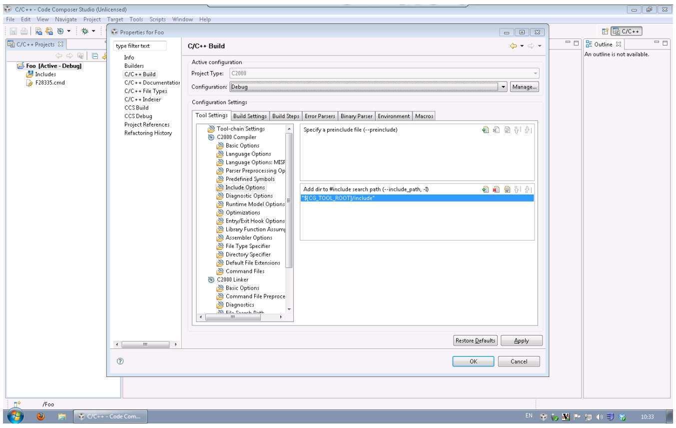


5.5.2: *Selection of the DSP model (a F28335), the linker command files and the runtime support library*

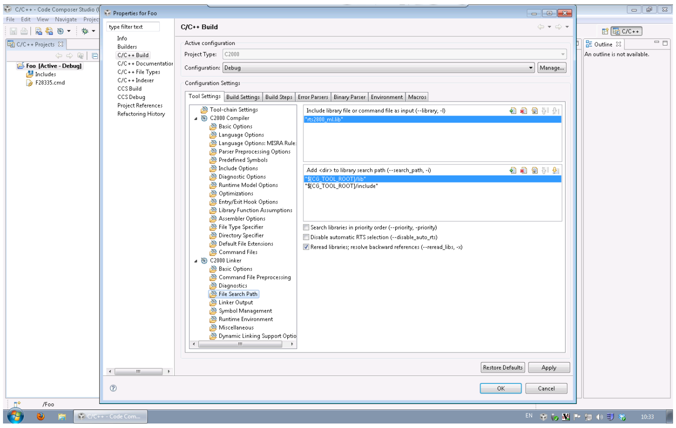


5.5.3: *Empty project templates*

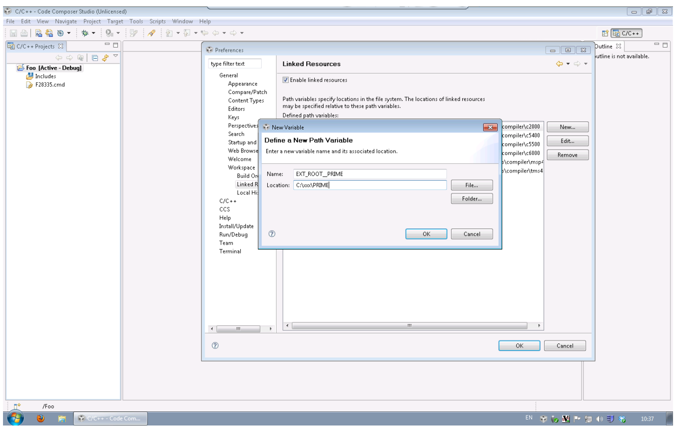
Figure 5.5: *Creation of a new empty project (Part 2-3)*



5.6.1: *Project properties: adding all required library headers files path*

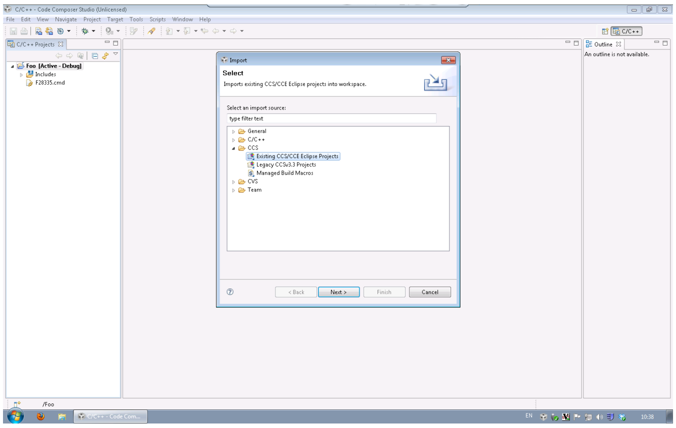


5.6.2: *Project properties: adding all required library binaries files path*

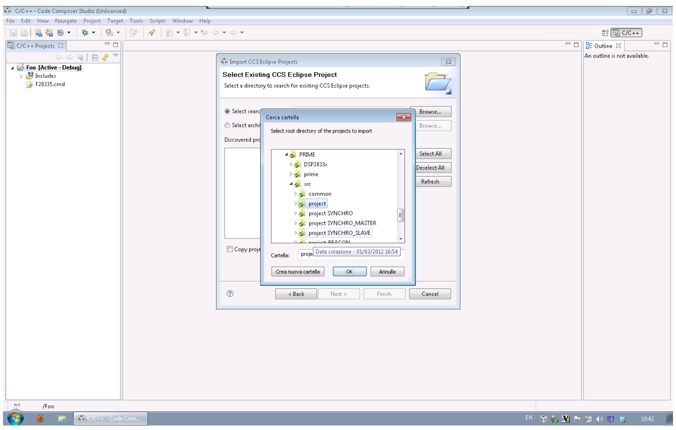


5.6.3: *IDE preferences: creation and managing of IDE variable for resolving path*

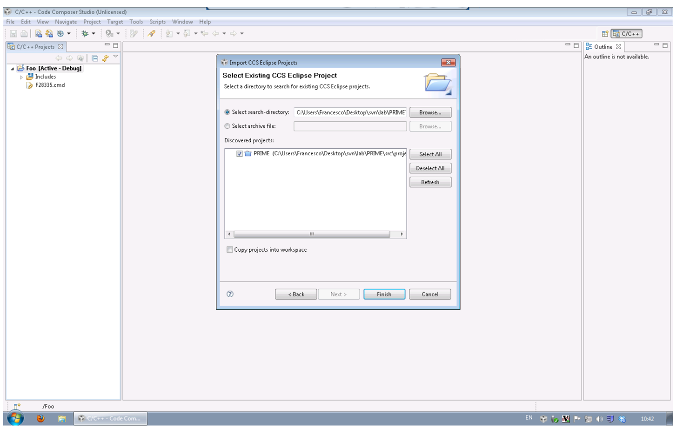
Figure 5.6: *Creation of a new empty project (Part 3-3)*



5.7.1: *Importing a CCStudio v.4 project*

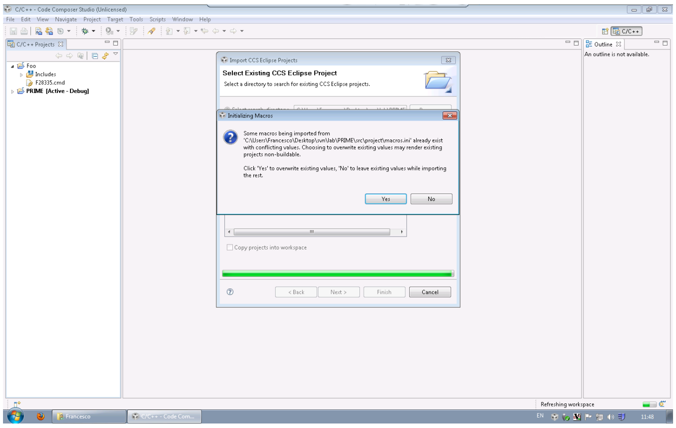


5.7.2: *Selection of the base PRIME project used in the work*

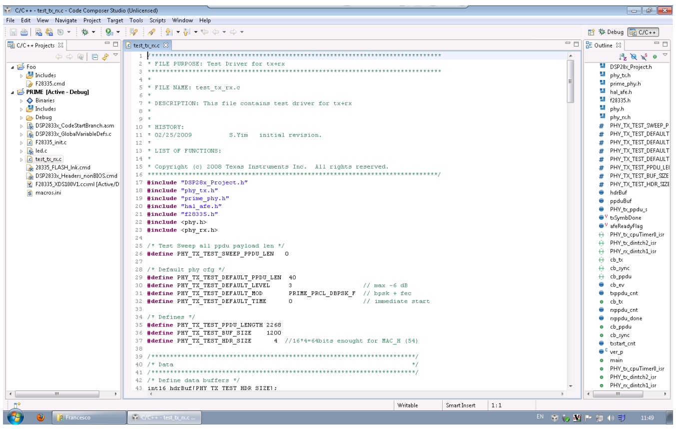


5.7.3: *End of the importing procedure*

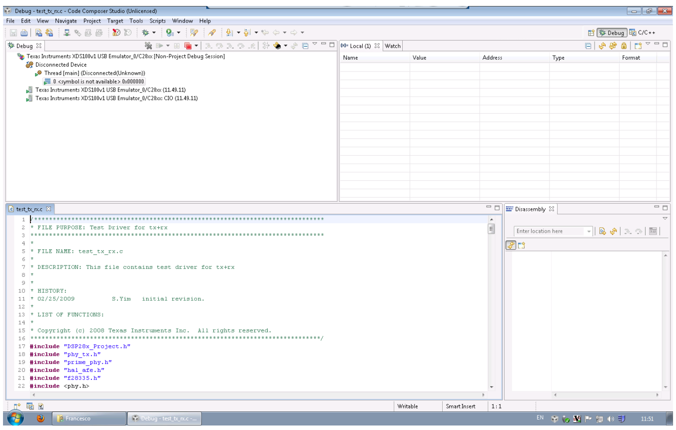
Figure 5.7: *Importing CCSstudio project procedure (Part 1-2)*



5.8.1: *Alert message due to "macros.ini" file that overwrite the "EXT_ROOT_PRIME" IDE variable*



5.8.2: *Main developing screen of the IDE*



5.8.3: *Debug window and CPU management*

Figure 5.8: *Importing CCSstudio project procedure (Part 1-2)*

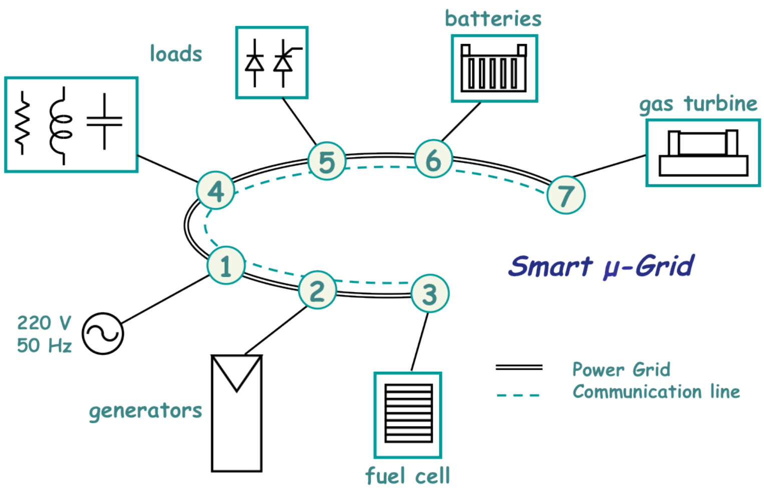


Figure 5.9: *Experiment Lab Scheme realized at DEI [36]*

der to accommodates a conspicuous number of facilities to allow the simulation, testing and measurement of Smart Micro Grid (SMG) phenomena [36].

In particular, it includes the following building blocks:

- Smart Microgrid Testing switchgear
- Power test instruments and systems
- Renewable energy resources

5.3.1 Smart Microgrid Testing Switchgear

The SMG Testing switchgear is a custom switchgear designed and built to meet, through flexibility and controllability, the needs of a multidisciplinary research activity in residential Smart Grids.

The system is composed of three principal sections: an input section, an output section, and a control section. The input section typically realizes the connection of the testing system to the main power source (e.g., off-grid sources like UPS or renewables like PV, fuell-cell, etc.), while the output section allows to connect the desired loads. Here, naturally, "input" and "output" do not imply any restriction to energy flows, indeed a bidirectional flow of energy is possible. The control section supervises voltages, currents, and temperatures to guarantee the proper and safety operation of

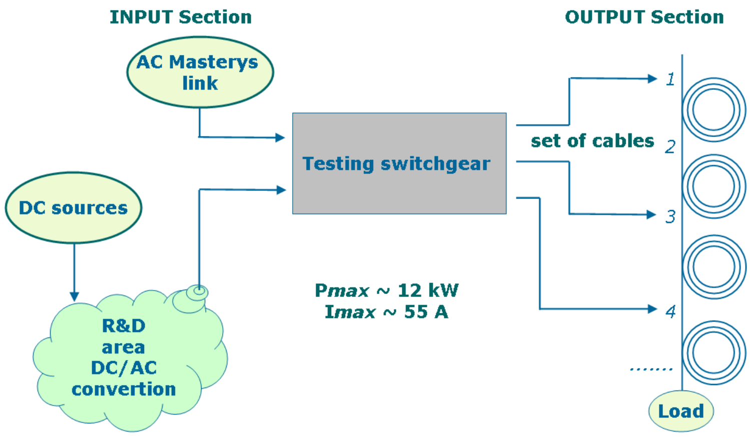
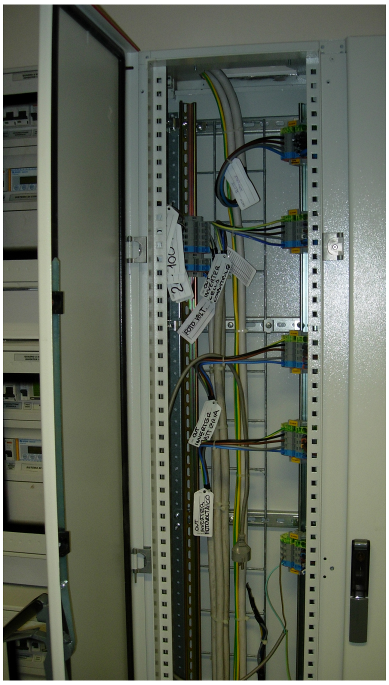


Figure 5.10: *Diagram of the Smart Micro Grid Testing switchgear [36]*

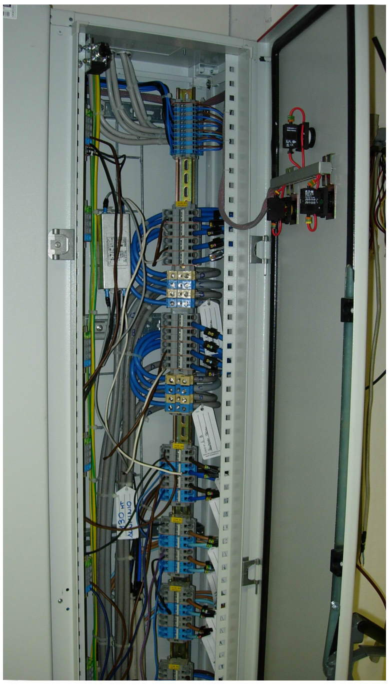
the apparatus, moreover it communicates via LAN network the switchgear's status.

The facility is also equipped with a set of cables (four pair of copper cables about 100 m long and four single aluminium cables about 130 m long) so that it allows to reproduce typical Smart micro-Grid environments (see diagram on Figure 5.10). The lugs of each cable at the output section of the switchgear are available, while at the input section are available the sources'. Hence, through the proper interconnection of cables and systems in the so called "output section" (shown in Figure 5.11.2), a diverse variety of grid configurations can be realized acting on switchgear's sockets. The "input section" allows to connect the external source (Figure 5.11.1) to the "control section" (Figure 5.11.3). The control section is composed of security (e.g. fuses), measurement (the "NEMOs", described in Section 6.1.1) and control equipment (e.g. shitch).

In these terms, the SMG Testing switchgear enables to build and analyze, into the research lab, electrical structures that simulate residential Smart micro-Grids. The special focus is on Smart micro-Grid distributed and dynamic phenomena, such as intermittent microgeneration, intermittent loads, interferences between smart devices' communication, and losses [36].



5.11.1: Input Section



5.11.2: Output Section

5.11.3: Control Section

Figure 5.11: *Smart Microgrid Testing Switchgear available in the experimental lab*

Figure 5.12: *Masterys BC UPS [36]*

5.3.2 Power Sources and Loads

Masterys BC (shown in Figure 5.12) is commercially available as an uninterruptible power source (UPS) for business critical and industrial applications. This UPS is used as point of common coupling (PCC) of the artificial power grid, separating power and radio-frequency signal (for PLC) between the artificial grid and the main distribution.

Its structure is that of a typical UPS, namely, its components are an AC/DC converter, a set of capacitors and batteries, and a DC/AC converter enhanced with a built-in tailored controller unit enabling the user to configure the machine's behavior (architecture scheme is shown in Figure 5.13). In particular it is possible to define the following aspects of the generated output voltage:

- RMS output nominal voltage and nominal output frequency (see Figure 5.14.1);
- Output voltage periodic swing from a definable minimum rms voltage to a maximum rms voltage, repeated over user defined periods;
- Add harmonics of arbitrary frequency and RMS voltage to the output(see Figure 5.14.3);

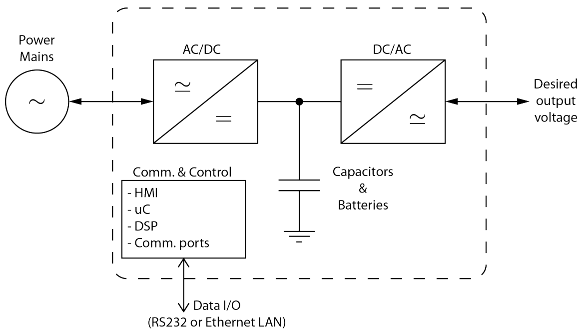


Figure 5.13: *Masterys BC UPS architecture scheme [37]*

- Introduce periodic frequency variations on the fundamental output component;
- Introduce a jitter in the output waveform (see Figure 5.14.4);
- Introduce configurable voltage dips into the output waveform (see Figure 5.14.2).

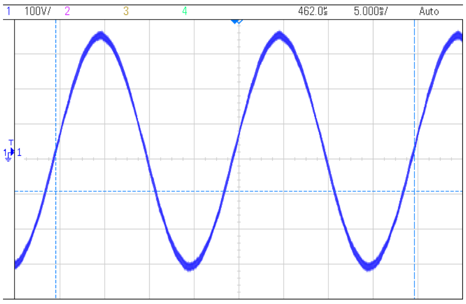
Once properly configured, Masterys will behave, at the output ports, as a three phase ideal voltage source capable of sustaining the defined voltage, through generating or sinking output currents. It can deliver to output loads or absorb and inject back to the power mains up to 64 kW of active power.

In the laboratory it is also available a Chroma 63804 programmable AC&DC electronic load that can simulate load conditions under high crest factor and varying power factors with real time compensation even when the voltage waveform is distorted. A full presentation and analysis of the programmable load is done in Section 6.1.2.

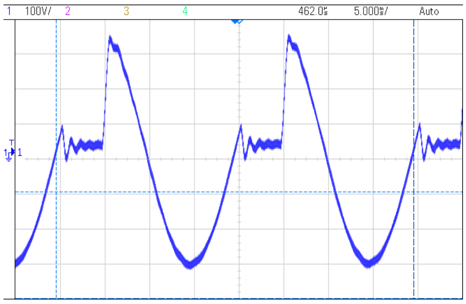
There are some energy sources that, at time of writing, are under installation and functional test phase. There are an high temperature 2kW PEM fuel cell, 3 kW PV panels, and 30 kWh batteries (leadacid, lithium, molten salts). The investment to develop this facility, including the instrumentation and data processing capabilities, ranges above 300k. Lately, as shown in Figrue 5.15, a modified version of Masterys BC is added.

5.3.3 The worktop

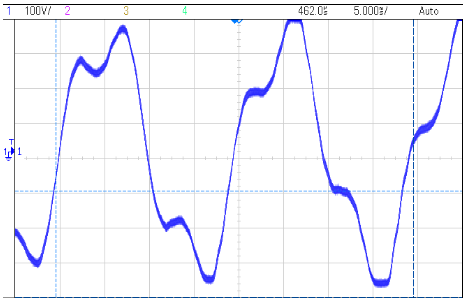
The worktop predisposed in the High Power Electronic Laboratory at DEI. In Figure 5.16.1, it is possible to see the available laboratory equipments:



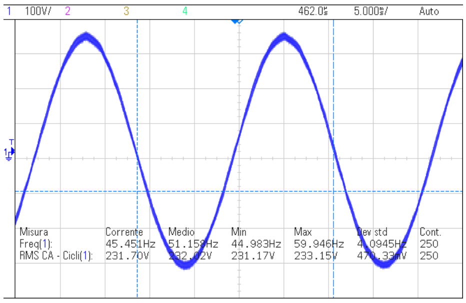
5.14.1: *Pure voltage waveform*



5.14.2: *Voltage waveform with holes*



5.14.3: *Voltage waveform with upper harmonics*



5.14.4: *Voltage waveform with jitter*

Figure 5.14: *Four possible cases of voltage waveform produced by UPS source*

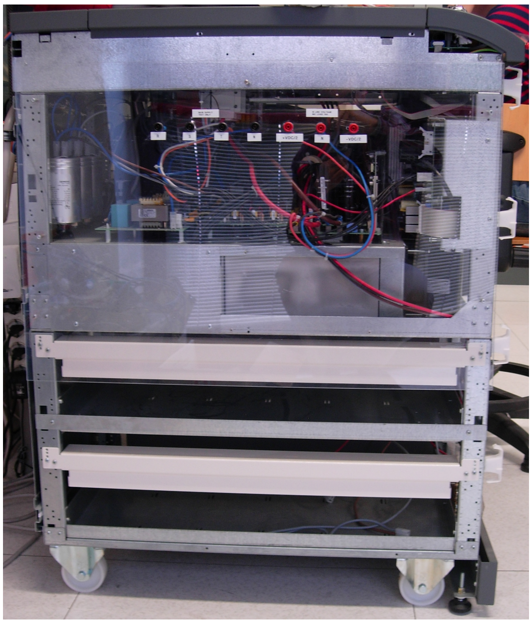


Figure 5.15: *A modified SICON Mastersys UPS*

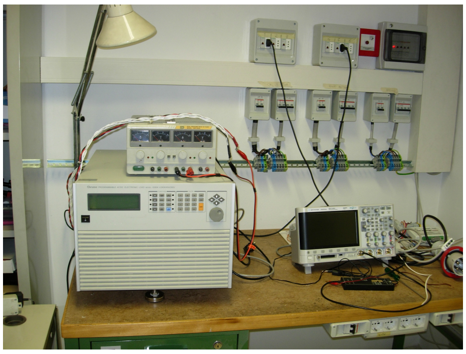


Figure 5.16: *Worktop of the Micro Smart Grid simulations*

- two PLC modems from Texas Instrument (see Section 5.1)
- the Chroma 63804 programmable load
- a digital oscilloscope from Agilent Technologies
- electricity outlet on the wall

The two modems support PRIME standard and, with the computer shown in Figure 5.16.2 and Code Composer Studio (CCS) Integrated Developing Environment (IDE) software, is possible to develop a new firmware capable to test smart grid concept. The oscilloscope, in conjunction of a 1/200 differential filter, is able to show the signal in the time domain and, with a fast Fourier transform (fft), to show the signal in the frequency domain.

All the equipments are connected to the artificial network via electricity outlets positioned on the wall. Hence, the Smart Grid experimental Lab accommodates numerous facilities to allow measurement, test and simulation of smart micro grid phenomena.

Chapter 6

Smart Grid Test Bed

In this chapter, the experiments implemented in the laboratory in order to test the theories described in previous chapterwill be illustrated. In particular, the goal of the experiments is doing a first demonstration of what is possible to do with Smart Grid technology.

At present time, European Community is pushing and financing companies and universities in order to develop Smart Grid concept. This work is part of the grid activity at Univestity of Padua. The research if focused on residential smart micro-grids and aims at develop an ICT architecture for the control of distributed Local Energy Managers (LEMs). To this end, it a plug & play control approach is followed, where each power processor identifies the surrounding network and communicates with neighbor units to establish a distributed and close-to-optimal control rule.

Concerning these aspect, a primary solution based on a elementary smart grid network will be presented. This experiment is developed in the power electronic laboratory of the Department of Information Engineering at Univestity of Padua and is intended as a proof of concept implementation. At first, the extra equipment used will be deeper presented and the intrinsic limits in this context will be discussed. At the end, the implementation of the test bed will be presented.

6.1 The Used Equipments

The developed experiment uses NEMO D4-L+, as measurement systems, a Chroma 63804 as AC programmable load and some “fixed” reactive loads.

Figure 6.1: *IME NEMO D4-L+ used in the laboratory*

6.1.1 IME NEMO D4-L+

The NEMO D4-L+ (shown in Figure 6.1) is a multifunction network monitor for low and medium voltage. For a four wire configuration, it is possible to measure: phase voltage, phase current, linked voltage, phase active power, phase reactive power, active, reactive, apparent three-phase power, frequency, three-phase power factor, phase current demand, max. phase current demand, power demand and power max. demand, working hours and minutes, voltage-current distortion harmonic, active energy, reactive energy, and partial active energy.

It uses a LCD to show the measured quantities. The device calculates the average of all measures each 1.2 second and displays the root mean square (RMS) value. It is also able to interface with other devices using RS-485 bus and JBUS/PROFIBUS protocol.

IME communication protocol

The IME D4-L+ device has a physical communication port using RS-485 standard in half-duplex mode [38]. In this case, as only two wires are used, only one instrument at a time can engage the line. This means that there must be a master which polls the slave instruments so the demand and the request are alternated. On the same physical line only 32 instruments can be connected (master included). In order to increase the number of the slave instruments, repeaters must be used. The communication parameters are:

Device address	Functional code	Data	CRC word

6.2.1: *The generic data packet message format*

Device address	Functional code	Data	CRC word

6.2.2: *The answer data packet format containing data*

Device address	Functional code + 0x80	Error code	CRC word

6.2.3: *The answer error packet format*

Figure 6.2: *Data messages packet format for the MODBUS protocol [39]*

Baud rate of 9600 bps, 8 bit number, 1 stop bit and no parity bit.

At Data link level, the data are transmitted in packets and are checked by a CRC word. After each command, a response telegram must follow, unless the command was a broadcast one.

At Application level protocol used is MODBUS/JBUS compatible (for full protocol reference, see [39]). Up to 255 different instruments can be managed by the protocol and there are no limitations to the number of possible retries done by the master. A delay between the response from the slave and the next command could be necessary.

RS-485

The RS-485 is a standard which defines the electrical characteristics of drivers and receivers only for use in balanced digital multipoint system, it does not specify or recommend any communications protocol [40]. Since it uses a differential balanced line over twisted pair, it can span relatively large distances (up to 1.200 m). It is also known as TIA/EIA-485.

RS-485 is used as the physical layer underlying many standard and proprietary automation protocols used to implement Industrial Control Systems, including the most common versions of Modbus and Profibus. These are used in programmable logic controllers and on factory floors. Since it is differential, it resists electromagnetic interference from motors and welding equipment [40].

MODBUS: Data Message Description

The packet exchanged between the master and nemo devices are MODBUS compliant. In Figure 6.2, the three types of packet used in the communication with nemo devices are shown: the first is the interrogation message while the others two are the answer message, the data- and error-packet respectively. In [39], the used parameters are:

- *Device address:* It is the device identification number of the network. It must be the same for the demand and the answer. It is 1 byte format from 0 to 0xFF, where 0 stands for broadcast messages with no answer.
- *Functional code:* It is the command code composed of one byte. The used functional code are:
  - 0x03: reading of consecutive words;
  - 0x10: writing of consecutive words;
- *Data:* They can be the address of the required words (in the demand) or the data (in the answer).
- *CRC word:* It is the result of the calculation done on all the bytes in the message. It uses the standard CRC-16-IBM[1] polynomial in the reversed format.

If the received message is incorrect (CRC16 is wrong) the polled slave does not answer. While, if the message is correct but there are errors (wrong functional code or data) it can not be accepted, so the slave answers with an error message using (for error codes definition, see [39]).

6.1.2 Chroma 63804 DC/AC Load

Chroma's 63800 Series AC&DC Electronic Loads are primarily designed for testing uninterruptible power supplies (UPS), Off-Grid Inverters, AC sources and other power devices such as switches, circuit breakers, fuses and connectors [41].

Chroma's 63800 AC/DC Electronic Load is designed for both AC and DC Load Simulations. Figure 6.4 shows the several load modes which are available. It can simulate loads with different crest factor, 1.414 $\sim$ 5.0, and varying power factor, 0 $\sim$ 1 lead or lag. Furthermore, voltage and current signals can be routed to an oscilloscope through analog outputs. The

[1] CRC-16-IBM has $x^{16} + x^{15} + x^2 + 1$ as polynomial generator.

Figure 6.3: *Programmable AC&DC Electronic Load Model 63800 Series*

instrument has two interfaces, GPIB and RS232, providing remote control monitor for system integration.

The most interesting features of model which was used in the laboratory, the Chroma 63804 model, are reported for AC load mode:

- Power Rating: 4500 W
- Voltage Range: 50V $\sim$ 350 Vrms
- Current Range: Up to 45 Arms
- Peak Current: Up to 135 A
- Frequency Range : 45 $\sim$ 440Hz
- Crest Factor Range: 1.414 $\sim$ 5.0
- Power Factor Range: 0 $\sim$ 1 lead or lag (Rectified mode)
- Constant Current (CC), Constant Resistor (CR), Constant Power (CP) working modes
- Constant and Rectified Load Modes
- Analog Voltage and Current Monitor

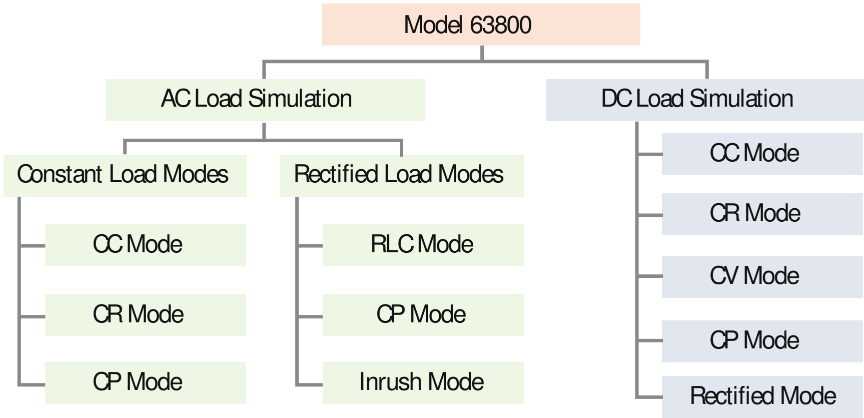


Figure 6.4: *Working modes for Chroma 63800 DC&AC Load series [42]*

- Measurement: voltage (V), current (I), power factor (PF), crest factor (CF), active power (P), reactive power (Q), apparent power (S), frequency (F), impedance (R), peak current (Ip+/-) and total harmonic distortions for voltage (THDv)

- Short circuit simulation

The instrument offers also the possibility to route voltage and current signals to an oscilloscope through analog outputs.

The load provides two unique operating modes for AC load simulation: Constant Load Modes and Rectified AC Load Modes. The device is used in Constant Load Mode for smart grid simulation; next, only the case of Constant Load Mode is treated.

In particular, the definitions of crest factor (CF) and power factor (PF) will be widely used. Herewith the definitions for both factors are reported:

$$\text{crest factor} \qquad CF_I = \frac{I_{peak}}{I_{RMS}} \tag{6.1}$$

$$\text{power factor} \qquad PF = \frac{P}{A} = \frac{\text{active power}}{\text{apparent power}} \tag{6.2}$$

AC Load Simulation: Constant Load Modes

The Constant Load Mode allow users to set the following operating modes: Constant Current (CC), Constant Resistor (CR) and Constant Power (CP) modes. The CC and CP modes in this category allow users to program

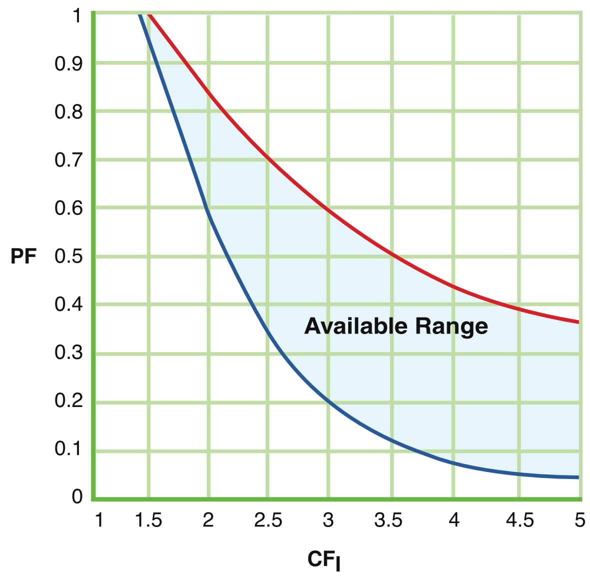


Figure 6.5: *Crest Factor vs. Power Factor control range [42]*

power factor (PF) or crest factor (CF), or both (for CR mode the PF is always set to 1).

When both the PF and CF of the loading current are programmed, the 63800 load controls the power factor from 1 to 0 by shifting the current (with CF defined) relative to the input voltage to get the desired displacement power factor. The power factor range is limited based on programmed crest factor. If the programmed PF is positive, then the current will lead the voltage waveform. On the other hand, when PF is set negative, the current will lag the voltage waveform.

As seen in Figure 6.5, for a crest factor of 1.414, the programmed power factor can only be 1 (for sine wave voltage waveform). However, for a $CF = 2.0$, the acceptable PF ranges from 0.608 to 0.85; for $CF = 3$, the PF can then be set from 0.211 to 0.6, etc. So, higher crest factors enable a wider range of power factors.

Chroma communication protocol

Chroma 63804 Load uses Standard Commands for Programmable Instruments (SCPI) protocol for both GPIB and RS232 interfaces. SCPI defines a standard for syntax and commands to use in controlling programmable test and measurement devices [43].

SCPI commands to an instrument may either perform a set operation (e.g. switching a power supply on) or a query operation (e.g. reading a voltage) [43]. Queries are issued to an instrument by appending a question-mark to the end of a command. Some commands can be used for both setting and querying an instrument. For example, the data-acquisition mode of an instrument could be set by using the `ACQuire:MODe` command or it could be queried by using the `ACQuire:MODe?` command. Some commands can both set and query an instrument at once. For example, the `*CAL?` command runs a self-calibration routine on some equipment, and then returns the results of the calibration.

Similar commands are grouped into a hierarchy or "tree" structure. For example, any instruction to read a measurement from an instrument will begin with "`MEASure`". Specific sub-commands within the hierarchy are nested with a colon (:) character. For example, the command to "Measure a DC voltage" would take the form `MEASure:VOLTage:DC?`, and the command to "Measure an AC current" would take the form `MEASure:CURRent:AC?` [42].

Regarding RS232 interfaces, the communication parameters are: Baud rate of 57600 bps, 8 bit number, 1 stop bit and no parity bit. The data and commands to/from the programmable load are composed of standard ascii character (for full command reference, see [42]).

6.2 Experiments Set Up

In this section is shown the adopted solution for the testbed. It will be discussed the experiment set up and problem encountered that have limited the simulation scenario where only two nodes are present in the grid.

In the experiments the following devices are included:

- two PLC modems: the used modem are made from Texas Instruments Power Line Modem Developer's Kit (TMDSPLCKIT-V2);
- one programmable load: Chroma 63804 Load with the possibility of remote controlling with RS232 interfaces;
- two power meters: IME NEMO D4-L+ are multifunction meters with a RS-485 interface to remote read the measured data;
- some home build loads;

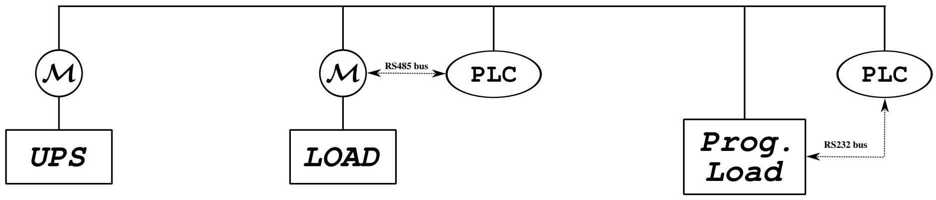


Figure 6.6: *Diagram principle of the smart microgrid testbed*

- other minor materials like: RS-232/RS-485 adapter to interface the NEMO device with the modem, an oscilloscope to monitor voltage and current waveform of the programmable load.

6.2.1 Hardware Implementation and Grid Structure

This material available in the laboratory are sufficient to implement the simple network described by the diagram of Figure 6.6. This simple example of a power network would be a proof of concept of what is possible do with the Smart Grid idea in conjunction with power line communications.

The experiment implements plug & play control approach described in Section 4.5.1 where only the reactive power is compensated. The purpose of this experiments is to reduce the current supplied by Point of Common Coupling (PCC) that, in this case, is represented by the UPS.

The power grid is composed of two nodes:

- *Simulated Load:* it simulates a generic load that is connected to the power line. Could be any devices, like motors, microwave or simply a light.

  In the experiments, the representative features of the load is the reactive power exchanged whereas the absorbed active power is ignored by plug & play control. Therefore, active power is indifferent and the simulated load can be fully reactive.

- *Programmable Load:* it is implemented by Chroma 63804 DC/AC Load. The ideal solution would have a programmable source that can also exchange reactive power with other power devices. This solution is not applicable since there are a lot of difficulties to find an externally controlled source. Currently, manufactures sell sources that are fully autonomous and do not have any possibility to interact with its controlled system. Hence, the solution here adopted is based on a programmable/controllable load instead of a controllable source.

From the exchanged reactive power point of view, loads and sources are equivalent, they exchange the reactive power with other devices indifferently. Thus, the load acts as a source in our case when working as a fully reactive device.

The "source" represented by the PL, as previously commented, should act as a fully reactive device but, in practice, with Chroma 63804 this is not possible. This load can be programmed with a PF from 0.1 to 1 that is not 0. Moreover, other issues came out when the PL works on small power factor. This issue and solution adopted will be discussed in a dedicated section.

The simulated load is associated with a measurement device implemented by a NEMO. The modem polls the NEMO and reads the information about the status of the load via a RS-485 bus. Since the modem is equipped with a RS-232 interface, a RS-232-RS-485 protocol adapter is used.

The simulated load are made by a bunch of resistors, inductors and capacitors. As previously commented, the relevant characteristic of this load is the reactive power exchanged and then, only reactive loads are taken into account. The most interesting loads used in the simulation are listed in Table 6.1.

Since there are no base nodes in the PLC network, the two nodes are in a master-slave configuration: the master node has the "intelligence" and commands the programmable load via a RS-232 interface. Whereas the slave nodes read the information from the NEMO and, when polled by the master, sends the status vector of the load to the master.

The second NEMO, located near the UPS, is used as a global meter and is independent of the "intelligence" that will be implemented. It is used

TYPE	*IMPEDANCE*	*VALUE*	*POWER FACTOR*
$R\|\|C$	$Z = 188 - j318\ \Omega$	$P = 281 - j166$ VA	$PF = 0.861$
C	$Z = -j1592\ \Omega$	$P = -j33$ VA	$PF = 0$
L	$Z = +j370\ \Omega$	$P = j143$ VA	$PF = 0$

Table 6.1: *Simulated loads used in the testbed*

to check the status of the network, like power usage and reactive power exchanged with the PCC simulated by the UPS.

6.2.2 Software Implementation

The aim of the project is to create an autonomous intelligence that is able to "monitor" the network, compute the "optimization parameter" and then operate to reduce the power loss due to inefficiency of the network. In order to do that, a smart controller is needed to implement the intelligence.

The modems are equipped with a TI CPU, the TMS320F28335 from C2000 DSP family. The tool used to program the modems is Code Composer Studio (CCS) Integrated Development Environment (IDE) version 4. The example project that is used to develop the new firmware is the "TI prime phy example" which enables the physical layer only. Since there are no Base Node available and thus only point-to-point communications are possible.

Apart from the absence of a Base Node, all physical packets are PRIME compliant. In order to speed up developing process and simplify the software architecture, the software stack is structured as follows:

- The Physical Layer is implemented by TI library and no source code is available. Therefore, there is no clue on how the libraries are implemented and how the CPU devices are set up. The documentation of the available API are available with the kit.

- The MAC Layer is partially implemented without using TI software library. Only the essentials function of PRIME protocol are implemented. In particular, data management and transmission APIs are fully compliant with PRIME standard. Those APIs are widely used in the project, while other APIs, like network registration and network management, are not used (neither implemented) since our network is composed by two nodes only.

- The Convergence Layer is not implemented. It has been seen that all developed applications do not need CL features like Segmentation and Reassembly.

- The Application Layer contains the function implemented to read the status and control the grid. Some of them are dedicated to read the data from measurement devices, the "NEMO", while other are devoted to manage neighbor distance table and control the programmable load (PL).

A note is needed, the neighbor distance table is manually implemented in this experiment. As previously mentioned, this limit is due to the lack of distance implementation of PRIME standard. A fist draft of distance measurement in PRIME network is implemented in [44]. This work with its future review is one of the missing feature in order to implement an autonomous intelligence into the grid. Another work is tho evaluate PRIME performance. A set of measurements and theoretical comparison is done in [45].

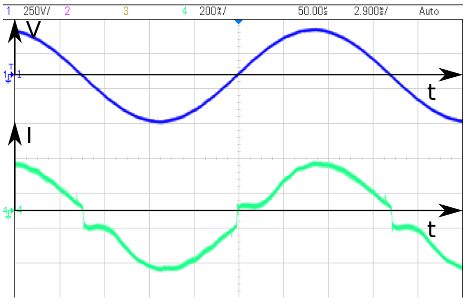
The two modems are configured in a Master/Slave configurations, where the Master is connected to the programmable load, which collects the data from neighbor nodes that is the Slave Node only. The slave node is connected to the NEMO and collect the data to the different loads connected. The Slave Node cyclically update the status vector of the loads (i.e. voltage, current, active and reactive power). On the other hand, the Master Node polls the Slave Node which answer with the status vector. Then, it elaborates the data and sets the programmable load to exchange the opposed amount of reactive power of the load and thus reducing the exchanged reactive power with the PCC. Later, a deeper analysis of the implemented algorithm is presented.

6.3 Implementation Issue

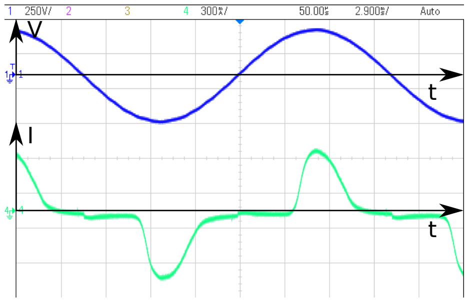
The hardware implementation is based on equipments previously mentioned. But some of them had shown some issues that have introduced some limits to the experiments. Next, the issues encountered and the solution adopted to work out of devices limits will be discussed.

Programmable Load on Field

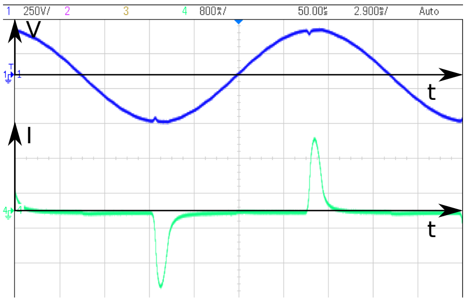
The Chroma AC programmable load, when working on AC system, has the possibility to change the power factor and thus to exchange reactive power with other source/loads. As mentioned before, the control range of PF vs. CF is limited by device characteristics and the available working range as shown in Figure 6.5.



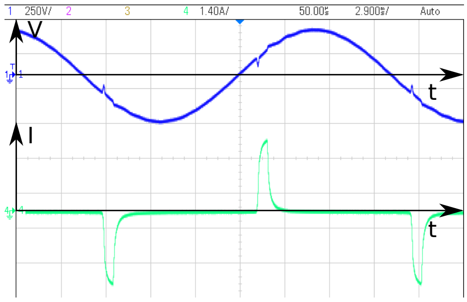
6.7.1: $PF = 1.0$ *and* $CF = 1.508$



6.7.2: $PF = 0.8$ *and* $CF = 2.274$



6.7.3: $PF = 0.5$ *and* $CF = 4.008$



6.7.4: $PF = 0.2$ *and* $CF = 4.161$

Figure 6.7: *Chroma 63804, powered at* $V = 230$ *V AC and* $P = 100$ *W, with different power factor and crest factor*

The first test conducted on the PL is powering it with electric power, a pure sine wave with effective voltage of $V = 230$ V. The measurement are done with an Agilent MSOX2024A Oscilloscope with a 1/200 differential attenuator filter on channel one in order to measure voltage waveform, and channel four is used a current probe on one of the three wires that power the PL (then, about 1/3 of the current is measured), in order to measure current waveform. The test result are shown on Figures 6.7 and, when working with a PF below 0.8, the CF should increase in order to remain into the working range (see Figure 6.5) and the current waveform is distorted almost to a square wave.

The distorted current waveform thus introduces harmonics in higher frequency and then the load is not linear. Generally, AC load can be approximated as linear since that the most power is feed by the fundamental. Hence, the programmable load can be approximated as a linear load when operates with a power factor in the range of $PF = 0.9 - 1$ that allow to set a "small" crest factor.

Measurement Devices on Field

NEMO device is a measurement device of the effective value of the source/load connected to it. It is inserted in a mobile encapsulation in order to test it with different loads and then check its performance.

Regarding the passive load (e.g. resistor or capacitor), it has shown an error of about $5 - 6$ % that is a common value for this type of equipment. One of the limits is its small sensitivity on reactive power around zero, it measures reactive powers above ± 20 VAR.

When NEMO device is put as measurement for Chroma programmable load, it shows a unrecognized behavior: when PL operates as a resistor ($PF = 1$) everything is measured correctly. On the other hand, when a reactive part is introduced ($PF < 1$ and then $CF > 1.5$), the NEMO measure only a smaller value of reactive power. The only explanation of this behavior is given by a filtering of higher harmonics due to current transformer used by the NEMO. Usually, this device is used with loads that show only few relevant harmonics (thus a sine wave current waveform, i.e. $CF \approx 1.414$), whereas the programmable load, when operatse as almost a reactive load, needs an higher crest factor and then more harmonics are relevant. To overcome to this issue, the crest factor should be set near to a pure sine wave.

The crest factor chosen in the testbed is $CF = 1.55$, that allows to set a power factor of $PF = 0.95$. In this set up, all power parameters (active, reactive and apparent power) are correctly measured by the NEMO.

Other solutions are possible but on the other hand meters able to measure more harmonics are extremely expensive. A measurement device is currently in preparation with aim of measuring the voltage and current phasor.

6.4 Laboratory Simulation

The laboratory structures has been already presented in Section 5.3. In this section the testbed set up and results are presented. As previously mentioned, the implementation is a simplified model where only two node are present to form the network structures shown in Figure 6.6.

In Figure 6.8 is shown the worktop described in Section 5.3.3. The testbed works as follows:

- The master modem, (1), commands the Chroma programmable load,

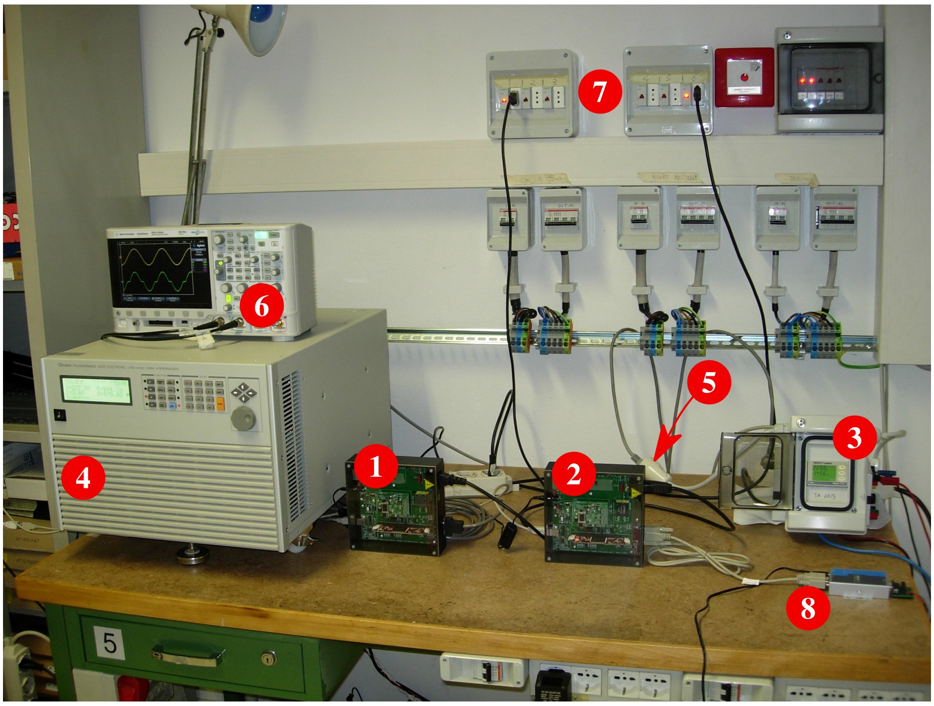


Figure 6.8: *The worktop in the laboratory where the testbed is implemented*

(4), via a RS-232 serial connections

- The slave modem, (2), reads the status vector from NEMO device (3) via a serial connection (the serial adapter (8) is needed in order to connect the modem, equipped with a RS-232 interface, and the NEMO, equipped with a RS-485 interface)
- The master modem periodically polls the slave modem, which answers with the status vectors of the simulated load.
- The simulated load, (5), is connected to NEMO device trough a power plug
- Both modem are connected to the grid with power plug, (7)

On the oscilloscope, (6), is possible to see (and measure) the power exchanged by the programmable load. At the end, there is also anther NEMO device, collocated in the main switchgear, measure the overall power exchanged between the power grid and the PCC (or UPS). This measure is strategic, as it shows the system performance.

At the end, the system is ready to be tested. First, the master node initiates the programmable load as a pure resistor of 100 W ($PF = 1$).

The master node periodically polls the slave modem and, after receiving the status vector from slave node, elaborates the data. If a reactive power compensations is needed, the master modem sets the PL with $PF = 0.95$ and $CF = 1.55$. Whereas, if the loads on the grid is a pure resistor, the master modems sets the PL on initial status (i.e. a pure resistor consuming 100 W).

The PL does not receive the amount of reactive power that has to exchange, but it can only receiver the active power that has to waste. From (6.2), it is possible to rewrite it in function of Q as

$$P = \frac{|Q|}{\sqrt{1 - PF^2}} = 3.203\,|Q| \tag{6.3}$$

since the power factor is choose as a constant value of $PF = 0.95$. The sign of the reactive power is programmed into the PL in the "sign" of the power factor. Mathematically (and by the its definition) the power factor can not be negative. But, as described in PL features, the sign of the power factor is used to set the sign of the reactive power exchanged by the PL. Therefore, a $PF = \pm 0.95$ is set accordingly.

Next, one or different loads of Table 6.1 are inserted in order "strees" the controlling system:

Test 1: In this first test, only the first $R||C$ load is plugged in. It is characterized of a power of $P = 281 - j166$ VA.

After a while, the master modems reacts and compensates the reactive power of the simulated load with an active power of 531 W with a "positive" power factor. The validation of the results is shown by the second NEMO, that at first shows a reactive power exchanged by the UPS of -0.17 kVAR and, after the compensation, of 0 kVAR. This confirms the validity of the test.

Test 2 In this case, the pure capacitor is used with a power of $P = -j33$ VA. Also in this case the control responds correctly and set the PL to exchange the opposite reactive power.

Test 3 In this test, the inductor reactance is used with a power of $P = j143$ VA. In this case, PL has to be set with a negative power in order to exchange a negative reactive power.

In this case, there is a small imprecision on the compensation, the second NEMO shown a non zero value. There are two possible explanations to this behavior. First, the PL is not perfectly symmetric and does not exchange the same reactive power with a positive and negative power factors. Second, the two NEMO devices do not use the same current transformer measurement device and then show a different approximation for this small value of powers. Thus, this behavior can be explained as a reading error by the two NEMOs.

Test 4 Next, a combination of the loads is used. In all case, the behavior of the system is coherent with previous cases. Also in those cases, when the inductor is present, the compensation is less precise.

Chapter 7

Conclusions and Future Improvements

In this thesis, a smart grid testbed is developed and tested. It is implemented in a smart microgrid with two PLC modems. The developed testbed is a simplified case of a more general case described by Plug & Play techniques. It would be as a proof of concept of Smart Grid idea.

In this work, limits are mostly due to the programmable load. This device can not work as a reactive and linear device, but an important component of active power has to be consumed. This gives a growth of the current by the grid even if there is reactive power compensation. Moving on a controllable source or a fully reactive controllable elements is the best solution, but it is not applicable since such device is not yet ready. Anyway, the concept here implemented with the programmable load is still valid.

Another improvement is the replacement of the measurement devices, the NEMO, which is a high performance measurement device based on MCP3909 microchip and, at time of writing, is under preparation by the Electronic Team of the department. It will capable of measure data necessary to determine both current and voltage phasors.

At the end, the software implemented in the firmware is capable to pilot the programmable load and read the data from the NEMO through the serial connection. It also implements a simplified version of the PRIME MAC layer capable of working in a point-to-point mode. The software is ready to be used in a network with more nodes and with a fully functional PRIME network, with the Base Node, since it accomplishes PRIME specifications.

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