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REPUBLIQUE DU SENEGAL  
UNIVERSITÉ GASTON BERGER DE SAINT-LOUIS

INSTITUT  POLYTECHNIQUE  
DE SAINT-LOUIS



MTP N°XXX

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**Master's Degree in Electromechanical Engineering**

**Master Thesis Project**

Presented by

**Gilbert Djidiack FAYE**

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Topic : Integration of smart meters in electrical grid:  
Application to the transmission and distribution grid of  
SENELEC (Senegal National Electricity Agency)

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**Master thesis project laboratory**

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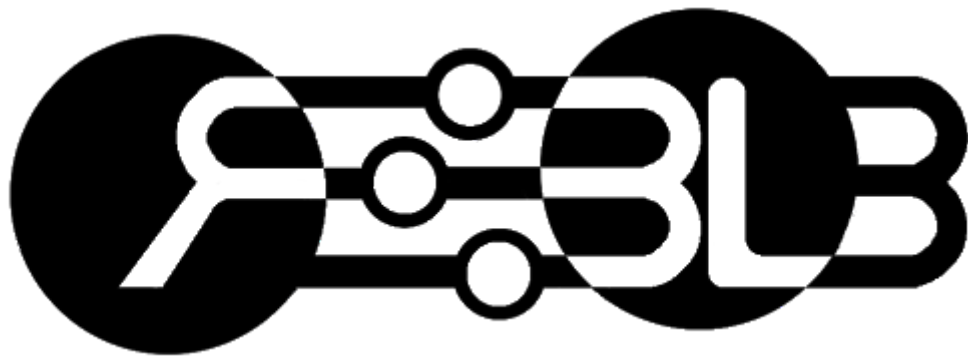
MTP presented on 12/03/2021 Academic Year 2019-2020

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**ROBOLABO**  
**LABORATORY OF ROBOTICS AND CONTROL**

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**Integration of smart meters in electrical grid**  
**Application to the transmission and distribution grid of SEN-**  
**ELEC**

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**Gilbert Djidiack FAYE**

## Abstract

The unpredictable increase in electrical demand affects the quality of the energy throughout the network. A solution to the problem is the increase of distributed generation units which burn fossil fuels. While this is an immediate solution to the problem the ecosystem gets affected by the emission of CO<sub>2</sub>. A promising solution is the integration of Distributed Renewable Energy Sources (DRES) to the conventional electrical system, thus, introducing the concept of smart microgrids (SMG) that require a safe, reliable and technically planned two-way communication system.

That's why the Senegal National Electricity Agency (SENELEC) decided to invest into this sector to equip itself with a smart grid that satisfies all criteria of a smart grid. For those purposes, smart meters named KAIFA are being deployed in all grids of SENELEC starting from power stations to the consumption points.

This research is within the scope of the performance improvement of the energy consumption. To this end, our work consists of providing an Advanced Metering Infrastructure (AMI) with the integration of this technology which will allow us to remotely control and supervise the High Voltage, Medium Voltage and Low Voltage grid to take appropriate decisions for its functioning.

Through this paper, we will first present the hosting structure in order to better understand the environment in which the research activities were carried out. Then we will focus on the characteristics of a smart meter from design to implementation in order to better understand how it works. Then we will propose an AMI with the acquisition system and the appropriate communication mode. For this purpose, a K - means optimization algorithm will be implemented in order to determine the exact number of Data Aggregation Points (DAPs) to be set up relative to the type of area (urban, suburban, rural and mixed). Finally we will end up modeling the electrical grid with GridLAB-D and the impact of these meters will be discussed with a view to assessing its effectiveness in demand side management.

**Keywords:** smart grid, smart meters, advanced metering infrastructure, K-means optimization algorithm, data aggregation points, GridLAB-D, demand side management.

I dedicate this paper, which is my graduation project, to my mother MATHILDE SARR and my father ALPHONSE FAYE. I also dedicate it to my brothers and sisters (who are my main motivations) and to all my friends who have supported me throughout my career.

## **Acknowledgments**

First of all I thank the good Lord for giving me the courage and patience to endure these long and difficult years of study.

I would like to thank my supervisor, Mr. Álvaro Gutiérrez Martín, Professor at the Polytechnic University of Madrid and Head of the Robotics and Control Laboratory, who has greatly contributed to this project and has guided me throughout this research project.

I would like to thank my home academic supervisor Dr Evrad Marie Diokel NGOM, Deputy Director of the Polytechnic Institute of Saint-Louis who has actively participated in the success of our training and who kindly agreed to supervise our work.

I cannot forget in my thanks Thomas SENE and Véronique Diouf who supported me during my stay and especially during the period of Covid-19.

I also thank all the staff of the Higher Technical School of Telecommunications Engineers of the Polytechnic University of Madrid for their welcome, their availability and their contribution in the success of this professional experience.

To my classmates in the fourth class of the IPSL for their support and kindness during these years of training, to the IPSL faculty and the people involved in our training for the skills they have acquired over the last five years, to the jury for their availability and for agreeing to review my work, I say thank you.

Finally, I thank all those who in one way or another have contributed to the success of this work and who could not be cited here.

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# Introduction

Emerging countries, including Senegal, need energy, especially gas and electricity, to grow and support their growth. This is increasingly reflected in an increase in the decentralized production of electricity and gas linked to the growth of renewable energies, which help reduce greenhouse gas emissions. In this study, we limit ourselves to electrical energy, the increase in demand for which significantly affects the energy efficiency of the entire electricity network. As a result, improving energy efficiency is becoming a necessity. This improvement should translate into changes in the way the energy of an electrical network is consumed by users, as the majority of the primary energy resources we use are wasted due to a lack of pragmatism. A small portion is actually used by our household appliances (oven, air conditioning, refrigerator-freezer, dryer, etc.). We must therefore tackle this waste, without profoundly changing the way our societies operate. Meeting these challenges and making a successful energy transition at the lowest possible cost requires making energy networks more flexible and intelligent. This terminology refers to an electrical power distribution system that automatically and autonomously adapts production to demand. This smart grid system uses information and communication technologies (ICT) to improve the production and distribution of electricity. It is based on smart meters, which are equipped with a bidirectional communication device allowing real-time operation of the measured elements (consumption, credit level, network quality, etc.).

In Senegal, SENELEC (National Electricity Company of Senegal) is the main company producing, transporting, distributing and selling energy. It is the driving force behind many of the changes noted in the management of the country's electrical energy. To improve its energy efficiency, this electricity company has decided to invest in this technological renewal in order to equip itself with a network capable of meeting all the criteria of a smart electricity network. This investment should be accompanied by in-depth studies. These will better help to improve energy efficiency at all stages of the production and distribution chain, i.e. from the conversion of primary energy to energy carriers to useful energy.

Thus, from March 1 to July 30, 2020 (5 months), as part of a final-year internship, we carried out a study at the Higher Technical School of Telecommunications Engineers of the Polytechnic University of Madrid (located in Spain) on the integration of smart meters

on an electrical grid as applied to SENELEC's transmission and distribution network. We were interested in advanced metering infrastructure, which happens to be a state-of-the-art solution including smart meters, two-way communications and centralized software for meter data management. Regardless the size of the electrical grid, the main issue for the integration of smart meters in general remains the technical feasibility of such projects. The first technical barrier identified is to restrict the locations of DAPs to be from a set of existing utility poles. Additional constraints are derived from network coverage and the maximum number of connections to the DAPs. This leads to the following question:

**«considering different meter densities and wireless communication technologies, it is possible to control and supervise the grid while minimizing the installation and transmission cost»**

The answer to this question will be illuminated by the adaptation of the K-means algorithm which allows to solve the formulated placement problems. To validate the algorithm we have proposed, we will perform simulations based on intelligent counting parameters, using Colaboratory, which is an environment particularly adapted to machine learning and data analysis and which allows the user to write and then execute the algorithm of his choice through the browser. In addition, to examine the flexibility of the grid with the integration of this technology, we focused on modeling a power grid using GridLAB-D software. GridLAB-D is a new power system simulation and analysis tool developed by the U.S. Department of Energy (DOE) at the Pacific Northwest National Laboratory (PNNL) in collaboration with industry and universities. These simulation tools (K-means algo and GridLAB) will be very useful for the achievement of our objectives, which are to :

- Describe the characteristics of a smart meter ;
- Propose an acquisition system and the adequate communication mode;
- Model SENELEC's «feeders» using GridLAB-D ;
- Examine the advantage of integrating these meters within the framework of demand management ;

We recall that this internship abroad was made possible thanks to the student and teacher exchange program between universities around the world called Erasmus+. It took place at "Escuela Técnica Superior de Ingenieros de Telecomunicaciones", precisely, in the Robotics and Control Laboratory, also called ROBOLABO. This laboratory works in several fields of robotics, namely:

- Swarm Intelligence
  - SwarmGrid Swarm Intelligence systems typically consist of a population of simple agents interacting locally with each other and with their environment. Inspiration often comes from nature, particularly biological systems. The agents follow very simple rules, and although there is no centralized control structures

dictating how individual agents should behave, local, and to a certain degree random, interactions between such agents lead to the emergence of "intelligent" global behavior.

- **Swarm Robotics** Swarm robotics is a new approach to the coordination of multi-robot systems which consist of large numbers of mostly simple physical robots. It is supposed that a desired collective behavior emerges from the interactions between the robots and interactions of robots with the environment. This approach emerged on the field of artificial swarm intelligence, as well as the biological studies of insects, ants and other fields in nature, where swarm behaviour occurs.
- **Control Systems**
  - **Local DSM Demand-Side Management (DSM)** is a set of techniques focused on modifying the way that users consume electricity from the grid. The goal of these techniques is to reduce the power consumption and increase the efficiency of the electricity grid. Typical lines of action are :
    - i) reduction of energy consumption
    - ii) reduction of the power consumed during the peaks
    - iii) increase the power consumed during the valleys
    - iv) shifting peak consumption to off-peak hours. creuses.

#### Sensor Networks

- **Monitoring and Smart Metering** Monitoring systems are able to get information from the environment where it is deployed for further analysis. Based on this analysis, control systems can be developed. These systems make use of a network of sensors to obtain such information. A smart meter is usually an electronic device that records consumption of electric energy periodically and communicates that information to a monitoring system. Smart meters enable two-way communication between the meter and a possible control system.
- **Mobile Sensor Networks** Mobile sensor networks are defined as sensor networks in which the sensor nodes are mobile. In Robolabo we are focused on the study of mobile sensor networks in which the reduction of consumption is pursued. Moreover, communication between the nodes in the networks is intended to be local, distributed and situated.

In summary, this internship took place in a favorable environment with a device equipped with new technologies capable of meeting the requirements of the study conducted.

We will now give the outline of our report.

In the first part, we will present the host organization and the program through which this opportunity was made possible. The second part will detail the characteristics of a smart meter. In the third part, we will describe and comment on the method used to

answer the study's problems and the results obtained. The modeling of the distribution system equipment will be discussed in the fourth part, then the consumers' reaction to the different pricing systems will be evaluated in the fifth part. Finally, the last part will present the partial conclusions and identify the limits of the study as well as avenues for further research.



# Presentation of the host organization

## 1.1 Presentation of the Erasmus+ program

The Erasmus program (EuRopean Action Scheme for the Mobility of University Students), generally known as Erasmus, is an exchange program for students and teachers between universities, major European schools and educational institutions around the world. The program aims to give students, interns, staff and generally young people under the age of 30, with or without diplomas, the opportunity to stay abroad to strengthen their skills and increase their employability.

### 1.1.1 History

#### A) The Previous ERASMUS

Travelling is youth ... A proverb which will only find incarnation in the Erasmus program later on. Indeed, it was not until 1971 that the Ministers of Education of the nine member countries of the European Community validated the principle of cooperation in the field of education. Five years later, they adopted a "schedule" which listed the various steps to be taken to achieve a better knowledge of the education systems of the member countries, including the implementation of transnational cooperation between higher education institutions and individual mobility. These are the "Joint Study Programs", or common study programs, which have been very successful but still lack ambition.

In 1983, the Council of Ministers of Education took a further step forward by laying down the principles of cooperation between higher education institutions in Europe. Its objective was to develop student mobility by promoting the recognition of their periods of study, distributing financial aid, facilitating their accommodation and simplifying administrative procedures. In 1985, Jacques Delors, then at the head of the European Commission, set an ambitious goal of having 10 percent of Europe's student population leave the country. In 1988, a resolution of the Council of Ministers stated that it was necessary to "strengthen the European identity and prepare for

European citizenship" and that mobility was the key to achieving this goal. Finally, this context was favourable to the birth of the Erasmus program.

#### **B) From ERAMUS to ERASMUS+.**

Erasmus is the first program designed on a European scale to facilitate the mobility of students and teachers. Acronym of "European Region Action Scheme for the Mobility of University Students", it aimed to develop the European citizenship of its beneficiaries and to create a Europe of higher education by supporting the cooperation of institutions. In its first year, it attracted 3,244 European students. Five years later, 150,000 of them tried the adventure. This success has prompted the European Commission to extend it to other sectors. This is how the Youth programme came into being in 1989. In 1995, it was the turn of the Comenius programme for school education and the Leonardo da Vinci programme for vocational training to see the light of day, quickly joined, in 2000, by the Grundtvig programme for adult education. A diversification of sectors and audiences that is also accompanied by a geographical opening beyond Europe with Erasmus Mundus, and a multiplication of the activities supported. In 2014, the five sectoral programmes will be brought together into a single programme: Erasmus+, which will also be enriched by a new one, sport.

#### **C) ERASMUS+ TODAY**

Erasmus + has 33 participating countries and 168 partner countries from all over the world. It is also aimed at a wide variety of audiences: kindergarten to high school students, vocational high school students, apprentices, jobseekers, students, young volunteers, teachers, trainers, educators and volunteers. Its budget is increased accordingly and in line with the European Commission's 2020 strategy for smart, sustainable and inclusive growth. This represents an increase of 40 percent compared with the previous program to more than 16 billion euros for the 2014-2020 period: 14.7 billion euros plus 1.68 billion euros for activities related to the international dimension of the program, i.e. activities outside Europe. It should enable more than 4 million Europeans to study, train, gain work experience or do volunteer work abroad.

### **1.1.2 Who can benefit from it?**

#### **A) Organizations**

The European program Erasmus+ is open to any organization active in the fields of education, training, youth or sport.

Several actions are also open to the participation of other actors in the labour market.

Under the Erasmus+ programme, organisations may carry out a number of development and networking activities, in particular with a view to improving the professional capacities of their staff, strengthening their organisational capacities and creating transnational cooperation partnerships with organisations from other countries in order to achieve innovative results or exchange good practice.

Erasmus+ projects are presented and managed by the participating organizations.

If a project is selected, the applicant organization becomes a beneficiary of an Erasmus+ grant.

### B) Individuals

The European program Erasmus+ offers people of all ages opportunities to develop and share their knowledge and know-how in organizations and institutions in many countries.

This includes, in particular :

- **primary and secondary education staff:** teachers, educational advisers, management and inspection staff, health, administrative and technical staff.
- **vocational education and training learners and staff:** students, apprentices, employees and trainees in continuing vocational training, trainers, company training managers, tutors and apprenticeship masters.
- **students and staff of higher education:** students, higher education apprentices, teachers, administrative staff, trainers and professionals of enterprises associated with the activities of higher education institutions.
- **adult and popular education staff:** students, higher education apprentices, teachers, administrative staff, trainers and professionals of enterprises associated with the activities of higher education institutions.
- **all young people (from 13 to 30 years old),** whatever their level of education, training or language skills: take part in youth meetings and contribute to the development of youth policies through organized debates with decision-makers.

**Namely:** since October 2018, volunteer projects are no longer managed by the Erasmus+ programme and are transferred to the "European Solidarity Corps" programme.

- **professionals and decision-makers in the youth sector:** take part in training activities, exchange of innovative practices or networking.
- **professionals, volunteers and voluntary workers in the field of sport, athletes and coaches:** participants in activities implemented in the framework of projects under the sport strand of the Erasmus+ programme.

### 1.1.3 Which countries are participating?

The Erasmus+ program is open to the following countries:

#### A) The countries participating in all the actions of the program called "program countries".

- the member countries of the European Union

- Iceland, Liechtenstein, Norway, Turkey, Northern Macedonia, Serbia

#### B) Partner countries

- the countries of the European neighborhood to the East (Armenia, Azerbaijan, Belarus, Georgia, Moldova, Ukraine) and to the South (Algeria, Morocco, Tunisia, Libya, Egypt, Palestine, Jordan, Israel, Lebanon, Syria), the Western Balkans (Albania, Bosnia-Herzegovina, Kosovo, Montenegro), the Russian Federation
- countries around the world: America, Asia, Africa - Caribbean - Pacific zone

## 1.2 Presentation of the Polytechnic University of Madrid

The Polytechnic University of Madrid (in Spanish Universidad Politécnica de Madrid or UPM), is a public university founded in 1971 by grouping together various technical training centers located on different campuses in the capital.

Its headquarters are located in the university city of Madrid, but the university is divided into several campuses throughout the capital. The different schools that make up the UPM offer mainly technical courses, since at its creation the experimental and social science courses were grouped together in the Complutense University of Madrid.

### 1.2.1 History

The origin of the institution goes back much further in time. Most of the centers were established during the reign of Carlos III, in the 18th century, and for many years these schools were practically the only ones in the country linked to the teaching of architecture and engineering.

For this reason, it is no exaggeration to say that much of the history of Spanish technology has been written by the schools of engineering and architecture.

UPM's first studies to start their specific teaching career in the civil field were in architecture. In the case of engineering, some, such as the Higher Technical School of Naval Engineers, began with a military character. The School of Mining Engineers was the first to have a civil character since its creation.

More recent is the birth in the twentieth century of three other colleges: the Technical College of Telecommunications Engineers, the Technical College of Aeronautical Engineers (both located in the university city) and the present Technical College of Engineers in Topography, Geodesy and Cartography located on the South Campus. They are joined by the Faculty of Physical Activity and Sports Sciences, in the University City, and the Faculty of Computer Science, on the Montegancedo Campus.

As for university schools of technical engineering, they were most often born almost simultaneously with the colleges of higher education as educational centers for the training of assistants or experts, a name that has gradually disappeared until reaching the present

name and degree.

In the university city are those of the technical forest, agriculture, aeronautical engineering and technical architecture. In the center of Madrid, the public works and industrial technical engineering departments, and on the south campus, the university schools of computer science and telecommunications. The same Fashion Design Center, attached to the UPM, is also located on the same Campus. UPM has also had an Institute of Educational Sciences since 1972.

At the beginning of the 19th century, the School of Civil Engineers, Canals and Ports was founded (1802), the result of the initiative of Agustín de Bethencourt, it says a lot about the restless and investigative spirit of the Spanish Enlightenment. In the same century, forestry and agricultural engineering schools were also born, which, like the roads, are now based in the university city of Madrid. Also that of industrial engineers, located next to the Paseo de la Castellana.

As stated in its statutes, the Polytechnic University of Madrid has among its objectives the creation, development, transmission and criticism of science, technology and culture. To this end, it also works from its Institutes and Research Centers, assimilating the changes produced in society and maintaining its vocation of excellence, for which it has national and international recognition.

### 1.2.2 Centres universitaires et campus

The Polytechnic University of Madrid is structured, for teaching and research purposes, in:

- Schools and faculties.
- Departments.
- University research institutes and research, development and innovation centers (R + D + i)

The Polytechnic University of Madrid integrates and recognizes university centers and campuses in its structure.

- Campus of university residence
  - E.T.S. de Arquitectura: School of architecture.
  - E.T.S. de Edificación: School of Construction.
  - E.T.S. de Ingeniería Aeronáutica y del Espacio: School of Aeronautical Engineering
  - E.T.S. de Ingeniería Agronómica, Alimentaria y de Biosistemas: School of Agricultural Engineers.
  - E.T.S. de Ingeniería de Montes, Forestal y del Medio Natural: School of Forest Engineers.

- E.T.S. de Ingenieros de Caminos, Canales y Puertos: School of Road, Canal and Port Engineers.
- E.T.S. de School of Telecommunications Engineers.
- E.T.S. de Ingenieros Navales: Naval engineering schools.
- Facultad de Ciencias de la Actividad Física y del Deporte (INEF): Faculty of Human Kinetics and Sport Science
- Instituto de Sistemas Optoelectrónicos y Microtecnología: Institute for Optoelectronic Systems and Microtechnology
- Instituto de Energía Solar: Institute of Solar Energy
- Instituto de Ciencias de la Educación (ICE): Institute of Education Sciences
- City of Madrid Campus
  - E.T.S. de Ingeniería Civil: School of Civil Engineering
  - E.T.S. de Ingeniería y Diseño Industrial: School of Engineering and Industrial Design
  - E.T.S. de Ingenieros de Minas y Energía: School of Mining and Energy Engineers
  - E.T.S. de Ingenieros Industriales: School of Industrial Engineers
  - Instituto de Fusión Nuclear: Nuclear Fusion Institute
- Montegancedo Campus
  - E.T.S. de Ingenieros Informáticos: School of Computer Engineers
  - Centro de Investigación en Biotecnología y Genómica de Plantas: Plant Genomics and Biotechnology Research Centre.
  - Centro de Tecnología Biomédica: Biomedical Technology Centre
  - Instituto de Microgravedad "Ignacio Da Riva": Ignacio Da Riva" Microgravity Institute
  - Centro domótica Integral: Integral Home Automation Center
- South Campus
  - E.T.S. de Ingeniería de Sistemas Informáticos: School of Computer Systems Engineering
  - E.T.S. de Ingeniería y Sistemas de Telecomunicación: School of Engineering and Telecommunication Systems
  - E.T.S. de Ingenieros en Topografía, Geodesia y Cartografía: School of Engineering in Topography, Geodesy and Cartography
  - Instituto de Investigación del Automóvil (INSIA): Automotive Research Institute
  - Centro Superior de Diseño de Moda de Madrid: Superior Center of Fashion Design of Madrid

- Centro de Investigación en Tecnologías Software y Sistemas Multimedia para la Sostenibilidad: Center for Research on Software and Multimedia Systems Technologies for Sustainability

### 1.3 Presentation of the E.T.S. of Telecommunications Engineers

The Higher Technical School of Telecommunications Engineers of the Polytechnic University of Madrid, located on the Campus of International Excellence of Moncloa (University City) is a national and international reference center in the field of teaching, research and technological development and innovation in the field of information and communication technologies (ICT).

The school maintains close relationships and contracts for research and educational collaboration with the most relevant companies in the field of ICT with a very active participation in projects funded by the EU Framework Program and the national R + D + i plan.

#### 1.3.1 Mission

- **Train professionals** in the field of telecommunications engineering and biomedical engineering with a solid knowledge of information, communications technology and biomedical engineering, both in its technological and socio-economic aspects, and with a clear commitment to the development of a professional career.
- **Actively contribute to the generation and transfer of technological knowledge** through research and innovation in a multidisciplinary and multicultural context.

#### 1.3.2 Vision

- **Promote the development of the information society through** the transversality and universality of information and communication technologies and biomedical engineering, by training professionals in the field of **telecommunication engineering and biomedical engineering** trained to design and develop systems, applications and services in multidisciplinary and multicultural fields, applying appropriate technologies.
- **Train professionals to the highest level of international excellence** Train professionals to the highest level of international excellence The students will have extensive capabilities to generate and apply scientific and technological knowledge to solve problems in their professional field.
- **Generate scientific and technological knowledge** at school in collaboration with national and international companies and technology and research centers based in Spain or abroad, involving students in the process as part of their training process, promoting the mobility of students and teachers with the best national and foreign centers.

- **To be a school of international reference and recognition** as a result of intertwined teaching and research activities, in which graduates acquire an important scientific base with intensities in one or more advanced areas of telecommunications and biomedical engineering, and with the most advanced level of scientific knowledge, technologies, systems, services and applications for the information society.
- **Promote and implement a broad research agenda** Promote and implement a broad research agenda development and innovation, in line with the most advanced level at all times, in technologies, systems, services and applications, as well as in scientific knowledge.
- **Being a pioneering school in the actions of pedagogical innovation and the development and use of new pedagogical methodologies** adapted to the objectives of the diplomas entrusted to it, promoting the best development of the specific skills of each student, guiding them progressively in the realization of self-training activities.
- **Provide graduate professionals with comprehensive training that includes socio-economic, techno-economic, sociotechnological and info-social aspects.** To train them in leadership and project management, entrepreneurial and innovative spirit, communication and working in multidisciplinary and multicultural teams.
- **Contributing, together with the Public Administrations, to the necessary evolution at any time of the professional profile in the field of Telecommunications and Biomedical Engineering.** The company is in permanent contact with companies and Professional Associations, seeking greater integration with the business and social reality of the trained professionals, and including in the training of the said professional profile the ethical aspects of the profession and everything related to respect for the environment, equal opportunities and economic and commercial aspects in this field.

### 1.3.3 Values

- **Capacity to adapt and evolve** This is due to the rapid variation in technologies, applications and services typical of the professional field of telecommunications and biomedical engineering, with a constant need for self-learning throughout one's working life.
- **The pursuit of excellence** as a desire to constantly improve in all fields of action, particularly in teaching, research, innovation and management.
- **Experience-based leadership** , for the history of a century of training students who have reached the highest levels of their professional practice at the national and international level, resulting from identical recognition from the School itself.
- **Critical spirit and rigorous and independent analysis**, necessary for debate, to know how to admit contrary opinions with respect and consideration, and to build solutions based on information from diverse sources.



- **Effort and perseverance** in the execution of activities , as an inherent and necessary culture for the success of present and future objectives and challenges.
- **Vocation of service to society** as training professionals who must contribute to the well-being of the latter, promoting confidence in the said society in the said professionals, both in the resolution of problems and in the anticipation of possible future situations that require action.
- **Professionalism of Human Resources** s, such as efficiency and effectiveness in performing assigned tasks.
- **Integrity as a professional code of conduct** which must begin in the form of a code of conduct from the student stage, exemplified by the teachers and staff of the School.
- **Ingenuity and creativity** as necessary elements to link multidisciplinary and multi-contextual knowledge in order to find imaginative and pragmatic solutions to problems, with the ability to optimize these solutions and anticipate problems.

#### 1.3.4 Infrastructures and resources

ETSIT-UPM has a series of material means and services that allow the teaching of a Bachelor's degree in Telecommunications Technology and Service Engineering, a Bachelor's degree and a Master's degree in Biomedical Engineering and a Master's degree in Telecommunications Engineering.

##### A) Infrastructures

- **4 buildings** . The Higher Technical School of Telecommunications Engineers of the Polytechnic University of Madrid is composed of four buildings that meet the requirements of universal accessibility, after the application of a long and costly action plan, given the complexity of the School's architectural structure.
  - **Building A, Sanz Mancebo**. It houses most of the classroom, the library, the publishing department and some special rooms such as the Aula Magna, the Assembly Hall, the Diploma Hall or the Conference Room.
  - **Building B, García Redondo**. It also houses some of the classrooms, teaching staff offices and research laboratories.
  - **Building C, López Araujo**. In addition to the offices and laboratories, it houses the Assembly Hall, the Joaquín Serna Museum and the Teachers' Room.
  - **Building D**. Mainly intended for corporate chairs and demonstrators of research projects.
- **More than 4,000 positions between classrooms and meeting rooms** . The classrooms have a capacity of 20 to 156 students each and are equipped with a minimum of projection, an overhead projector, air conditioning and Wi-Fi connection. Some have additional equipment, such as meeting tables or audio-visual aids.

- In terms of rooms, there is a **Aula Magna** with a capacity of 156 people, a **meeting room** with a capacity of 192 people and a **meeting room** (78 people), among others.
- **More than 600 positions in the teaching laboratories** . They serve the different practices that students practice throughout the degree. There are laboratories for digital electronic systems, telematics and computer networks, signal processing, simulation, optical communications, electronic materials and instrumentation, etc.
- **Laboratories and research centers**. Most of the center's surface area, more than  $9000\text{ m}^2$ , is dedicated to research and development in various fields: radio frequency, signal processing, computer networks and applications, communication systems, photonic and electronic technologies, new materials, bioengineering, etc.. There are 15 departments and 33 research groups, as well as 3 institutes and research centers with their own entities. This activity is complemented by company chairs and more than 700 agreements with companies. At the ETSIT-UPM, more than 500 research projects are carried out, which generate 40 percent of the *RD* benefits of the whole UPM and receive numerous mentions (scientific articles, monographic publications, patents, articles, national) and international awards).
- **Library**. It has 460 reading stations and 8 multi-purpose rooms for group work (48 stations in total). Access to infinite electronic resources to the full text of prestigious scientific journals. Documentary collection specialized in the disciplines of titling of more than 70,000 books, in addition to numerous volumes in other formats (videos, CDs, DVDs, etc.). Among the services it offers to students are the loan of books, laptops, graphic calculators, cameras and video cameras, language learning resources or group work rooms. It is open every day of the week (Monday to Sunday, also on holidays during exam hours).
- **Cyber library**. This room, located inside the library, has 60 booths with network and data sockets and WiFi connection. It is of privileged use for laptops (the library has 50 laptops available for loan).
- **18 premises of student associations** of various natures (technical-professional, cultural, sports, etc.), for exclusive use and with means placed at their disposal.
- **ETSIT Museum "Professor Joaquín Serna"**: it consists of a wide range of devices and instruments used in telecommunications: radars, telephone exchanges, radio stations, collections of valves, electronic components and tools used in teaching telecommunications in the last decades of the 19th century and throughout the 20th.

#### B) Human Resources

- **More than 2,500 students** enrolled in various degrees, including 300 foreigners.
- **269 teachers**. More specifically, 61 professors, 156 full professors, 13 contract professors, 19 part-time associate professors, 12 assistants and 8 workshop and

laboratory professors. The pedagogical experience of these personnel is enriched by their participation in research programs and projects.

- **134 administrative and service staff positions.** These personnel participate in the daily activities of the School (academic management, administrative tasks, laboratory maintenance, etc.).

#### C) Accords internationaux

- More than **80 exchange agreements** with foreign universities.
- **120 agreements** with universities.
- **15 double degree agreements** with foreign universities.

## Features of a smart meter

### 2.1 Architecture of a smart meter

Typically, a two-chip architecture for a smart meter illustrates three possible architectures for a smart meter that includes Analog Front End (AFE) metrology, Analog Digital Converter and Digital Signal Processor (DSP)[3].

#### 2.1.1 System on Chip (SoC)

An energy measurement system on chip (SoC) takes the different bit-streams from the isolated modulators and uses the onboard digital filters of the SoC to produce ADC sample readings[3].

Figure 2.1 shows the bloc diagram of a System on Chip.

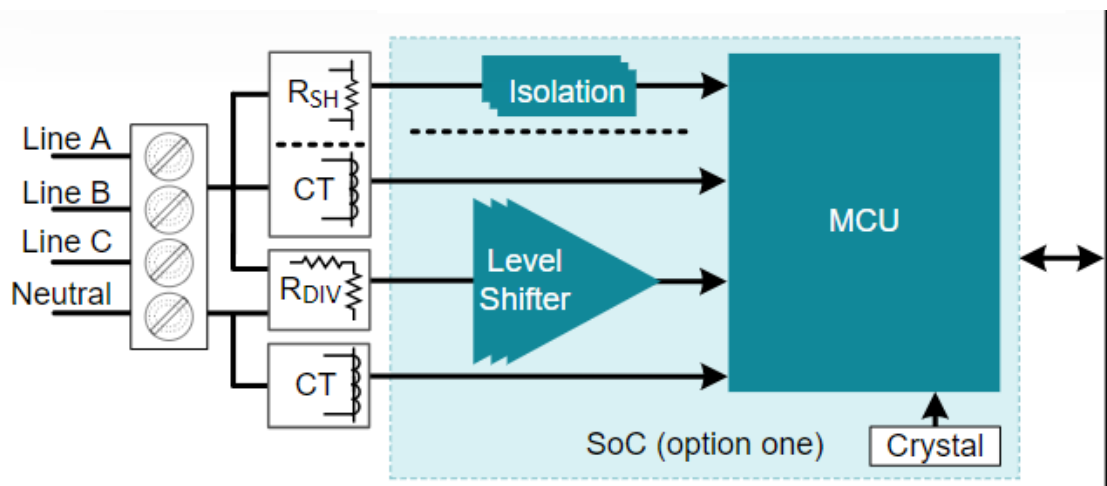


Figure 2.1: System on Chip Bloc Diagram (Obtained from Texas Instruments).

### 2.1.2 Standalone Analogic Digital Converter

As the accuracy and amount of processing expected from electricity meters increases, it becomes more difficult to find a metrology SoC that fulfills both the processing and accuracy requirements of an electricity meter. To address this limitation, a standalone ADC can be used with a host microcontroller (MCU) to simultaneously overcome the processing and accuracy limitations of electricity meter SoCs.

The standalone ADC senses the Mains voltage and current. When there are new ADC samples available, the host MCU communicates to the standalone ADC via SPI (Serial Peripheral Interface) to get the new samples. The host microcontroller uses the new ADC samples from the standalone ADC to calculate metrology parameters[3].

Figure 2.2 shows the bloc diagram of a Standalone Analogic Digital Converter system.

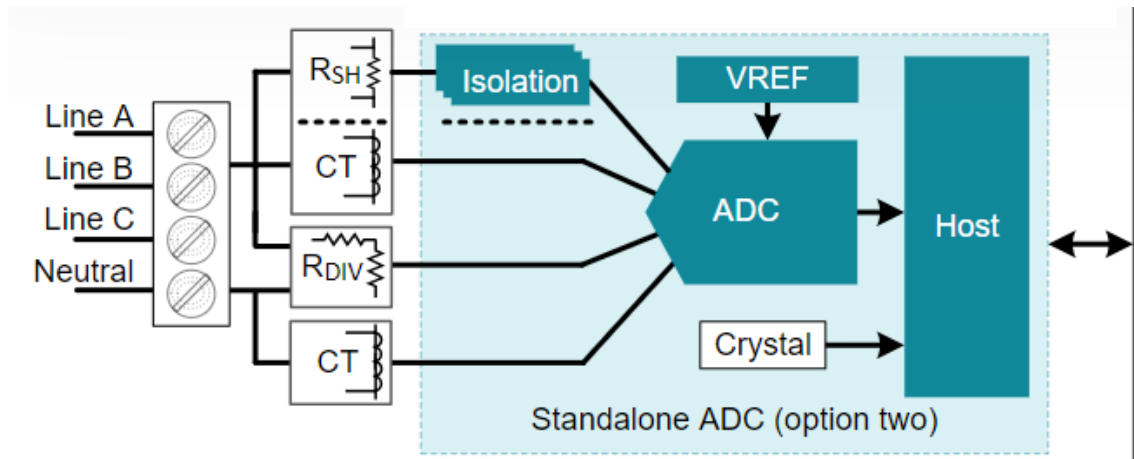


Figure 2.2: Standalone ADC Bloc Diagram (Obtained from Texas Instruments).

### 2.1.3 Metrology and Host

The metrology Analog Front End's (AFE) sense the voltage and current for each phase, calculates the metrology parameters for the phase, and then sends out the calculated parameters to a host microcontroller using a Universal Asynchronous receiver-transmitter (UART) port[3].

Figure 2.3 shows the bloc diagram of a metrology and host system.

External digital isolators capacitively isolate the UART communication between the host microcontroller and the metrology AFE, which allows the host microcontroller to communicate to different metrology AFEs that are referenced with respect to different phases. Because the metrology AFEs measure both voltage and current and have their UART pins externally isolated, voltage sensing is isolated in addition to the required current sensing isolation necessary for implementing shunts in poly-phase systems. As a

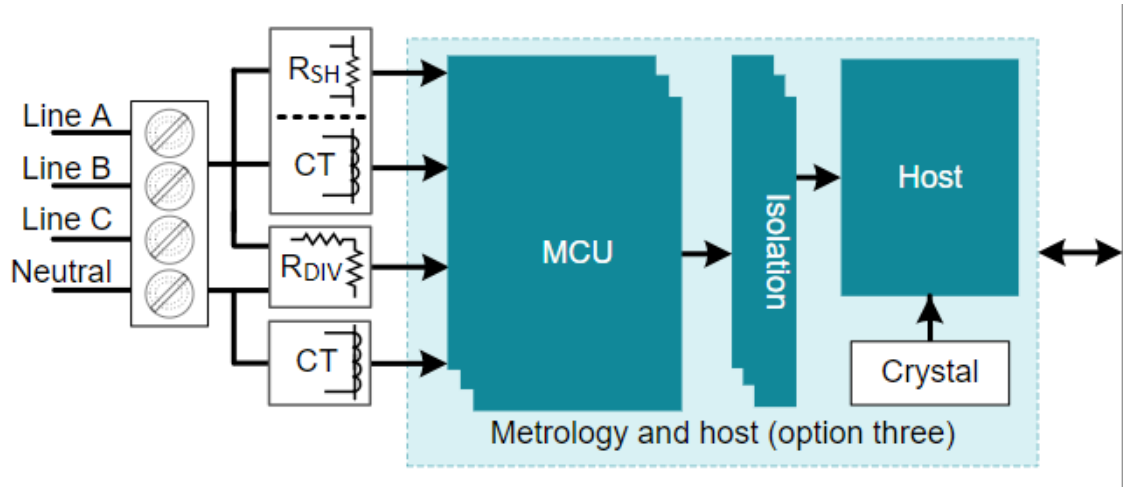


Figure 2.3: Metrology AFE Block Diagram (Obtained from Texas Instruments).

result, the host microcontroller is completely isolated from mains voltage. Also, because metrology parameters are calculated locally at the metrology AFEs instead of at the host microcontroller, less CPU bandwidth is needed from the host to calculate metrology parameters.

## 2.2 The Hardware Structure of a Smart Meter

Fig. 2.4 shows the functional block diagram of a smart meter. It includes signal acquisition, signal conditioning, Analogue to Digital Conversation (ADC), computation and communication [4].



Figure 2.4: Functional block diagram of a smart meter.

Smart meters use voltage and current sensors to get the input signals. Signal conditioning, ADC, and computations are done inside the micro controller unit (MCU). Additional hardware components are required for other operations like communication, time and date measurements, and data backup and storage. A smart meter is typically composed of following hardware components:

- Voltage and current sensing unit

- Power supply
- Energy measurement unit (metering IC)
- Microcontroller
- Real time clock
- Communicating system.

Figure 2.5 shows the hardware structure of a modern smart meter.

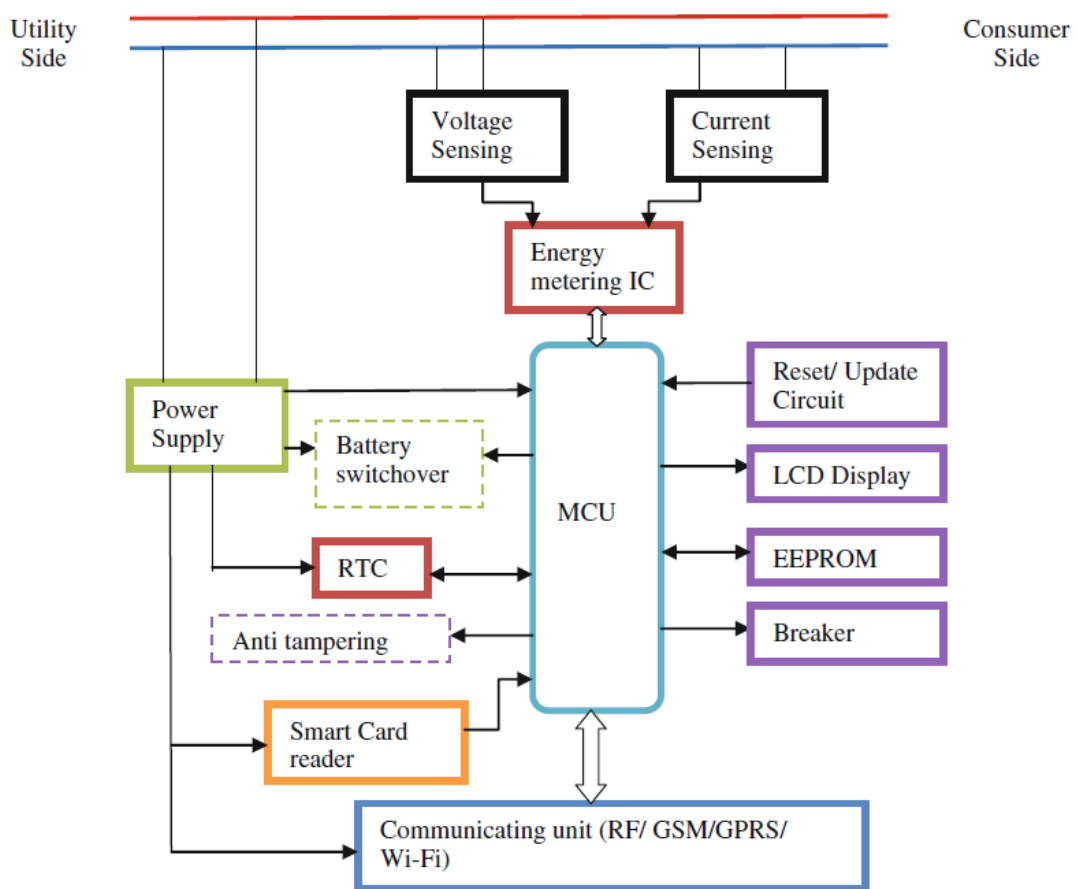


Figure 2.5: Hardware structure of a modern smart meter

### 2.2.1 The voltage Sensing Unit

Simple resistor dividers are widely used as voltage sensors in digital meters due to low cost. Figure 2.6 shows the configuration of a resistor divider type voltage sensor. The values of  $R_1$  and  $R_2$  should be chosen such that the AC mains voltage is divided down to

fit the input range of the ADC of the energy measurement chip. According to Fig. 2.6 the AC voltage is applied to R1 and output is taken from the middle point of the divider. R2 should be grounded. The output voltage from the divider (to ADC) is given by (2.1).

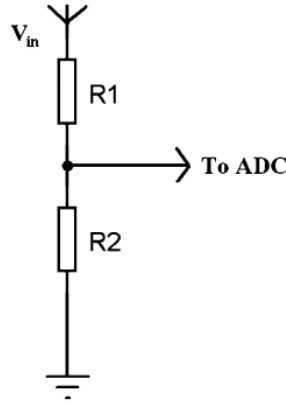


Figure 2.6: Resistor divider configuration.

$$V_0 = \frac{R2}{R1 + R2} V_{in} \quad (2.1)$$

where:

$V_0$  is the output voltage  
 $V_{in}$  is the input voltage

### 2.2.2 The Current Sensing Unit

The current sensing unit typically consists with current sensors and anti aliasing filters. Four types of current sensors are widely used in smart meters. They are:

- Hall effect-based linear current sensors
- Current transformers
- Shunt Resistor
- Rogowski coils.

#### (A) Hall effect-based linear current sensors

These sensors consist of a chip and a copper conduction path located near the surface of the die. The current flowing through the copper conduction path generates a magnetic field. This magnetic field is sensed by the Hall IC and converted into a proportional voltage [5]. Figure 2.7 shows an example of ACS 712 Hall IC which is available in the market.





Figure 2.7: ACS 712 Hall IC (Obtained from Allegro MicroSystems, Inc.).

### **(B) Current transformers**

Current transformers (CTs) produce a secondary current which is proportional to the primary current. Magnetic properties of CTs are highly linear over wide range of primary current, and temperature. The primary is connected in series with the device [6]. The isolation is provided from primary to secondary side thus ensuring high reliability for metering devices. Figure 2.8 shows the typical through-hole type current transformers which are widely used in metering applications [8].

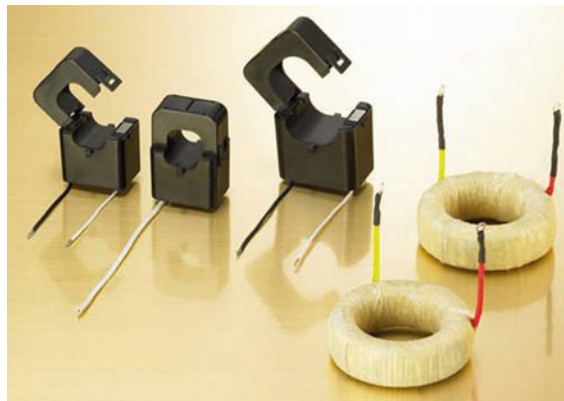


Figure 2.8: Through-hole type current transformers (Obtained from Taehwatrans Co. Ltd.).

### **(C) Shunt Resistor**

Shunt resistors are widely used in metering applications because of their lower cost than other types of current sensors. These sensors are simply placed in series with the load

current path. Their resistances are typically in the range of  $100\ \mu\Omega$ –  $500\ m\Omega$ . The power dissipated is proportional to the square of the current. Therefore a very small resistance should be selected to minimize the heat dissipation [7, 9]. Therefore, when the resistance is known, the current can be calculated according to Ohm's law. The circuit diagram of a shunt resistor is shown in Fig. 2.9.

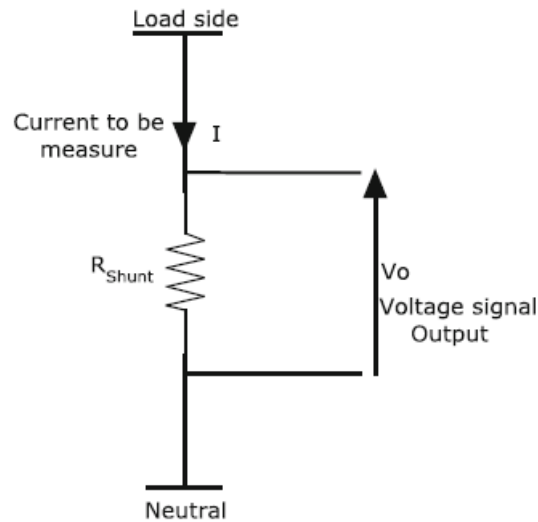


Figure 2.9: Circuit diagram of a shunt resistor.

#### (D) Rogowski coil sensor

Rogowski coils were introduced to the electrical industry as far back as in 1912, to measure the magnetic fields, but these could not be used for current measurements, since the power produced was not sufficient to drive electromechanical equipments. With the development of solid state electronics and microprocessor based systems, Rogowski coils have provided wide range of opportunities. These sensors are coils with non magnetic core for which the name air cored is used. They give an output voltage which is proportional to the rate of change of current. They linearly convert the primary current up to all short circuit levels. Due to the absence of iron, they are saturation free. They have many advantages over conventional CTs, which include [10]

- High measurement accuracy
- Wide measurement range
- Wide frequency range
- Can withstand unlimited short circuit currents
- Small in size and weight

- Low production cost.

However Rogowski coils cannot produce a voltage signal which is directly proportional to the current flow. The relationship between the output voltage and the current flow is given by (2.2).

$$V = k \frac{dI}{dt} \quad (2.2)$$

where;

$V$  is the output voltage

$I$  is the current to be measured

$t$  is the time and

$k$  is a constant

Current signal should be recovered from  $dI/dt$  signal. Rearranging the terms in (2.2)

$$I = \frac{1}{k} \int V dt \quad (2.3)$$

According to (2.3), the output voltage should be integrated with respect to time to get the original current signal. Figure 2.10 shows some of commercially available Rogowski coils [17].



Figure 2.10: Commercially available Rogowski coils (Obtained from Taehwatrans Co. Ltd.).

### 2.2.3 Power Supply Unit

Power supply unit may vary from smart meter designer to designer. However this unit typically consists of step-down transformers, rectifiers, AC-DC converters, DC-DC converters and regulators. Energy measurement chip designers provide their own reference power supply schematics.

However the power output from these circuits may not be sufficient to drive other hardware components in the smart meter. Therefore the required power to drive the energy chip, MCU, LCD, battery charger and communication unit should be taken into consideration before designing a power supply. Figure 2.11 shows the block diagram of a typical power supply used in smart meters.

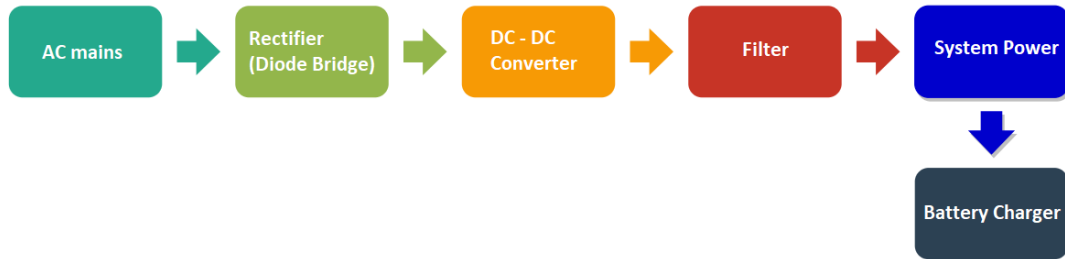


Figure 2.11: A typical power supply used in smart meters.

First the AC line voltage is rectified through a diode bridge. Sometimes the AC voltage is stepped down before the rectification. Then the unregulated voltage output is fed to a DC–DC converter or a regulator IC. DC–DC converter consist of an inductor, a capacitor, and an electronic switch. The electronic switch in this converter can be a MOSFET, power transistor or IGBT. The output is more filtered and fed as the system power. The battery charging unit controls a rechargeable battery.

Some energy measurement chips have inbuilt power management systems. For an example ADE 5166/ADE5169 ADE5566/ADE5569 chips have inbuilt power management circuitry that manages the regular power supply for battery switchover and power supply failures. Figure 2.12 shows the power supply architecture of the above chips.

They are driven by two supply voltages which are VDD andVBAT. VDD is the input voltage from an external supply and VBAT is the battery input. These chips provide automatic battery switchover between VDD and VBAT based on the voltage level detected at VDD or VDCIN. More details on power management system can be obtained referring to the datasheets from Analog Devices website [13].

#### 2.2.4 Energy Measurement Unit

Energy measurement unit could be a standard energy measurement chip or the system MCU itself. Modern energy measurement chips have digital signal processor (DSP) to perform signal conditioning, ADC and energy calculations. They provide active, reactive, and apparent energy information as data or frequency (pulse) output. RMS voltage measurement, RMS current measurement, frequency, temperature measurement, tampering detection, power management, THD, line SAG detection and communication are also possible in some of them. They are designed according to IEC and ANSI accuracy standards.

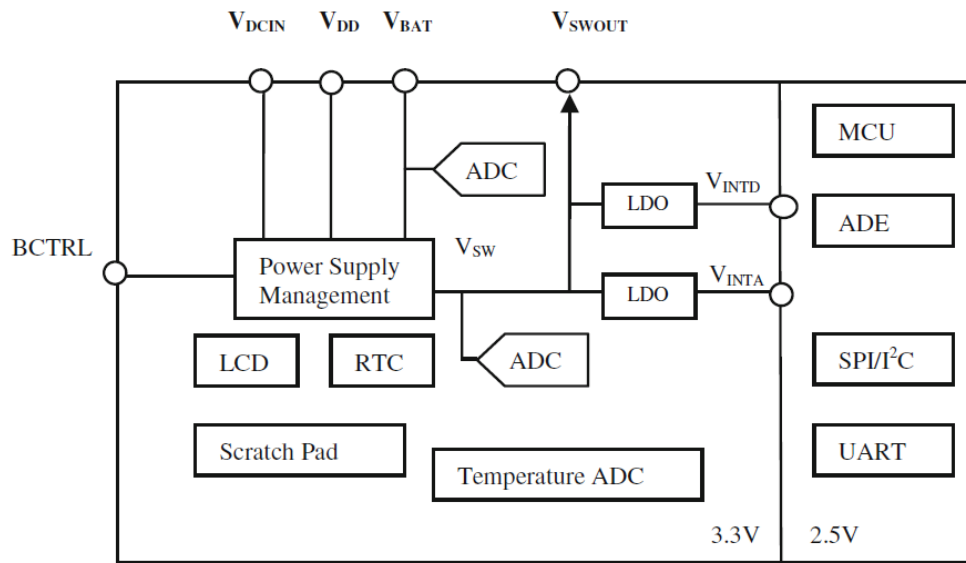


Figure 2.12: Power supply architecture of ADE 5166 (Obtained from Analog Devices, Inc.).

### 2.2.5 Microcontroller

A microcontroller is an integrated circuit that is housed within each component that it needs to perform the necessary operations and that can perform a particular task routinely without requiring another boom. It contains a microprocessor, memory units and input-output interfaces, analog-to-digital conversion (ADC), pulse width modulation (PWM) and various control and communication modules.

All functions inside the smart meter are performed by the MCU. It is considered as the core of the meter. It controls the following functions

- Communication with the energy measurement chip
- Calculations based on the data received
- Display electrical parameters, tariff and cost of electricity
- Smartcard reading
- Tamper detection
- Data management with EEPROM
- Communication with other communication devices
- Power management.

### 2.2.6 Real Time Clock

Real time clock is an essential hardware component in all smart meters which keeps track of the current time. It provides time and date information and alarm signals. Most smart meters have a separately driven RTC unit which can be accessed by the meter. The drift has been found as 60 min per year [14]. Smart meters connected to a smart network are periodically synchronized with actual time to avoid time drifts. Meters which are not connected to such network should have a high accurate RTC or should be corrected for the time at regular intervals.

### 2.2.7 Communicating Systems

Several communication protocols are used in AMI [15]. AMI can consist with a Home Area Network (HAN), a Neighborhood Area Network (NAN) and a Wide Area Network (WAN). Smart meters are the key elements in AMI which need to communicate with domestic appliances, other type of meters (typically water and gas meters), neighboring smart meters, and the energy supplier. Smart meters need to communicate with domestic appliances, other types of smart meters (typically water and gas meters), neighboring smart meters and the energy supplier.

HAN is used to establish a communication link between the smart meter and the smart appliances, other meters, in-home display, and the micro generation unit. The communication protocol can be a wired or wireless media [7]. Zig-bee, Z-wave, Wi-Fi, and power line communication (PLC) are widely used protocols in HANs.

PLC might be a cost effective approach for a HAN but it has many drawbacks such as longer data transmit time, less bandwidth. Zig-Bee communication has been recognized as a cost effective, less complexity, low power, and reliable media to handle a HAN [16].

A NAN is used to transfer the data between neighboring smart meters. Zigbee communication protocol is widely used in NAN due to high speed of data transferring and low cost [7].

Smart meter data might be directly transferred to the server through wireless media. The communication is established between the meter and the server through a data concentrator for billing purposes, indication of power outages, remote disablement and enablement of supply, security tamper detections, and remote configurations [17]. GSM, GPRS, 3G, and WiMax communication technologies can be used to connect the meter to the WAN. GSM provides wider coverage than other media.

## 2.3 Basic Functionalities

### 2.3.1 Signal conditioning

The signal conditioning is the amplification and adjustment of the input signals coming from the current and voltage sensors. Basically this stage includes addition/subtraction,

attenuation/amplification and filtering [7]. Nowadays energy measurement chips have built-in architecture for this stage. In ADC, proper sampling frequency should be selected to restore the original input waveform. Improper sampling can give rise to aliasing problems which is an artifact of all sampled systems regardless the architecture [11]. Aliasing means that frequency components higher than half the sampling rate shift into the frequency band of desired. To avoid inaccuracy due to aliasing, it is necessary to remove components of the input signal above the Nyquist frequency (that is, half the sampling rate of the ADC). This is done by introducing a single pole RC low pass filter.

Figure 2.13 illustrates the effect of aliasing discussed in ADE5166 sampling section. The sampling frequency is 819.2 kHz while the Nyquist frequency is 409.6 kHz. Frequency components above the Nyquist frequency are imaged below 409.6 kHz. Frequencies near to 819.2 kHz move into the band of interest of metering. Here the metering band is 40 Hz to 2 kHz. By introducing a simple low pass filter, the high frequencies near to 819.2 kHz can be attenuated [12].

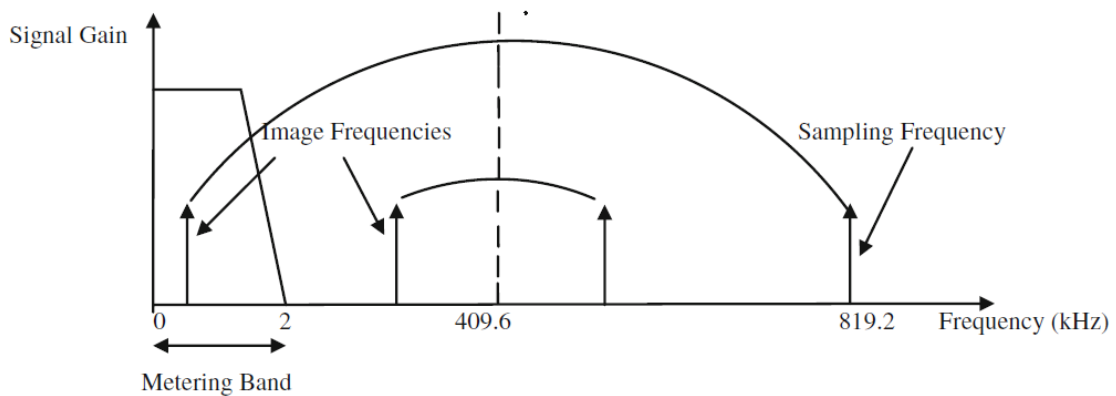


Figure 2.13: Effect of aliasing (Courtesy of Analog Devices, Inc.)

### 2.3.2 Analogic to digital conversion

ADC unit converts the analogic signal inputs coming from the voltage and current channels to digital. Delta-sigma modulator is the most popular ADC architectures used in modern energy measurement chips. Figure 2.14 shows the block diagram of a first order sigma-delta modulator and a digital low pass filter [12].

First the output of DAC is subtracted from the input signal coming through the analog low-pass filter. Next the resulting signal is integrated and fed to the comparator. Comparator converts the input signal to a single-bit digital output.

However ADC causes a quantization noise which is shaped by oversampling. Generally the majority of noise lies at higher frequencies. A digital low pass filter can be added to

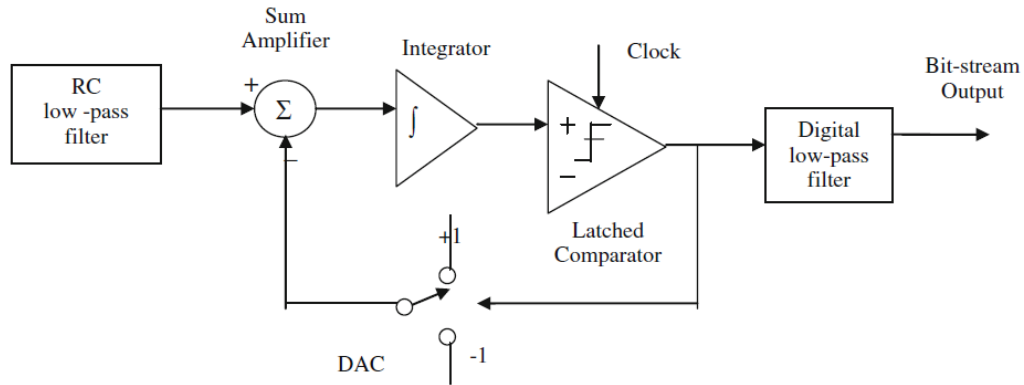


Figure 2.14: First order sigma-delta modulator (Obtained from Analog Devices, Inc.)).

the output of the sigma-delta modulator to cut off higher frequencies.

### 2.3.3 Basic Electrical Parameters Calculation

The performances and features can vary from energy metering chip to another. Most chips provide general calculation procedure for active power and energy. However some of them are capable of measuring other electrical parameters as well.

In the real world, many systems consist of non linear loads which cause harmonics in the supply system. Many researchers and organizations have put a lot of effort to clarify the definitions of power quantities in non-sinusoidal systems. The IEEE Std 1459 was published in 2010 by power system instrumentation and measurement committee of IEEE to provide information on measuring electrical parameters under sinusoidal, non-sinusoidal, balanced or unbalanced load systems [20].

For an example let's take ADE7880 energy measurement chip. ADE7880 is a high accurate 3 phase energy measurement chip which supports IEC 62053-21, IEC 62053-22, IEC 62053-23, EN 50470-1, EN 50470-3, ANSI C12.20, and IEEE1459 standards. This chip has been used in energy metering systems, power quality monitoring, solar inverters, process monitoring, and protective devices due to its complete harmonic analysis. It measures RMS voltage, RMS current, all harmonics (up to the 63rd harmonic), active, reactive and apparent powers, power factor, THD, harmonic distortion, total (fundamental and harmonic) active and apparent energy and fundamental active/reactive energy on each phase [19].

#### (A) RMS voltage and current calculation under non-sinusoidal waveforms

Let us take the time varying voltage or current signal as  $f(t)$  which contains power system frequency component, DC component and harmonic components.



$$f(t) = F_0 + \sqrt{2}F_1\sin(\omega t - \alpha_1) + \sqrt{2}\sum_{n=2}^{\infty} F_n\sin(n\omega t - \alpha_n) \quad (2.4)$$

or

$$f(t) = F_0 + \sqrt{2}\sum_{n=1}^{\infty} F_n\sin(n\omega t - \alpha_n) \quad (2.5)$$

where:

$f(t)$  is the time varying voltage or current signal

$F_1$  is the RMS of fundamental signal

$F_0$  is the DC signal

$F_h$  is the RMS of the hth harmonic signal

In the chip, this  $f(t)$  signal is squared, low pass filtered and taken the square root of the results. The procedure can be explained as follows.

First the voltage or the current signal is squared.

$$f^2(t) = [F_0 + \sqrt{2}\sum_{h=1}^{\infty} F_h\sin(h\omega t - \alpha_h)][F_0 + \sqrt{2}\sum_{h=1}^{\infty} F_h\sin(h\omega t - \alpha_h)] \quad (2.6)$$

$$f^2 = F_0^2 + 2\sqrt{2}F_0\sum_{h=1}^{\infty} F_h\sin(h\omega t - \alpha_h) + [F_0 + \sqrt{2}\sum_{h=1}^{\infty} F_h\sin(h\omega t - \alpha_h)]^2$$

$$\begin{aligned} f^2(t) = F_0^2 + \sum_{h=1}^{\infty} F_h^2 + 2\sqrt{2}F_0\sum_{h=1}^{\infty} F_h\sin(h\omega t - \alpha_h) + \sum_{h=1}^{\infty} F_h^2\cos 2(h\omega t - \alpha_h) \\ + 2\sum_{h,m=1}^{\infty} 2F_hF_m\sin(h\omega t - \alpha_h)\sin(m\omega t - \alpha_m) \end{aligned} \quad (2.7)$$

This signal is passed through a low pass filter. Then the output will be

$$F_{RMS}^2 = F_0^2 + \sum_{h=1}^{\infty} F_h^2 \quad (2.8)$$

All the time varying terms ( $\omega$  terms) are get cancelled after low pass filtering. RMS value of the signal is obtained by taking the square root of (2.8)

$$F_{RMS} = \sqrt{F_0^2 + \sum_{h=1}^{\infty} F_h^2} \quad (2.9)$$

**(B) Total active power and energy calculation under non-sinusoidal waveforms**

In steady state conditions periodic instantaneous voltage and current have power system frequency components, DC components and harmonic components.

Therefore the current and voltage can be written as

$$v(t) = V_0 + \sqrt{2}V_1 \sin(\omega t - \alpha_1) + \sqrt{2} \sum_{h=2}^{\infty} V_h \sin(h\omega t - \alpha_h) \quad (2.10)$$

$$i(t) = I_0 + \sqrt{2}I_1 \sin(\omega t - \alpha_1) + \sqrt{2} \sum_{h=2}^{\infty} I_h \sin(h\omega t - \alpha_h) \quad (2.11)$$

where;

$h$  is the harmonic order

$V_1$  is the RMS of fundamental voltage

$V_0$  is the DC voltage

$V_h$  is the RMS of the  $h$ th harmonic voltage

$I_1$  is the RMS of fundamental current

$I_0$  is the DC current

$I_h$  is the RMS of the  $h$ th harmonic current

The instantaneous power can be obtained from the product of voltage and current signal

$$p(t) = v(t) \times i(t)$$

$$p(t) = [V_0 + \sqrt{2}V_1 \sin(\omega t - \alpha_1) + \sqrt{2} \sum_{h=2}^{\infty} V_h \sin(h\omega t - \alpha_h)] [I_0 + \sqrt{2}I_1 \sin(\omega t - \alpha_1) + \sqrt{2} \sum_{h=2}^{\infty} I_h \sin(h\omega t - \alpha_h)] \quad (2.12)$$

By simplifying we can get

$$\begin{aligned} p(t) = & V_0 I_0 + \sum_{h=1}^{\infty} V_h I_h \cos(\beta_h - \alpha_h) [1 - \cos(2h\omega t - 2\alpha_h)] \\ & - \sum_{h=1}^{\infty} V_h I_h \cos(\beta_h) \sin(2h\omega t - 2\alpha_h) \\ & + 2 \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} V_m I_n \sin(m\omega t - \alpha_m) \sin(m\omega t - \beta_n) \\ & + \sqrt{2} V_0 \sum_{h=1}^{\infty} I_h \sin(h\omega t - \beta_h) \\ & + \sqrt{2} I_0 \sum_{h=1}^{\infty} V_h \sin(h\omega t - \alpha_h) \text{ où } m \neq n \end{aligned} \quad (2.13)$$

where;

$p(t)$  is the instantaneous power signal under non-sinusoidal wave forms

In other words

$$p(t) = p_a + p_q \quad (2.14)$$

where;

$$p_a = V_0 I_0 + \sum_{h=1}^{\infty} V_h I_h \cos(\beta_h - \alpha_h) [1 - \cos(2h\omega t - 2\alpha_h)] \quad (2.15)$$

$$p_a = V_0 I_0 + \sum_{h=1}^{\infty} V_h I_h \cos(\beta_h - \alpha_h) - \sum_{h=1}^{\infty} V_h I_h \cos(2h\omega t - 2\alpha_h) \quad (2.16)$$

$p_a$  is the part of the instantaneous power that is equal to the sum of harmonic active powers. The terms  $V_0 I_0$  and  $V_h I_h \cos(\beta_h - \alpha_h)$  contribute to net transfer of energy while  $V_h I_h \cos(2h\omega t - 2\alpha_h)$  doesn't contribute to net transfer of energy.

$$p_q = - \sum_{h=1}^{\infty} V_h I_h \cos(\beta_h) \sin(2h\omega t - 2\alpha_h) \quad (2.17)$$

$p_q$  is a term that does not represent a net transfer of energy

### A.1 Active power calculation

The active power can be obtained by integrating the instantaneous power signal and getting the average value over number of line cycles. By simplification we can obtain that the active power is equal to the sum of fundamental active power and harmonic active power. Therefore we can write

$$P = P_1 + P_H \quad (2.18)$$

where;

$P$  is the active power

$P_1$  is the fundamental active power

$P_H$  is the harmonic active power or the nonfundamental active power

And

$$P_1 = \frac{1}{nT} \int_0^{nT} v_1(t) i_1(t) dt = V_1 I_1 \cos(\beta_1 - \alpha_1) \quad (2.19)$$

where;

$v_1(t)$  the fundamental instantaneous voltage

$i_1(t)$  the fundamental instantaneous current

$$P_H = V_0 I_0 + \sum_{h=2}^{\infty} V_h I_h \cos(\beta_h - \alpha_h) \quad (2.20)$$

The ADE 7880 energy measurement chip uses this method to calculate the active power in each phase. First, the instantaneous power signal is obtained by multiplying the current and voltage signal in each phase. Then this signal is low pass filtered to obtain the DC component which is equal to the active power in each phase. This chip has separate mechanism to isolate the active powers in each harmonic. The user can select the order of harmonics to be monitored and can read the power in required harmonic by accessing to the internal readable registers.

### A.2 Active energy calculation

The active energy in each phase is calculated by using (2.20)

$$E_A = \int_0^{nT} p(t)dt = nT[V_0 I_0 + \sum_{h=1}^{\infty} V_h I_h \cos(\beta_h - \alpha_h)] \quad (2.21)$$

where;

$E_A$  is the active energy

### (C) Fundamental reactive power and energy calculation under non-sinusoidal wave-forms

ADE 7880 energy measurement chip has the capability to measure the fundamental reactive power as well as the harmonic reactive powers in each phase. First, the instantaneous reactive power signal is generated. It is done by multiplying the each harmonics of the voltage signals by phase shifted ( $90^\circ$  phase shift) corresponding harmonic currents. Then this signal is low pass filtered to extract the DC component which is equal to the summation of each harmonic reactive power. A proprietary algorithm is used to compute the fundamental reactive power in the chip. This can be explained as follows.

The  $90^\circ$  phase shifted current can be written as

$$i'(t) = I_0 + \sqrt{2} \sum_{h=1}^{\infty} I_h \sin(h\omega t - \beta_h + \frac{\pi}{2}) \quad (2.22)$$

where;

$i'(t)$  is the  $90^\circ$  phase shifted current signal

Then the instantaneous reactive power signal is

$$q(t) = v(t)i'(t)$$

$$q(t) = [V_0 + \sqrt{2}V_1 \sin(\omega t - \alpha_1) + \sqrt{2} \sum_{h=2}^{\infty} V_h \sin(h\omega t - \alpha_h)][I_0 + \sqrt{2} \sum_{h=1}^{\infty} I_h \sin(h\omega t - \beta_h + \frac{\pi}{2})] \quad (2.23)$$

$$\begin{aligned}
q(t) = & V_0 I_0 + V_0 \sum_{h=1}^{\infty} \sqrt{2} I_h \sin(h\omega t - \beta_h + \frac{\pi}{2}) \\
& + I_0 \sum_{h=1}^{\infty} \sqrt{2} V_h \sin(h\omega t - \alpha_h) + \sum_{h=1}^{\infty} V_h I_h [\cos(\beta_h - \alpha_h - \frac{\pi}{2}) - \cos(h\omega t - \alpha_h - \beta_h \frac{\pi}{2})] \\
& + \sum_{n,m=1}^{\infty} V_n I_m \cos((h-m)\omega t - \alpha_h \beta_h - \frac{\pi}{2}) - \cos((h+m)\omega t - \alpha_h - \beta_h + \frac{\pi}{2})]
\end{aligned} \tag{2.24}$$

where;

$q(t)$  is the instantaneous reactive power signal under non-sinusoidal waveforms

### A.1 Reactive power calculation

The average total reactive power can be obtained according to (2.26)

$$Q = \frac{1}{nT} \int_0^{nT} q(t) dt = V_0 I_0 + \sum_{h=1}^{\infty} V_h I_h \cos(\beta_h - \alpha_h - \frac{\pi}{2}) \tag{2.25}$$

$$Q = V_0 I_0 + \sum_{h=1}^{\infty} V_h I_h \sin(\beta_h - \alpha_h) \tag{2.26}$$

After the low pass filtering the frequency terms of are filtered out and the DC component is extracted. This gives the total reactive power in one phase (2.24).

### A.2 Reactive energy calculation

The reactive energy in each phase is calculated by using (2.27)

$$E_R = \int_0^{nT} q(t) dt = nT [V_0 I_0 + \sum_{h=1}^{\infty} V_h I_h \sin(\beta_h - \alpha_h)] \tag{2.27}$$

where;

$E_R$  is the reactive energy

## 2.3.4 Four Quadrant Operation

Some of energy chips are capable of measuring both positive and negative active and reactive energy which is known as four quadrant operation. They have different registers to determine the polarity of power. By accessing these registers the direction of power flow can be determined. Using an external MCU, the active power inflow, active power out flow, reactive power inflow and reactive power outflow can be separately measured, stored and displayed.

Figure 2.15 illustrates the sign of active and reactive power with the voltage and current directions.

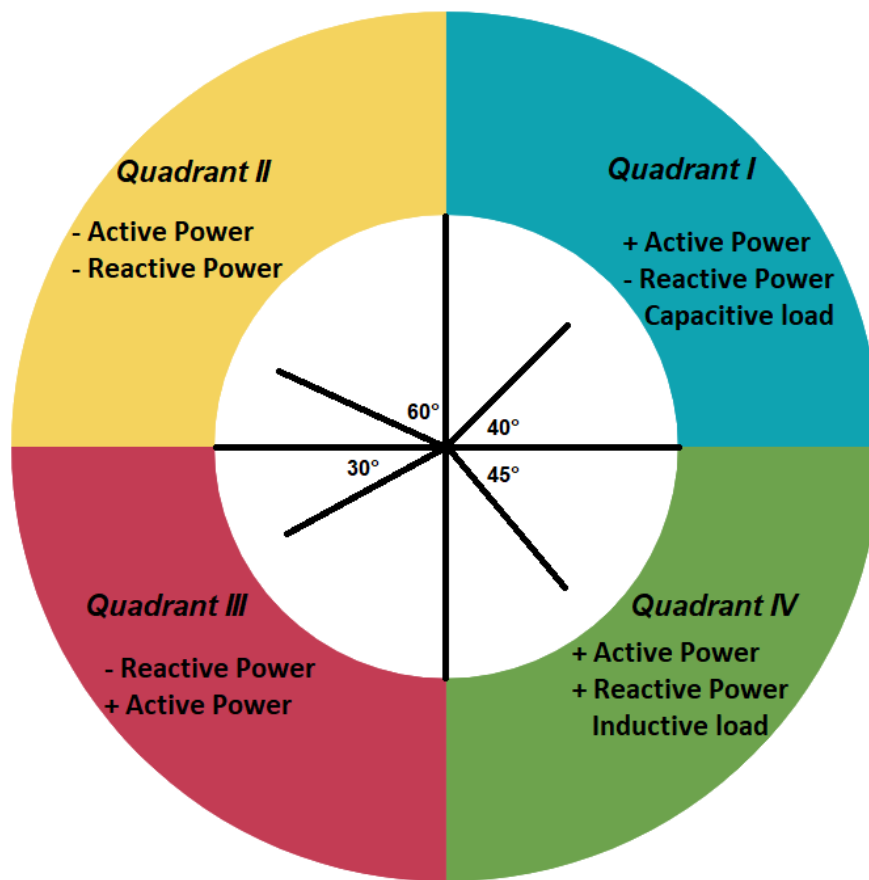


Figure 2.15: Four quadrant operation

The connected load of the consumer is capacitive in quadrant I and the power factor is considered as leading. The power factor is lagging when the load is inductive in quadrant IV.

# Process Acquisition and Communication System

## 3.1 System Model

Consider a distribution network using overhead lines suspended from utility poles and underground cables to deliver electricity to electrical transformer stations for distribution to consumption points equipped with smart meters (SM). Some utility poles host Data Aggregation Points (DAPs), each of which wirelessly connected to a subset of the SMs. The DAPs themselves are also connected to a utility center (UC).

To model this, let us consider a network of  $N_{SM}$  SMs,  $K$  DAPs and one utility center (UC), and assume that  $N_{poles}$  are located within this network. The locations of SMs, utility poles, and the UC are known and given by  $SM = \{s_i\}_{i=1,\dots,N_{SM}}$ ,  $P = \{p_j\}_{j=1,\dots,N_{poles}}$  and  $u$ , respectively, whereas the value of  $K$  and the location of DAPs,  $A = \{a_k\}_{k=1,\dots,K}$ , are to be optimised. The SMs and DAPs can be equipped with different communication technologies such as RU65 Lora Wireless Module developed by Kaifa Technology, as WiFi, WiMAX, IEEE 802.15.4 (ZigBee), and the 802.15.4g standard specifically by IEEE for smart utility networks (SUNs) [21]. The number of SMs is obtained based on their densities for different environments using [22].

$$N_{SM} = \rho_{SM}\pi r^2 \quad (3.1)$$

where  $r$  is the radius of the area-of-interest (AoI) and  $\rho_{SM}$  is the smart meter density in that area. The value of  $\rho_{SM}$  depends on the AoI being rural, urban or sub-urban [22].

### 3.1.1 Data Aggregation Model

DAPs are placed on top of the utility poles, and their task is to collect the data from SMs and send them to the UC. We assume a one-hop communication from SMs to the DAPs (SM-DAP) and at least from DAPs to the UC (DAP-UC) the fact that UC are not equidistant from DAPs. DAPs also combine and compress the received data from SMs

before transmission to the UC. We denote the compression ratio by  $\beta$ . The value of  $\beta$  can be between  $1/2$  to  $2/3$  depending on correlation between data and the algorithm employed in the DAP [23]. Different numbers of SMs, from a few up to 2000 [22], can be connected to one DAP. Usually, a relatively large number of SMs can be supported by a single DAP; noting that the congestion probability is very low due to the low frequency and amount of data messages sent from the meters. We denote the maximum number of SMs that can be connected to one DAP by  $A$ . Furthermore, we define the ratio between the number of available utility poles and the number of SMs in a given service area as  $\varrho = \frac{N_{poles}}{N_{SM}}$ . It is reasonable to assume that for a denser environment (e.g. an urban area), a utility pole contributes to the energy distribution over a larger number of smart meters, and hence,  $\varrho$  is smaller.

### 3.1.2 Transmission Model

The smart meters adjust their transmission power  $P_{tx}$  according to the link reliability to ensure that they can connect to the DAP with a given transmission success probability. The energy consumed for transmitting  $M$  bytes of data over distance  $d$  can be represented as

$$E_{tx} = 8M\gamma E_b\kappa PL(d) \quad (3.2)$$

where  $\gamma$  is the ratio of the total power consumption in the modem and the power consumed for transmission,  $E_b$  is the required received energy per bit,  $\kappa$  is the fading margin, and  $PL(d)$  represents the path-loss at distance  $d$ . The path-loss can be modeled as

$$PL(d) = PL(d_0)\left(\frac{d}{d_0}\right)^\alpha \quad (3.3)$$

where  $PL(d_0)$  is the path-loss at the reference distance  $d_0$  and  $\alpha$  is the path-loss exponent. Note that the factor 8 in (3.2) accounts for  $M$  being packet size in bytes and  $E_b$  denoting energy per bit.

## 3.2 Problem Formulation

Given the DAP and transmission model above, we now formulate the DAP placement problem. The basic objective is to select a subset of pole locations from  $P$  to install DAPs on top of them such that the required number of DAPs is minimized while providing radio coverage for all SMs. This objective minimizes the installation cost, which is defined as the purchase and labor price for the initial placement of a DAP. In addition, we are interested in minimizing the communication cost, which we measure in terms of the consumed energy for transmitting data. Note that the power model (3.2) implies a transmission cost proportional to  $d^\alpha$ , which we consider a more realistic model compared to the transmission-cost function being linear in  $d$  adopted in [24].

Assume that the network is supposed to work for a duration of  $T_m$ . To mathematically formulate our cost function, let  $a$  denote the installation cost (in FCFA) of one DAP. The



total installation cost,  $C_{inst}$ , is then a times the number of poles selected for DAP placement. Also, let  $g$  denote the energy price (e.g., the price for consuming 1 kWh of energy). Then, the transmission cost can be computed as

$$C_{tx} = gE_{tx} \frac{T_m}{T_I} \quad (3.4)$$

where  $T_I$  is the time interval between the transmissions, so that the third term represents the total number of transmissions that one SM sends during  $T_m$ . For radio coverage we require each SM to be connected to at least one DAP, which means that the SM-DAP distance needs to be smaller than the SM transmission range  $d_{max}$ . Furthermore, up to a maximum of  $A$  SMs can be connected to a single DAP. Hence, the DAP-placement problem can be written as

$$\min_{\{x_i\}, \{y_{ij}\}} C_{inst} + C_{tx} = \sum_{j=1}^{N_{poles}} ax_j + b \sum_{i=1}^{N_{SM}} \sum_{j=1}^{N_{poles}} y_{ij} (PL(d_{ij} + \beta PL(d'_j))) \quad (3.5)$$

subject to

$$d_{ij} \leq d_{max}, \quad 1 \leq i \leq N_{SM}, 1 \leq j \leq N_{poles} \quad (3.6)$$

$$d'_j \leq d'_{max}, \quad 1 \leq j \leq N_{poles} \quad (3.7)$$

$$\sum_{j=1}^{N_{poles}} y_{ij} = 1, \quad 1 \leq i \leq N_{SM} \quad (3.8)$$

$$\sum_{j=1}^{N_{poles}} y_{ij} \leq A, \quad 1 \leq j \leq N_{poles} \quad (3.9)$$

$$y_{ij} \leq x_j, \quad 1 \leq i \leq N_{SM}, 1 \leq j \leq N_{poles} \quad (3.10)$$

$$x_j \in 0, 1, \quad 1 \leq j \leq N_{poles} \quad (3.11)$$

$$y_{ij} \in 0, 1, \quad 1 \leq i \leq N_{SM}, 1 \leq j \leq N_{poles} \quad (3.12)$$

where  $b = g8ME_b\kappa T_m/T_I$ ,  $d_{ij}$  and  $d'_j$  denote the distance between SM  $i$  and pole  $j$  and between pole  $j$  and the UC, respectively. The values of  $d_{max}$  and  $d'_{max}$  correspond to the transmission range of SMs to the DAPs and DAPs to the UC, respectively. The binary variable  $x_j$  is an indicator for whether a DAP is installed on pole  $j$ , and the binary variables  $y_{ij}$  indicate whether the SM  $i$  is connected to the DAP on the pole  $j$ . The first term in the objective accounts the installation cost of DAPs, and the two terms in the second sum in the objective represent the total cost of transmission from SMs to their corresponding DAPs and from DAPs to the UC, respectively. Constraints (3.6), (3.7), and (3.8) ensure radio coverage, and constraint (3.9) limits the maximal number of SMs per DAP. Furthermore, constraint (3.10) ensures that the relation between DAP selection and

placement is maintained, i.e., a smart meter can only be connected to a pole which is selected for DAP installation. The optimization in (3.5) is a type of integer programming and solving it optimally incurs an exponential time complexity. For large networks, a lower complexity algorithm is required to solve the placement problem. The optimization in (3.5) can also be viewed as a clustering problem with additional constraints on the cluster size and head locations. This motivates the use of a modified K-means algorithm, as will be explained in the next section.

### 3.3 K-Means Approach

In this section, we show how the K-means algorithm can be adapted to find a near-optimal DAP placement based on the optimization problem (3.5). In the K-means algorithm, the number of clusters,  $K$ , is a parameter whose value should be known. In our problem, finding an appropriate value for  $K$  which provides the AMI coverage is a challenging task. Therefore, we start from a minimum initial estimate for  $K$ ,

$$K_0 = \lceil \frac{N_{SM}}{\min\{A, \rho_{SM}\pi d_{max}^2\}} \rceil \quad (3.13)$$

and then increment it. The initial estimate in (3.13) provides a (loose) lower bound for the value of  $K$ . This is because in higher densities ( $\rho_{SM}\pi d_{max}^2 \geq A$ ) the constrain (3.9) cannot be satisfied for any values  $K < K_0$  and the placement problem would be infeasible. Similarly, in lower densities ( $\rho_{SM}\pi d_{max}^2 < A$ ), we need at least  $K_0$  DAPs to ensure that all SMs get at least one DAP in their transmission range.

In each iteration of the conventional K-means algorithm, the nodes (here, SMs) choose their nearest cluster head. Accordingly, we set  $y_{ik} = 1$  if the  $i$ th SM belongs to the  $k$ th cluster, and  $y_{ik} = 0$  otherwise. Then, the cluster head locations are updated to the centroid of their connected SMs. The K-means algorithm terminates when the difference in the updated cluster head locations in two consecutive iterations is less than a threshold. Since we need to account for both the SM-DAP and DA-PUC transmission costs, we modify the K-means algorithm and incorporate the utility center location,  $u$ , in the update equation of the cluster heads as

$$a_k = \frac{\omega u + \sum_{i=1}^{N_{poles}} y_{ik} S_i}{\omega + \sum_{i=1}^{N_{poles}} y_{ik}} \quad (3.14)$$

where  $\omega = \beta \frac{d_{max}}{d'_{max}}$  is a function of both the compression ratio  $\beta$ , to consider the effect of data compression on DAP-UC links, and the coverage ratio, i.e.  $\frac{d_{max}}{d'_{max}}$ , so that the cluster heads which have few SMs are not pulled towards the UC and consequently lose their connection to the SMs.

The optimization procedure is summarized in Algorithm 1. Starting from  $K_0$ , we run the modified K-means with “NumTries” different initial placements, map the final

clusterhead locations to their nearest poles, and then choose the solution with the lowest cost. Since initial placements in the K-means algorithm affect its final solution, different runs are needed for exploring different configurations and finding a solution closer to the optimum. Finally, we stop when the cost for the best solution found for  $K + 1$  clusters is larger than that with  $K$  clusters by a given “tolerance” value.

---

Algorithm 1 : Iterative K-means algorithm for DAP placement optimization.

---

Require:  $SM; P; u; a; b; \alpha; \beta; \gamma; M$ .

- 1: Get  $K_0$  from (3.13).
- 2:  $k \leftarrow 0$
- 3: do
- 4:    $K \leftarrow K_0 + k$ .
- 5:   for  $i = 0 : \text{NumTries}-1$  do
- 6:     Uniformly-randomly initialize the cluster head locations.
- 7:     Run the modified K-means algorithm.
- 8:     Map aks to their nearest poles.
- 9:      $F_i \leftarrow$  Achieved cost from (3.5). Or,  $F_i \leftarrow 1$  if any of (3.6) -(3.9) are not satisfied.
- 10: end for
- 11:    $C_k \leftarrow \min\{F_i\}$ :
- 12:    $\text{diff} \leftarrow C_k - C_{k-1}$ :
- 13:    $k \leftarrow k + 1$ .
- 14: while  $\text{diff} < \text{tolerance}$
- 15: return  $\min\{C_k\}$

### 3.4 Numerical Results

We test the efficiency of our proposed DAP placement algorithm in different scenarios, namely urban, suburban, and rural environments, whose pertinent parameters are obtained from [22]. There are also several choice for selecting the communication technology. Two choice of these links are WiMAX, due to its coverage of a few kilometers witha good reliability and CR104 RF Module used by Akilee for which the transmission range is limited to a few hundred meters. Table (3.1) summarizes the parameters used in our simulations for the above-mentioned environments and transmission technologies. The location of smart meters and poles are uniformly randomly chosen in the AoIs with radii of 1, 2, and 5 kilometers as examples for urban, suburban and rural environments, respectively. We assume a required signal-to-noise ratio (SNR) of  $\eta = Eb/N'_0 = 10dB$ , where  $N'_0 = N_0F$  and  $N'_0$  and  $F$  are the receiver noise power spectral density and noise factor, respectively. As suggested in [3], we use the COST231 path-loss model for the urban and suburban environments and the Erceg type C model for the rural areas. The parameters chosen for the SM-DAP links are as follows: SM height is 2 m, DAP height is 10 m, center frequency is 1800 MHz (WiMAX) and 868 MHz (RU65 Lora). The parameters chosen for the DAP-UC links are: DAP height is 10 m, WiMAX base-station antenna height is 30 m, and centre frequency is 1800 MHz. We also let  $A = 2000$  [22].

Parameter	Value	Parameter	Value
$\rho_{SM}$	2000(per $km^2$ , urban)[17] 800(per $km^2$ , suburban)[17] 10(per $km^2$ , rural)[17]	r	1 km urban 2 km suburban 5 km rural
$d_{max}$	100 m (CR104 RF)[25] 1 km (WiMAX)[24]	$\varrho$	$\frac{1}{3}$ sub(urban) $\frac{1}{10}$ rural
$d'_{max}$	5 km (WiMAX)[24]	$\beta$	$\frac{1}{2}$
$T_m$	15 years	$T_I$	245 min
$M$	2400 bytes	$g$	110 FCFA/kWh
$N_0$	-174 dBm/Hz	$\eta$	10 dB
$F$	7 dB	$\kappa$	10 dB
PL model	COST231 sub(urban)[17] Erceg Type C rural[17]	$a$	1500000 FCFA / 2000€
$A$	2000	$\gamma$	2

Table 3.1: SIMULATION PARAMETERS

Topology	SM-DAP link	$N_{SM}$	$K^*$	avg SM per DAP
Urban	WiMAX	6283	4	1570.75
	CR104 RF	6283	618	10.17
Suburban	WiMAX	10053	25	412.12
	CR104 RF	10053	999	10.06
Rural	WiMAX	785	73	10.75
	CR104 RF	785	248	3.17
Mixed	WiMAX	17121	67	255.54
	CR104 RF	17121	1814	9.44

Table 3.2: DAP-PLACEMENT OPTIMIZATION RESULTS FOR DIFFERENT TOPOLOGIES.

Figure 2 shows the results of optimization of the DAP locations using Algorithm 1 for different topologies and transmission technologies. Furthermore, Table (3.3) compares the values of  $N_{SM}$ ,  $K$ , and the minimum, maximum and average number of SMs served by a DAP for different topologies, including those considered in Figure 2.

The sub-figures on the left and right side of Figure 2 correspond to the use of, respectively, WiMAX and CR104 RF for the SM-DAP links. Figures 3.1 and 3.2 (corresponding to the second row of Table (3.3)) show the optimized DAP placement in a suburban area, and figures 3.3 and 3.4 (corresponding to the third row of Table (3.3)) show the optimized placements for a rural area. We observe that for the RU65 Lora technology, due to the limited transmission range (100 m), more DAPs are required than when WiMAX is applied. In fact, the results in Table (3.3) show about three (rural) to 150 (urban) times fewer DAPs for WiMAX. This suggests that relaying should be applied for reducing the cost of DAP installation when using CR104 RF. This would come with an increase in delay,

which would not be critical for meter data though. We can also observe from Figure 2 that since the SMs are placed sparsely in a rural setting, there are on average much fewer (3-10) SMs connected to one DAP, compared to the suburban and urban scenarios where on average 402 and 1570 SMs are connected via WiMAX to one DAP.

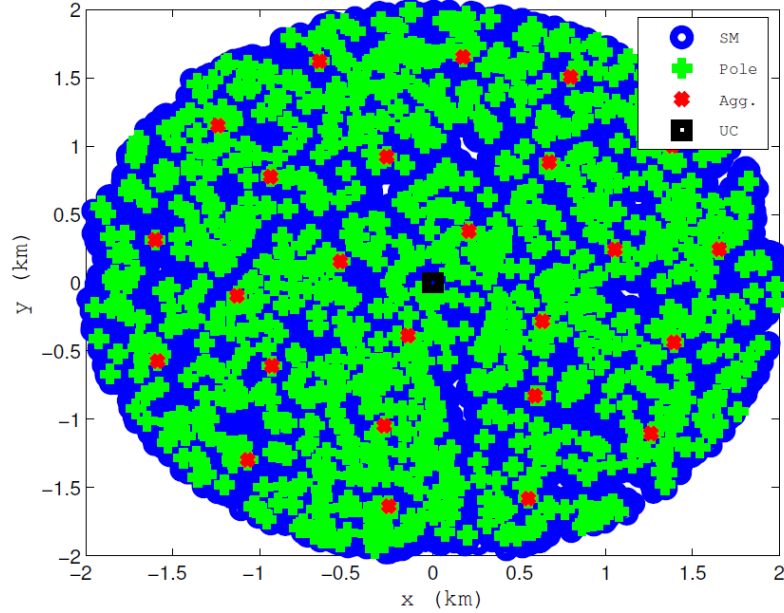


Figure 3.1: WiMAX Suburban area

Figures 3.5 and 3.6 (corresponding to the last row of Table (3.3)) consider a mixed urban, suburban, and rural area scenario, with different densities over radii of 1, 2, and 5 km, respectively. This model gives a simple representation of cities, with larger SM densities in downtown and surrounding residential areas, and sparse SM distributions in rural parts around them. We can again observe that a single-hop CR104 RF based DAP supports typically 10 SMs, while a WiMAX can serve 255 on average, and up to 1000 SMs in the urban and suburban areas. Also note that the total number of DAPs placed in the mixed scenario is smaller than the sum of DAPs needed for each of the individual scenarios, mainly because the areas overlap in the mixed topology.

## 3.5 Application

La présente répartition a été élaborée par l'Agence Nationale de la Statistique et de la Démographie au cours d'un atelier tenu en mai 2015 selon ses projections démographiques [23].

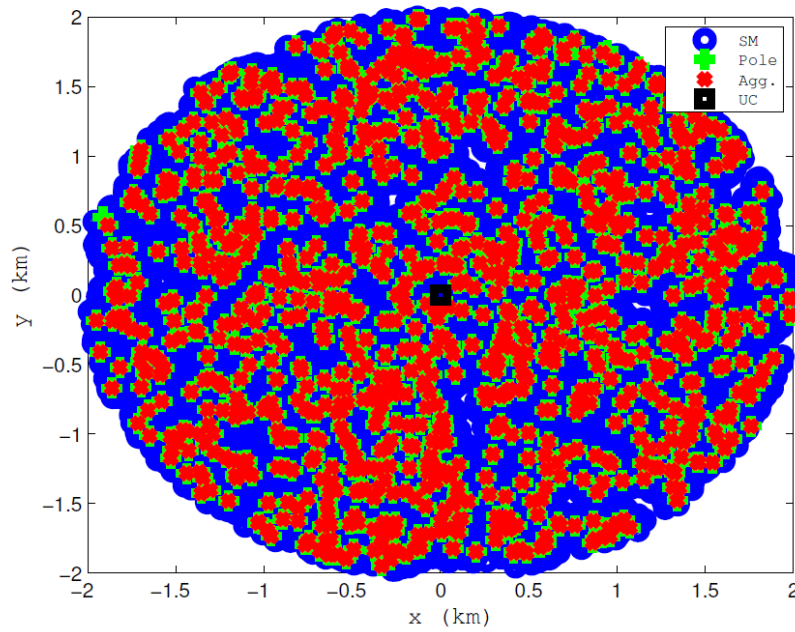


Figure 3.2: CR104 RF Suburban area

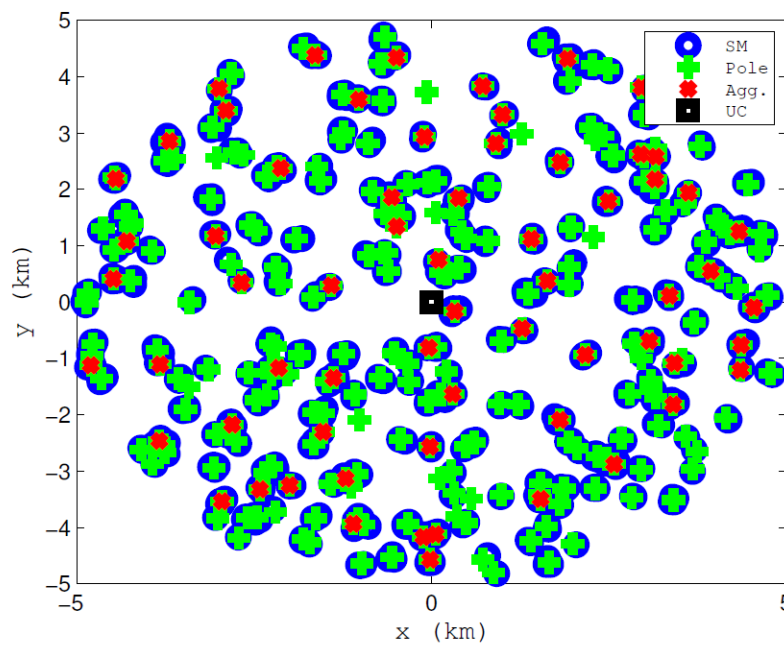


Figure 3.3: WiMAX Rural area

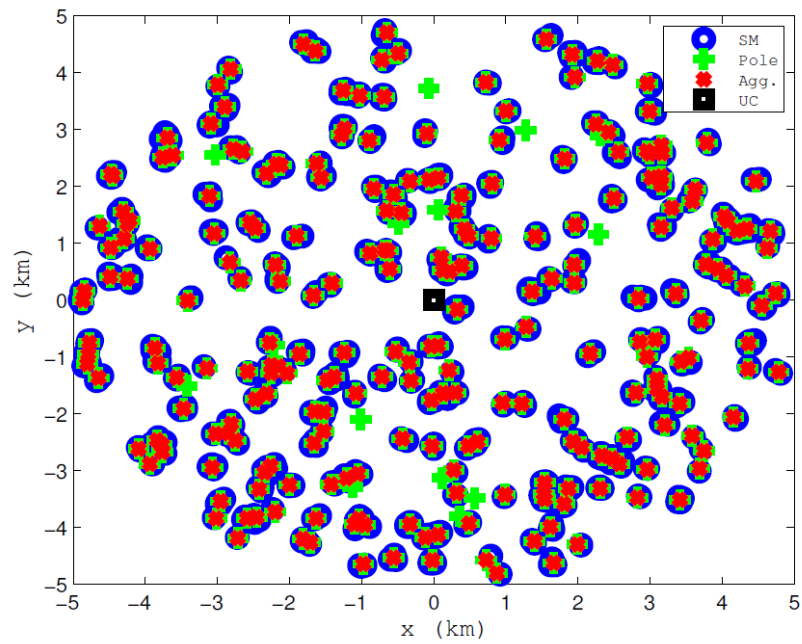


Figure 3.4: CR104 RF Rural area

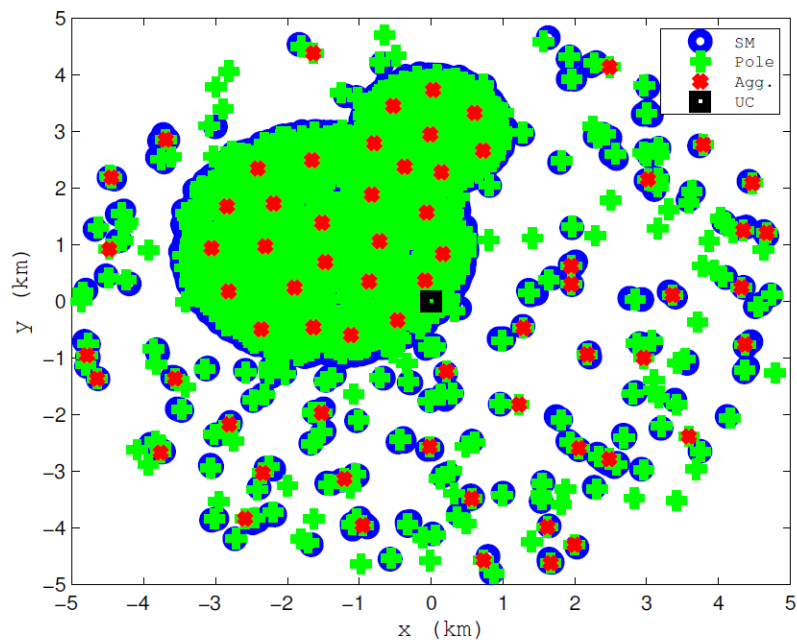


Figure 3.5: WiMAX Mixed area

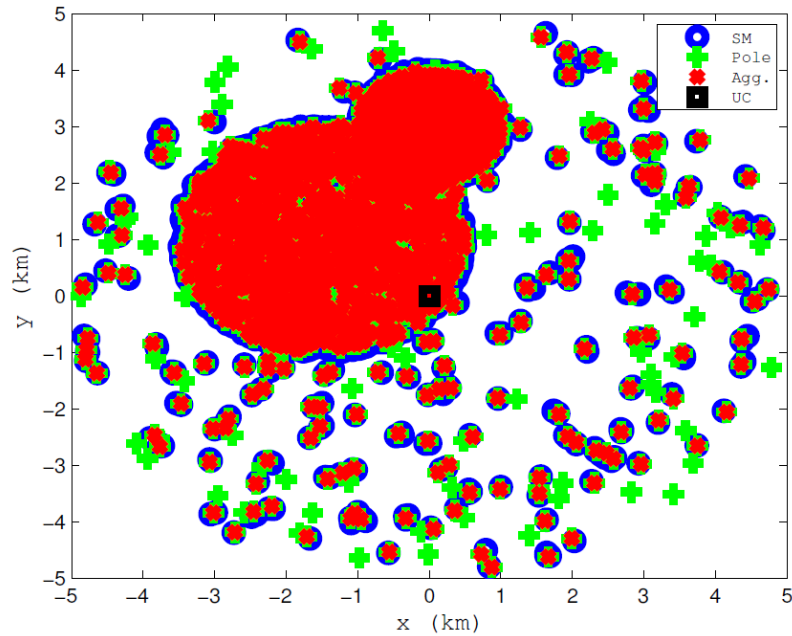


Figure 3.6: CR104 RF Mixed area

Regions	Area Type	average SMs/DAP	Residence	DAPs Total	Cost Millions F CFA / Mille €
Dakar	Urban	1570	496 145	316	474 / 632
Diourbel	Rural	10	156 537	15 654	23451 / 31308
Tambacounda	Rural	10	70 292	7 030	10545 / 14060
Saint-Louis	Mixed	255	110 191	433	650 / 866
Thies	Mixed	255	194 708	764	1146 / 1528
Fatick	Rural	10	72 402	7 241	10852 / 14482
Kaffrine	Rural	10	54 012	5 402	8103 / 10804
Kaolack	Mixed	255	95 292	374	561 / 748
Kedougou	Rural	10	19 048	1 905	2858 / 3810
Kolda	Rural	10	70 931	7 094	10641 / 14188
Louga	Rural	10	97 381	9 739	14609 / 19478
Matam	Rural	10	53 947	5 395	8093 / 10790
Sedhiou	Rural	10	40 870	4 088	6132 / 8176
Ziguinchor	Mixed	255	75 956	298	447 / 596

Table 3.3: Regional distribution of residence, area type, DAPs total and cost.



# SENELEC Distribution System Modeling

## 4.1 GridLAB-D

*GridLAB – D<sup>TM</sup>* is a new power distribution system simulation and analysis tool that was developed by U.S Department of Energy (DOE) at Pacific Northwest National Laboratory (PNNL) under funding for Office of Electricity in collaboration with industry and academia. This software provides valuable information to users who design and operate distribution systems, and to utilities that wish to take advantage of the latest energy technologies[1]. Given the need to provide the analysis capabilities required to study the interactions of the future power system, *GridLAB – D<sup>TM</sup>* has been used to perform:

- Distribution Automation Design/Evaluation
- Peak Load Management
- Distributed Generation and Storage
- Rate Structure Analysis

## 4.2 Distribution System Equipments

### 4.2.1 Overhead lines

Overhead lines are one of three specific line types incorporated into the powerflow distribution-level module. The overhead line object will take spacing and conductor parameters and translate those values to appropriate impedance matrices based for the specific overhead transmission line configuration.

#### (A)Object Code

A typical overhead line would be written as :

```

object overhead_line {
    name CAPDESBICHES_KM22;
    phases ABC;
    from substation_meter_CAPDESBICHES;
    to KM22_PosteSecteur_KM22;
    length 10000;
    configuration line_configuration_1;
}

```

### (B)Configuration Code

For overhead lines, the line configuration object must specify the overhead line conductor types used in the particular setup. A typical overhead line conductor would be implemented as:

```

object line_configuration {
    name line_configuration_1;
    conductor_A overhead_line_conductor_1;
    conductor_B overhead_line_conductor_1;
    conductor_C overhead_line_conductor_1;
    conductor_N overhead_line_conductor_1;
    spacing line_spacing_1;
}

```

```

object overhead_line_conductor {
    name overhead_line_conductor_1;
    geometric_mean_radius 0.01200 ft; //the geometric_mean_radius of t
    resistance 0.1; //The resistance of the conductor,
}

```

```

object line_spacing {
    name line_spacing_5001;
    distance_AB 2.5;
    distance_AC 7.0;
    distance_BC 4.5;
    distance_AN 5.656854;
    distance_BN 4.272002;
    distance_CN 5.0; //Distance between conductors of phase C
                    //and the neutral phase.
}

```

### 4.2.2 Underground cables

Underground lines represent burial distribution cables in a powerflow system. In terms of GridLAB-D implementation, they are nearly identical to the overhead line objects.

#### (A) Object Code

A typical underground line object would be written as:

```
object underground_line {
    name CAPDESBICHES_HAMAYA;
    phases ABC;
    from substation_meter_CAPDESBICHES;
    to SecoursCFPP_PosteClient_HAMAYA;
    length 1689;
    configuration line_configuration_10012;
}
```

#### (B) Configuration Code

Underground lines often contain concentric shielding layers around the central conductor. As a result, they require more parameters than the *overhead\_line\_conductor* objects to fully describe them. A typical underground line object is:

```
object line_configuration {
    name line_configuration_10012;
    conductor_A underground_line_conductor_10003;
    conductor_B underground_line_conductor_10003;
    conductor_C underground_line_conductor_10003;
    conductor_N underground_line_conductor_10003;
    spacing line_spacing_50012;
}

// Phase Conductor
object underground_line_conductor {
    name underground_line_conductor_10003;
    outer_diameter 1.060000; //Diameter of the outside of the cable ,
                             including jacketing and shielding.
    conductor_gmr 0.011100; //Geometric mean radius of the conductor.
    conductor_diameter 0.368000; // Diameter of the conductor.
    conductor_resistance 0.970000; //Resistance of the conductor.
    neutral_gmr 0.011100; //Geometric mean radius of the concentric
                           neutral of the cable.
    neutral_resistance 0.970000; //Resistance of the concentric
                                  neutral of the cable.
    neutral_diameter 0.0640837; //Diameter of the concentric
                                  neutral of the cable.
}
```

```

        neutral_strands 6.000000; //Number of strands composing
                                the concentric neutral conductor.
        shield_gmr 0.000000;      //Geometric mean radius of the
                                shielding of the cable.
        shield_resistance 0.000000; //Resistance of the cable shielding.
    }

    object line_spacing {
        name line_spacing_50012;
        distance_AB 0.5;
        distance_AC 1.0;
        distance_BC 0.5;
        distance_AN 0.0;
        distance_BN 0.0;
        distance_CN 0.0; //Distance between conductors of phase C
                        and the neutral phase.
    }

```

### 4.2.3 Transformers

Transformers provide a means to change the voltage from one node to another in the distribution system. Similar to the different line objects, a transformer object requires a configuration object to specify the details of the implementation.

#### (A) Object Code

A typical transform implementation is:

```

object transformer {
    name substation_transformer_CAPDESBICHES;
    from Poste_source_CAPDESBICHES;
    to substation_meter_CAPDESBICHES;
    phases ABCN;
    configuration substation_transformer_config_PS90KV;
}

```

#### (B) Configuration Code

The transformer configuration object describes the details of a particular transformer implementation. It includes information like the power rating, connection type, and nominal voltage on each side. A typical delta-delta transformer configuration would be implemented as:

```

object transformer_configuration {
    name substation_transformer_config_PS90KV;
    connect_type DELTA_DELTA; \\A delta to delta connected transformer.
}

```

```

install_type PADMOUNT; //A pad, or ground level transformer.
primary_voltage 90000; //Nominal voltage of the primary
secondary_voltage 30000; //Nominal voltage of the secondary
power_rating 8.4 MVA; //Nominal power rating
impedance 0.00033+0.0022j; //De-referenced characteristic
                           impedance of the transformer
}

```

#### 4.2.4 Voltage regulators

Regulators are essentially tap-changing transformers that attempt to maintain a voltage level at a specified point in the system. Regulators are one of two objects in the powerflow module that incorporate a form of automatic control. To take full advantage of this functionality, simulations of greater than one time step (time-varying simulations) are recommended. Similar to transformer and line objects, regulators require a regulator configuration to determine many of their operating parameters.

##### (A) Object Code

A typical implementation would be:

```

object regulator {
    name substation_regulator;
    phases "ABC";
    from SIES_PostaSecteur_FoyerDeCharite;
to SIES_PostaSecteur_Sipres3Mbao;
    configuration regulator_configuration_1;
}

```

##### (B) Configuration Code

The regulator configuration object describes the details of a particular regulator object implementation. This includes details such as the control scheme, regulator type, sensing information, and time delays. A typical regulator configuration would look similar to:

```

object regulator_configuration {
    name regulator_configuration_1;
    connect_type 1; //Wye connected regulator implementation
    band_center 230.000; //Center point of the voltage level desired.
    band_width 2.0; //Allowed range for the voltage.
    time_delay 30.0; //Amount of time from a change request to the
        physical changing of the tap position on the regulator.
    raise_taps 16; //Upper limit of tap positions allowed
        in the regulator.
}

```

```

lower_taps 16; //Lower limit of tap positions allowed
               in the regulator.
compensator_r_setting_A 0.6; //Compensator resistive value
                              for phase A.
compensator_x_setting_A 1.3;
compensator_r_setting_B 1.4;
compensator_x_setting_B 2.6;
compensator_r_setting_C 0.2;
compensator_x_setting_C 1.4;
CT_phase "ABC"; //Current transducer connection phase.
PT_phase "ABC"; //Power transducer connection phase.
Control MANUAL;
}

```

#### 4.2.5 Capacitors

Capacitors are used for reactive power compensation and voltage support scenarios. The capacitor implements a switchable set of capacitors. capacitor objects are one of two objects in the powerflow module that incorporate a form of automatic control. To take full advantage of this functionality, simulations of greater than one time step (time-varying simulations) are recommended. Single-phase powerflow connections (phase S) are not supported by capacitors at this time.

##### (A) Object Code

A typical capacitor implementation is:

```

object capacitor {
    name substation_capacitor;
    phases "ABCN";
    control MANUAL;
    capacitor_A 0.5 KVar; //Capacitor size information for capacitor
                          connected to phase A
    capacitor_B 0.5 KVar;
    capacitor_C 0.5 KVar;
    control_level INDIVIDUAL;
    switchA OPEN; //Status of the switch OPEN.
    switchB OPEN;
    switchC CLOSED; //Status of the switch CLOSED.
    nominal_voltage 230;
}

```

#### 4.2.6 Meter

Meters provide a measurement point for power and energy on the system at a specific point. Coupled with a recorder or collector, the meter object provides a method determine

how much power and energy have been used by downstream connections, as well as how much current is flowing through the meter object at the present time. A typical implementation would be

```
object meter {
    name load_meter;
    phases ABCN;
    nominal_voltage 230;
    object recorder {
        name load_recorder;
        file load_data.csv;
        interval 60;
        property "measured_voltage_A.real , measured_voltage_A.imag ,
        measured_power_A.real , measured_power_A.imag";
    };
}
```

#### 4.2.7 Load

##### Time-invariant load models (ZIP Models)

These load models are used for static single solution power flow calculations. They are generally used for capacity planning studies where only peak load is examined.

##### Time-variant load models

These are sometimes referred to as load profiles where ZIP coefficients change with time.

```
object load {
    parent KM22_PostaSecteur_meter_PA3;
    name KM22_load_PA3;
    nominal_voltage 230;
    constant_current_C -0.59 + 9.67j;
    constant_impedance_B 221.9+104.43j;
    constant_power_A 42000.00+21000.00j;
}
```

##### Physical Load Models

Physical load models are based on a physical process. Processes can include: HVAC, energy storage, and thermal processes.

```
object freezer {
    size random.uniform(20,40); //Storage volume of the freezer
    thermostat_deadband random.uniform(2,3); //The 'slack' in the
        thermostat, and the temperature to cool the freezer
    setpoint random.uniform(10,20); //The temperature the thermostat is
```

```
        set at to stay colder than
UA 6.5; //The relative heat loss of the freezer
power_factor 0.95; //The power factor
rated_capacity (size * 34.0); //Cooling capacity of the freezer
        under optimum conditions.
}
```



# Impacts of smart meters on electrical grid

In order to examine the benefits of the project, we used the GridLAB-D simulation environment to perform in-depth simulations on representative technologies. The unique structure of GridLAB-D allows the efficient evaluation of complex emerging technologies such as voltage optimization and demand management.

The technologies deployed can be classified in one of two categories: direct and enabling. Direct technologies are those that provide direct benefit to the system (Distribution Automation (DA), Demand Response (DR), Energy Storage (ES) and Distributed Generation (DG)). Enabling technologies are those that may not provide a direct benefit to the system, but they enable other beneficial technologies. (Smart Meters, Communication Infrastructure and Human Machine Interface) [21].

## 5.1 Domaines Technologiques de la Réponse à la Demande

Demand Response (DR) can be defined as changes in electric usage by consumers in response to changes in electricity prices or incentive payments designed to induce changes in consumer consumption patterns[21]. In general, this includes a broad range of pricing programs and technologies including the deployment of Advanced Metering Infrastructure (AMI). Those that are currently deploying DR programs included various combinations of alternate rate structures and enabling technologies. Alternate rate structures included Time-of-Use (TOU), Critical Peak Pricing (CPP), and Critical Peak Rebates (CPR) or Peak Time Rebates (PTR). Five forms of demand response were selected as being appropriate for simulation in GridLAB-D. These included Time-of-Use with and without enabling technologies, Time-of-Use with a Critical Peak Pricing overlay, again with and without enabling technologies, and Direct Load Control.

### 5.1.1 Les systèmes de tarification

Time of Use (TOU) pricing breaks down the day into blocks of time that have a specific, pre-determined price associated with them. Typically, the ToU applies a price higher than the traditional fixed price to its peak block and a price lower than its off-peak block, in order to provide an incentive to shift some users to these periods. This is the simplest and most commonly used form of dynamic pricing.

Critical Peak Pricing (CPP) provides an answer to these criticisms. It is based on the same principles as a ToU, but allows for an emergency signal to be sent one day in advance to warn of the extreme peak period, or «event period». During these periods, the price rises significantly compared to the peak block rate, providing a strong incentive for the consumer not to consume at that time.

Real Time Pricing (RTP) is supposed to be the most efficient tariff as it allows the hourly transmission to consumers of changes in the price per kWh on the wholesale market. It then deals with the actual cost of electricity at the time it is consumed.

The Peak Time Rebate (PTR) differs from other tariffs in that its principle is not to charge an extra cost for peak consumers, but to remunerate reductions in consumption during these periods. As is the case with CPP pricing, consumers on PTR are informed one day in advance « of the event periods ». During these periods, a compensation is granted to the consumer for each kWh consumed below a reference load curve, or baseline. Apart from notifications, the consumer is subject to a ToU tariff. When an event is notified, the baseline reflects what should have been consumed compared to a peak block demand profile. The difference between this reference load curve and what is actually consumed represents the gain for the consumer.

### 5.1.2 Specific Implementation of TOU, CPP and DLC

It was determined that five cases would be investigated:

- TOU/CPP with enabling technologies
- TOU/CPP without enabling technologies
- TOU with enabling technologies
- TOU without enabling technologies
- DLC Direct Load Control

Enabling technologies were considered to be HVACs, hot water heater controls, and various forms of IHDs. Cases without enabling technologies were assumed to be equipped with programmable various forms of IHDs, and relied mainly upon direct consumer reaction to rate changes.

### 5.1.3 Mesures alternatives de TOU, CPP et DLC

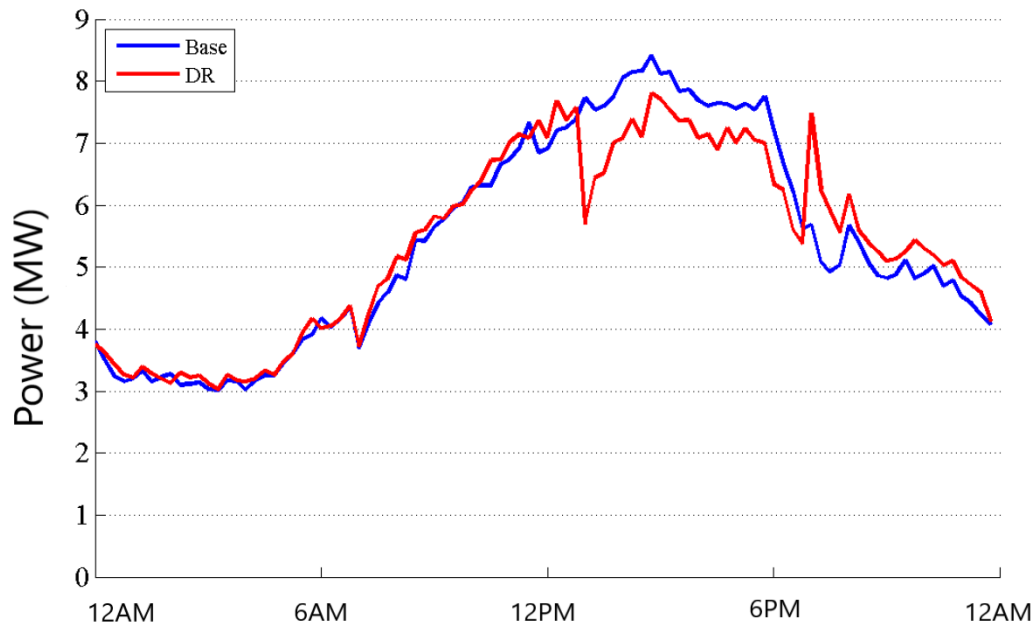


Figure 5.1: Times series comparison of TOU/CPP with enabling technologies on a peak day.

Notice that each of the three cases that use enabling technologies, initially shows a significant reduction in demand. DLC shows the largest initial reduction with CPP a close second, while TOU, even with automated equipment, shows far less reduction. As time proceeds and the HVAC systems return to new equilibrium operating points, the reduction in demand is less pronounced.

At the end of the peak period, when the CPP or TOU signal is released to a lower price level or the DLC command is discontinued, a significant rebound in the demand can be seen as the air conditioning systems simultaneously react to move the internal house air temperatures back to their normal settings.

The CPP (or TOU or DLC) signal not only acts in concert with the automated equipment to reduce the peak demand, but also has the effect of synchronizing the load during the release, diminishing diversity within the system.

Until diversity can be restored, the total load increases, often creating a new, larger peak than was previously seen. This is not seen with the cases without enabling technologies.

The enabling technologies that interpret the control signal (whether CPP, TOU, or DLC) into a change in load behavior tend to synchronize the response of all the units on the system, and the change happens at the same time.

Without the automated controllers, the change in demand relies upon the way people respond to the change in price, and people do not necessarily synchronize with a control signal. In a way, the non-automated system relies on human interaction to maintain

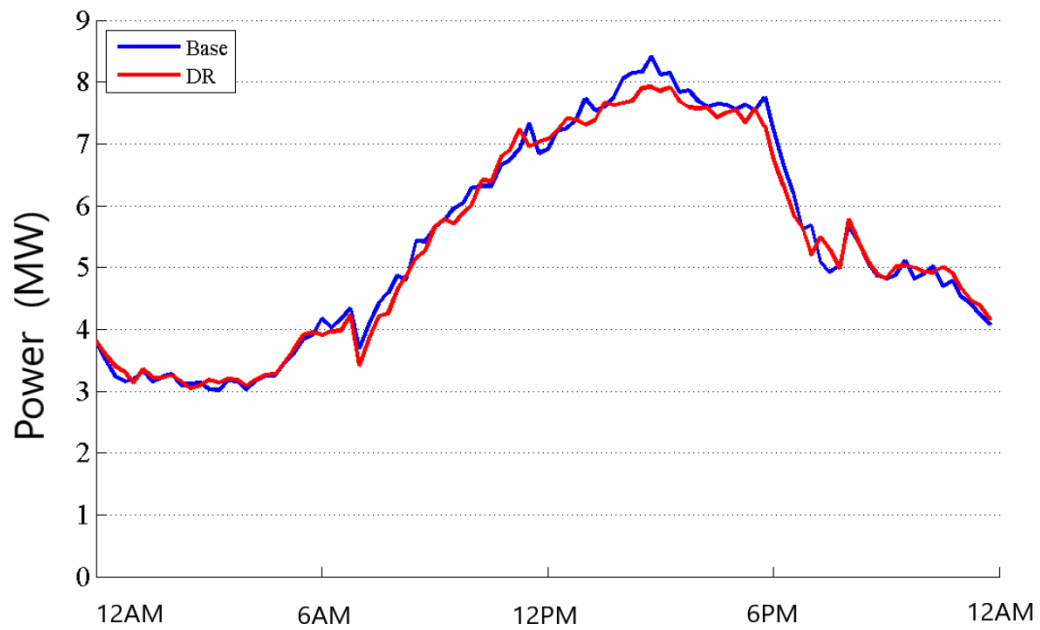


Figure 5.2: Times series comparison of TOU/CPP without enabling technologies on a peak day.

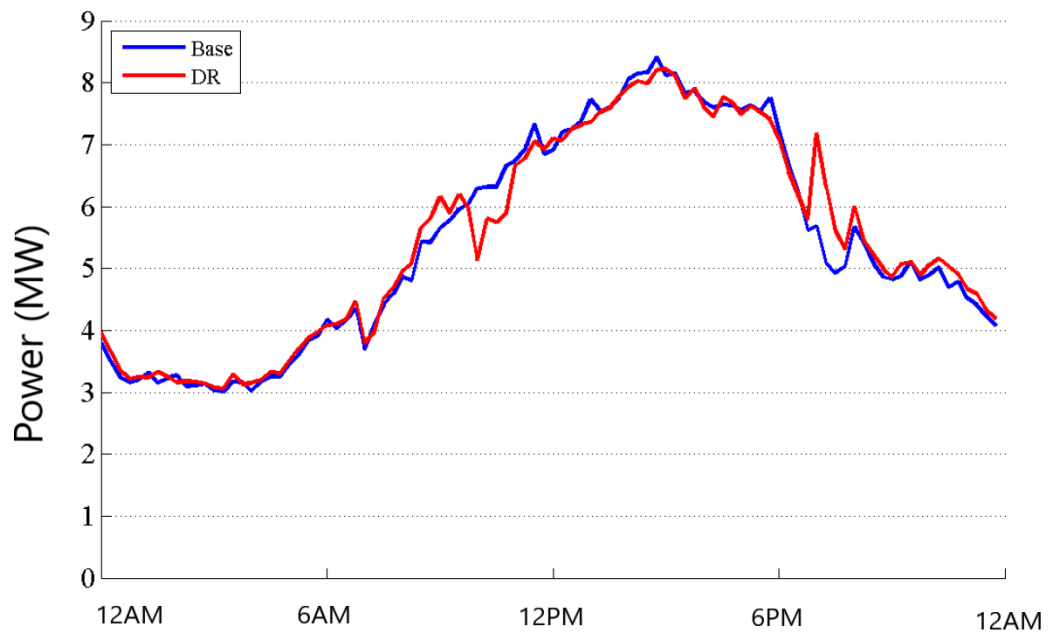


Figure 5.3: Times series comparison of TOU with enabling technologies on a peak day.

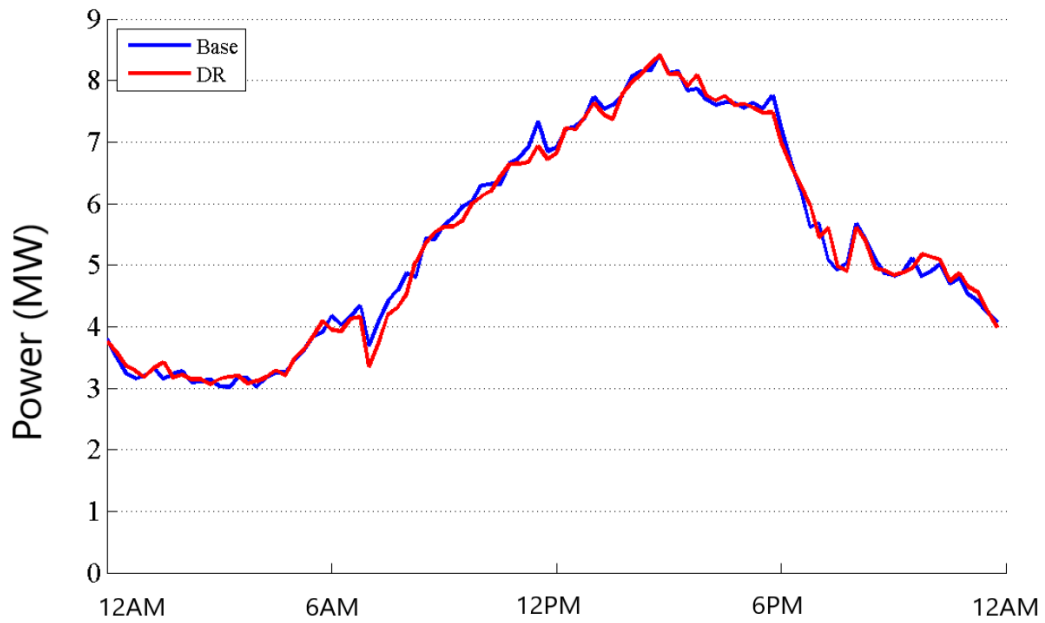


Figure 5.4: Times series comparison of TOU/CPP without enabling technologies on a peak day.

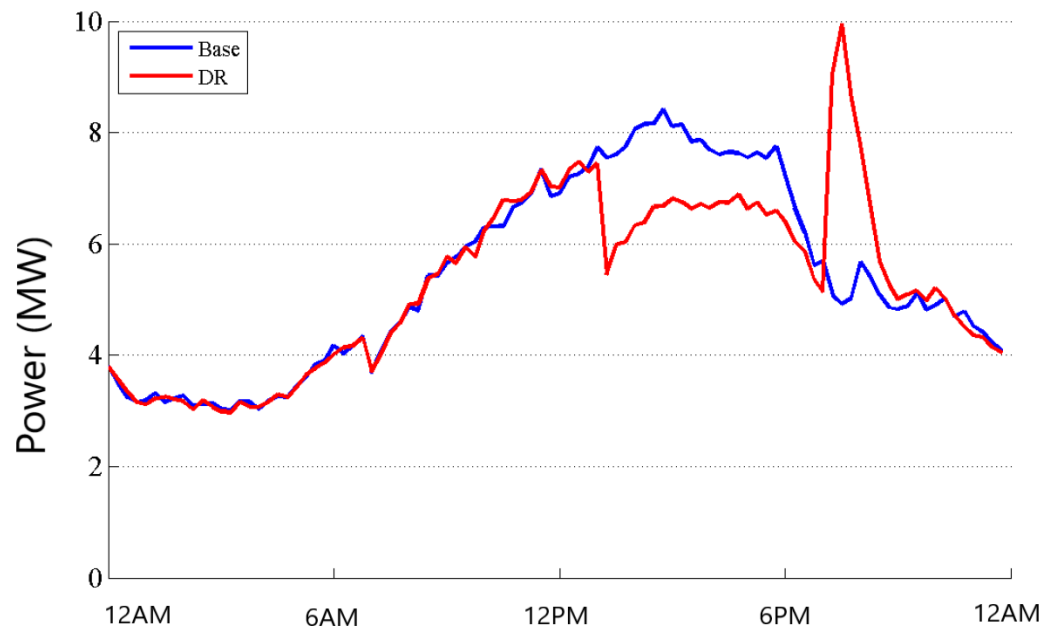


Figure 5.5: Times series comparison of DLC on a peak day.

diversity.

# Conclusion and future works

In this paper, we have considered the problem of DAP placement in AMIs of a smart grid. To this end, we have identified the top of the existing utility poles as possible DAP locations. We have formulated the placement problem as an integer program. Noting the relation to clustering problems, we have adapted the well-known K-means algorithm for obtaining suboptimal solutions to the placement problem. Numerical results for different wireless communication technologies and SM densities have emphasized the effect of transmission range of the wireless technology for data aggregation with relatively few DAPs. We note that we only considered single-hop communication, which is preferable for low latency transmission. Comparing to the brute-force search for finding the optimal placement, we have demonstrated for small-scale examples that proposed method can be used with a low time complexity to achieve a near-optimal cost. Finally, the GRIDLAB-D simulation environment is used to evaluate the technology deployed and its beneficial contribution to the technological areas of demand response.

During the course of this project, a wealth of new knowledge and skills were researched and acquired. However, a fairly visible lack of data was noted for the realization of the project in detail.

The project could be improved by modeling the missing feeders in SENELEC's distribution network. Thus other direct technologies such as Distribution Automation, Energy Storage and Distributed Generation could be studied through the GRIDLAB-D simulation environment.

## Liste of abbreviations, acronyms and symbols

<b>AMI</b>	Advancing metering infrastructure
<b>CAN</b>	Analog-to-Digital Converter
<b>SoC</b>	System on Chip
<b>AFE</b>	Analog Front End
<b>DSP</b>	Digital Signal Processing
<b>UART</b>	Universal Asynchronous receiver-transmitter
<b>CPU</b>	Central Processing Unit
<b>MCU</b>	Microcontroller
<b>CT</b>	Current transformer
<b>IGBT</b>	Insulated Gate Bipolar Transistor
<b>IEC</b>	International Electrotechnical Commission
<b>EN</b>	European Standards
<b>ANSI</b>	American National Standards Institute
<b>IEEE</b>	Institute of Electrical and Electronics Engineers
<b>PWM</b>	Pulse Width Modulation
<b>EEPROM</b>	Electrically-erasable programmable read-only memory
<b>NAN</b>	Neighborhood Area Network
<b>HAN</b>	Home Area Network
<b>WAN</b>	Wide Area Network
<b>PLC</b>	Power-line communication
<b>GSM</b>	Global System for Mobile Communications
<b>GPRS</b>	General Packet Radio Service
<b>SM</b>	Smart meter
<b>DAP</b>	Data Aggregation Point
<b>UC</b>	Utility Center



**SUN** Smart Utility networks  
**AI** Area of Interest  
**DOE** U.S. Department of Energy  
**PNNL** Pacific Northwest National Laboratory  
**DA** Distribution Automation  
**DR** Demand Response  
**ES** Energy Storage  
**DG** Distributed Generation  
**TOU** Time of Use  
**CPP** Critical Peak Pricing  
**RTP** Real time Pricing  
**PTR** Peak Time Rebate  
**DLC** Direct Load Control  
**HAVC** Heating, ventilation, and air conditioning

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