Electronics, Automatic control and Systems
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Identity

Composition of the team (or participants)

Team leader: S. Grieu, (PR UPVD)

Not permanent personnel:
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PhD students:
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Keywords
Modelling, diagnosis and control of systems, embedded systems, microgrids, energy production systems, components and materials characterization

Les thèmes
Microgrid efficiency and distributed generation management
Control and optimization of energy production systems
Characterization of components and materials

Collaboration

National

International
Contracts
- CIFRE (Industrial Agreement of Training through Research) Pyrescom/PROMES-CNRS, coordinator: Pyrescom
- CIFRE Cofely GDF-Suez/PROMES-CNRS, coordinator: Cofely GDF-Suez (Cylergie)
- CIFRE EDF R&D/PROMES-CNRS, coordinator: EDF R&D
- Partnership agreement CNES/PROMES-CNRS, Evaluation of commercial optic fibers, coordinator: PROMES-CNRS
- Partnership agreement Uniteck/PROMES-CNRS, Innovative architecture for converters/inverters, coordinator: Uniteck
- Project ANR DROID (DistRibuted Optical Fiber Dosimeter), coordinator: PROMES-CNRS
- Project OSEO PRIMERGI (Research program, engineering and maintenance for renewable energy and industrial management), coordinator: LAAS-CNRS
- Project Languedoc-Roussillon region RIDER (Research for IT Driven Energy Efficiency), coordinator: IBM Montpellier
- Project EUROGIA CSPIMP (Concentrated Solar Power efficiency IMProvment), coordinator: Thermodyn (General Electric Oil & Gas)
- Project PReSeD-CI EPINES-ASPA, coordinator: LPMCT, University of Abidjan, Ivory Coast
- Project CRE La Compagnie du Vent/PROMES-CNRS (Smart grid for new uses), coordinator: La Compagnie du Vent

References
12, 69, 92, 119, 120, 124, 164, 170, 171, 174, 186, 187, 208, 218, 239, 252, 253, 254, 258, 264, 274
Scientific report

INTRODUCTION

National and international context

The ELIAUS group (Electronics, Automatic control and Systems) has multidisciplinary activities. It is composed of automatic control and electronics engineers. Its experience in system optimization, in particular energy systems, is recognized both from a national and an international perspective. Its skills cover a wide range of scientific disciplines, including the identification and control of complex systems, the development of embedded systems and innovative measuring devices as well as the characterization of components and materials. From a methodological point of view, the ELIAUS group uses various tools, in particular artificial intelligence tools, signal and image processing tools and model predictive control structures. ELIAUS's activities are organized according to three thematic axes, defined as follows: (1) microgrid efficiency and distributed generation management, (2) control and optimization of energy production systems, in particular solar systems, and (3) components and materials characterization. For several years, the group takes part in national and international research projects together with key players in the energy industry (Cofely GDF-Suez, La Compagnie du Vent GDF-Suez, EDF, General Electric Oil & Gas, Acciona Energia…) and local companies (Pyrescom, Selecom, Uniteck…). The ELIAUS group wants to strengthen its activities related to the instrumentation and control of solar power plants (such activity has been initiated in 2012 through the CSPIMP research project, during which the group developed a sky imager as well as algorithms dedicated to the solar resource assessment and forecasting, with the aim of improving power plant operation) and the management of distributed generation, at the microgrid scale. The ELIAUS group is able to contribute in a significant way to these scientific fields.

Issues and challenges

Due to the rarefaction of fossil fuels and, as a result, an increasing distributed power generation, new management and supervision tools, allowing energy efficiency to be promoted, are necessary. At the microgrid scale (i.e. a building or a smart district), load shifting mechanisms, the control of appliances, in particular HVAC systems, energy storage, and the way the microgrid and the electricity grid interact are key concerns for the group. ELIAUS and La Compagnie du Vent work together in the development of a supervisor dedicated to the management of the energy fluxes in an industrial microgrid. Regarding the instrumentation and control of concentrated solar power plants, the development, in collaboration with EDF R&D, of a closed-loop aim-point strategy (for solar towers), allowing the disturbances impacting the solar field to be rejected, is being considered. Another short-term prospect could be adapting the sky imager as well as the algorithms developed during CSPIMP to improve the management of Acciona’s PV plants. In the next months, such plants will be equipped with storage systems. Regarding the characterization of components and materials, ELIAUS’s activities contribute to the efficiency of energy production and conversion systems. In this context, characterizing optic fibers in radiative environment, by measuring the radiation-induced attenuation, in particular to develop innovative sensors, is key. Characterizing dielectric materials using the thermal step method, as well as antimonide cells dedicated to solar concentration, aims at improving solar cell efficiency. New algorithms for the thermophysical characterization of materials, dealing with the detection of invisible defects and the aging of solar receptors, are currently being developed.

Scientific objectives

Knowledge models, semi-empirical models, as well as black-box models are developed, based in particular on artificial intelligence tools, according to the complexity of the studied systems and available information. Several control structures are considered, ranging from easily implantable approaches to advanced approaches allowing constraint problems to be solved. Due to its efficiency and because it is clearly in line with such problems, model predictive control, which is based on anticipating the behaviour of the considered system, is prioritized. Embedded systems are also developed, as well as innovative measuring devices and fault detection and diagnosis tools. Forecasting the energy resource, in particular the solar resource, using models based on the concept of time series or image processing algorithms is key in the development of management and supervision approaches.
Summary

1. Microgrid efficiency and distributed generation management
   1.1. Multi-scale modelling of the thermal behaviour of buildings
   1.2. Management of HVAC systems in non-residential buildings
   1.3. Energy resources management in a residential microgrid

2. Control and optimization of energy production systems
   2.1. Solar resource assessment for the management of CSP plants
   2.2. Supervision tool for solar photovoltaic facilities
   2.3. MPPT charge controller for lead-acid batteries, dedicated to low-power photovoltaic applications
   2.4. Predictive management of multi-energy district boilers

3. Characterization of components and materials
   3.1. Characterization of optic fibers in radiative environment
      3.1.1. Evaluation of commercial optic fibers
      3.1.2. Development of a distributed optic fiber dosimeter
      3.1.3. Optic fiber sensor based on Raman effect for the measurement of high temperatures in radiative environments
   3.2. Characterization of dielectric materials dedicated to photovoltaic applications
1. MICROGRID EFFICIENCY AND DISTRIBUTED GENERATION MANAGEMENT

The first thematic axis deals with managing the distributed power generation and microgrid efficiency. So, in this section of the document are presented (1.1) a generic procedure for the multi-scale modelling of the thermal behaviour of buildings, developed during the RIDER (Réseau et Inter-connectivité Des Energies classiques et Renouvelables) project, (1.2) a new and intelligent approach dedicated to the management of HVAC systems in non-residential buildings (Batnrj project) and (1.3) a predictive and multi-criteria approach for the management of the energy resources in a residential microgrid.

1.1. Multi-scale modelling of the thermal behaviour of buildings

Context

The large energy consumption in the building sector is problematic. So, the RIDER project has been initiated to show that Information and Communication Technologies (ICT) can be used to optimize the energy efficiency of buildings or groups of buildings. In that context, the ELIAUS group has taken interest in improving the automatic control of heating and cooling systems. Nowadays, on-off controllers and Proportional-Integral-Derivative (PID) controllers are commonly used. However, such controllers do not allow to take into account internal gains, buildings' inherent properties (like thermal mass), or constraints such as the price of energy. A way to overcome these limitations is to use model predictive control. This advanced method of process control allows anticipating future events and taking control actions accordingly. A model of the process is used to predict its future evolution and optimize the control signal. In the project, the ELIAUS group has been in charge of developing a procedure allowing the thermal behaviour of buildings to be modelled at different scales: the local scale (e.g. a room), the medium scale (e.g. several rooms or a floor), and the global scale (a whole building). In addition, the procedure is adaptable, without major change, to different buildings, in different locations. A consequence of these constraints is that the modelling phase becomes the main issue: the model has to be complex enough to be "multi-scale", while simple enough to be integrated to MPC; also, a priori knowledge must, of course, be avoided.

Materials and methods

To assess the feasibility of this problem, the ELIAUS group has first modelled an existing building using the EnergyPlus software. This step in the RIDER project has allowed performing various tests using the EnergyPlus model that are hard or even impossible to carry out on a real building. The building under study was built in 2008 and is home for the "Renewable Energy" department of the engineering school Polytech Montpellier. Located less than 100 m from the PROMES-CNRS laboratory, it has been the main source of data to achieve RIDER project's goals. The closeness between PROMES-CNRS and the engineering school Polytech Montpellier has permitted access and instrumentation of the site, while the proximity of the two buildings has allowed an efficient and fast maintenance of deployed hardware. Once the EnergyPlus model obtained, it has been validated in several steps: first the envelope during warm and cold seasons, then the building with its Heating, Ventilation and Air-Conditioning (HVAC) system. The results have been satisfying and we could then use this EnergyPlus model to study the feasibility of the problem. The second step has been to use the EnergyPlus model to develop a multi-scale modelling procedure. The chosen procedure, namely system identification, consists in searching an appropriate mathematical model for a given process using experimental data. No a priori information is mandatory. Here, the experimental data have been obtained from the EnergyPlus model. Using an EnergyPlus/Matlab co-simulation, numerous tests on the building have been performed, many of which would not have been possible on the real building. These experimentations have made possible to: (1) select the most influential input/output signals, (2) determine the minimal building excitation allowing to model the building's thermal behaviour, and (3) observe that a linear state-space model is able to reconcile simplicity with adaptability to different scales. Again, we have obtained satisfying results. Finally, the last step in this study has dealt with verifying the adaptability of the proposed modelling procedure. Since we did not have experimental data originating from different buildings, an EnergyPlus/Matlab co-simulation has again been used. It has made sure that the modelling procedure can be applied to various buildings, in various locations with different meteorological conditions, for various HVAC systems.

Results

Table 1 summarizes a part of the obtained results, for all the rooms in the building and four different locations (Perpignan, in France, Tampa, San Francisco, and Madison, in the United States). One can remark that, in most cases, the fit coefficient is higher than 70%. Although a decrease in performance has been noticed for extreme meteorological conditions (during the tested period, outdoor temperature in Madison was around -15°C), the results have been once again found satisfying.
Tableau 1: Evaluation of the building model, for different locations (fit, in %).

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1.2. Management of HVAC systems in non-residential buildings

Context

Within non-residential buildings, almost half of the energy consumption is due to Heating, Ventilation and Air-Conditioning (HVAC). In addition, older, oversized or poorly maintained systems may be using more energy and costing more to operate than necessary. As a consequence, new approaches dealing with energy resources management are needed to make HVAC systems more efficient. That is why, in that context, the Pyrescom Company and PROMES-CNRS have decided to go into partnership (Batnrj project). The aim of the project was to improve the operation of zoned HVAC systems, using model predictive control techniques, in order to minimize energy consumption and meet thermal comfort requirements. To this end, we have developed computationally tractable algorithms one can implement in an embedded system with limited resources and considered a non-residential building located in Perpignan (industrial estate "Saint Charles") as a case study. This study has focused on the three following rooms of the building: the offices on both floors and the manufacturing area. Each HVAC subsystem is managed by a local controller. Heat transfer between the rooms has been taken into consideration.

Materials and methods

In order for the proposed management strategy to be evaluated, the thermal behaviour of a real non-residential building has been modelled using the EnergyPlus software, which is able to perform accurate building simulations. It is a 1000 m² two-storey structure equipped with a zoned HVAC system. It faces south and agrees with the French Thermal Regulation of year 2005. Using the proposed predictive strategy, indoor temperature is controlled and the operation of all the HVAC subsystems is optimized by computing the right time to turn them on and off, in both heating and cooling modes (t\text{opt}). As a key point, thermal comfort constraints have to be met. The Predicted Mean Vote (PMV) index has been used as a thermal comfort indicator. The PMV index allows the thermal sensation of people in their environment to be evaluated. We have used feedforward artificial neural networks trained with the cascade-correlation algorithm in order to develop the controller's internal models and modelled the air (T_j^a, in the room j) and radiant (T_j^r, in the room j) temperatures as well as the electrical power consumed by the building's HVAC subsystems, for both operation modes (heating, from November 1 to March 31, and cooling, from June 1 to September 30) and the three considered rooms. The predictive approach is based on three blocks: a calculation block, an optimization block, and a decision block. It also includes a standard forecasting unit allowing outdoor temperature (T_{\text{out}}) and solar radiation (I_s) to be accurately forecasted (Figure 1) using previous day values corrected by current values. The forecasting horizon has been set to 8 hours. Room occupancy (O_j, for the room j) is known in advance and, as a result, can be anticipated easily. During occupancy periods, the calculation block defines at time step the temperature set-points for which the thermal comfort constraints are met in the three considered rooms. The optimization block deals with searching for the right time to turn the HVAC subsystems on or off in that rooms, with the aim of minimizing the total consumption of electrical power while satisfying the thermal comfort constraints. The HVAC temperature set-points are set by the decision block, according to the information provided by both the optimization and calculation blocks.
In order to solve the optimization problem (i.e. minimizing the consumption of electrical power in the three considered rooms of the building while meeting the thermal comfort constraints, by turning the HVAC subsystems on then off at the right time), we have decided for a genetic algorithm. So, at each time step, a subsystem can be turned on or turned off. Its operation mode can also be maintained as it is. The proposed strategy is robust and efficient. It is able to reject the disturbances and modelling errors (Figure 1).

**Results**

We have considered five non-predictive strategies, including four basic scheduling techniques, in order to highlight the benefits of the predictive approach developed for non-residential buildings equipped with zoned HVAC systems. The first technique (S1) is the simplest of all techniques: the subsystems operate all the time, including during non-occupancy periods. The second technique (S2) is based on a scheduler. It is used to stop the HVAC subsystems during periods of non-occupancy and to turn them on in the morning, two hours before people arrive at the building (i.e. at 6 a.m.). The subsystems are turned off when people leave (i.e. at 6 p.m.). Using the third technique (S3), the HVAC subsystems are turned off two hours before people leave the building (at 4 p.m.). Using the fourth technique (S4), the HVAC subsystems are alternatively switched on and off. In that case, the subsystems are one hour on and one hour off between 6 a.m. and 5 p.m. S5 is about pre-heating or pre-cooling the building during off-peak periods. With such a strategy, the HVAC subsystems operate between 5 a.m. and 7 a.m. (pre-heating or pre-cooling time) but do not operate between 7 a.m. and 8 a.m. then between 12 p.m. and 1 p.m. (i.e. during the lunch break). The simulation period is from November 1 to March 31 (heating mode) and June 1 to September 30 (cooling mode).

Table 2 summarizes the results. In order to evaluate performance regarding thermal comfort in the building, we have considered the percentage of time for which the PMV index is out of the desired interval [-0.5;+0.5] during occupancy periods (discomfort criterion). Whatever the operation mode, the predictive strategy (S6 in Table 2) offers the best compromise between thermal comfort and energy consumption. Using S6, and taking S2 as a reference (S2 is the technique currently used in the real non-residential building located in Perpignan we have modelled using the EnergyPlus software), energy consumption is reduced by 15% in heating mode and 5% in cooling mode. The thermal discomfort is reduced by 56% in heating mode and 50% in cooling mode.
1.3. Energy resources management in a residential microgrid

Context

The scarcity of fossil resources and an increasing demand in energy (leading to greenhouse gas emissions) are worldwide concerns. In this context, renewables are developing very fast and efficiently managing energy resources in the building sector, which is a big consumer of energy, is key. As a result, new approaches for the management of distributed power generation, allowing demand and supply of energy to be balanced and the injection to the grid to be controlled, are needed. So, a new approach to energy resources management in a residential microgrid (i.e. a building one can equip with energy production and storage systems) has been proposed and evaluated in simulation, using energy and economic criteria. Its aim is to improve energy efficiency as well as interaction with the electricity grid. The building operates in grid-connected mode. Two management strategies have been developed: a non-predictive strategy (which is the reference strategy) and a strategy based on anticipating the microgrid load, the electricity grid load and the local production of renewable energy. Whatever the strategy, the electricity grid status has been taken into consideration, using grid thresholds, with the aim of minimizing the impact of both the injection and extraction processes. As a key point, the energy production and storage systems one can equip the building with have been designed optimally. The considered energy mix has been evaluated and the impact of shifting building loads has been investigated.

Materials and methods

The thermal behaviour of the building as well as the energy production (photovoltaic solar panels and a vertical-axis windmill) and storage (batteries) systems have been modelled. The building is equipped with both an HVAC (Heating, Ventilation and Air-Conditioning) system and a tank for domestic hot water production. The home appliances are controlled by local regulators. Taking a look at the building load, we have highlighted the main posts for energy use. The overall thermal insulation of the structure agrees with relatively new French standards for buildings (RT2005). Note that we have calculated the thermal gains in each of the rooms. Within a given room, the temperature has been supposed to be homogeneous. In addition, because of their impact on energy consumption, the inhabitants’ lifestyle and habits have been taken into account through occupancy scenarios and temperature set points. Demand Response (DR) mechanisms have allowed some domestic loads to be shifted from on-peak (or part-peak) to off-peak periods. Jointly with the efficient management of the energy production and storage systems, DR mechanisms have been considered in order to limit the impact of the building on the electricity grid. We have proposed various energy and economic criteria to be used as performance indicators: in  

Production and consumption are balanced and underproduction. Only the predictive strategy is described here. As stated above, it is based on anticipating the microgrid load, the electricity grid load and the local production of renewable energy.

- **Overproduction.** The amount of renewable energy produced at time index k is higher than the instantaneous energy consumption. As a consequence, the local production covers all the energy needs of the building and no energy is extracted from the grid. The surplus of energy produced in situ is managed taking the electricity grid status into consideration as well as the ability of the microgrid to meet its needs during the next peak in energy consumption. In case of an on-peak period and if the microgrid is able to meet its energy needs, the surplus of energy produced in situ is stored in whole or in part.

- **Production and consumption are balanced.** All the renewable energy produced is consumed in situ. In opposition to what is observed with the non-predictive strategy (in that case, there is usually no interaction between the building, the electricity grid and the batteries), energy can be extracted from the grid, during part-peak or off-peak periods to charge the batteries or to meet future needs of the microgrid, if the local production is not able to cope with.

- **Underproduction.** The amount of renewable energy produced at time index k is lower than the instantaneous energy consumption. As a result, all the renewable energy produced is consumed in situ. In opposition to what is observed with the non-predictive strategy, energy is released from the batteries in case of on-peak periods. During part-peak or off-peak periods, energy can also be released from the batteries if the microgrid is able to meet its needs during the next peak in energy consumption. Otherwise, energy is extracted from the grid.
The rolling forecast horizon is variable. It is related to the current status of the electricity grid and the way it will evolve (a grid threshold lower than 30% is for an off-peak period, a grid threshold between 30% and 70% is for a part-peak period, a grid threshold higher than 70% is for an on-peak period). We have used observations corrected by outdoor temperature (for the load of the grid and the load of the microgrid), solar radiation and wind speed (for the local production of renewable energy) to forecast the behaviour of the system. The optimization problem is formulated as find \( P_{PV} \) (the PV panels peak power), \( P_{WT} \) (the wind turbine peak power) and \( E_{bat} \) (the rated capacity of the batteries) so that \( J_{ren} \) is maximized. \( J_{ren} \) is defined as a combination of the renewable energy coverage rate \( (\%_{ren}) \) and the percentage ratio of the renewable energy consumed to the renewable energy produced \( (\%_{rev}) \). \( P_{PV} \) is constrained by the available roof surface area. Regarding \( P_{WT} \), its maximum possible value is 20 kWp, according to the vertical-axis wind turbines one can find in the market and install on a residential building roof. Finally, \( E_{bat} \) is constrained by the size of the batteries.

Results

The simulation results highlight that, thanks to the optimal design (sizing) of the energy production and storage systems, using one of the proposed management strategies, one can meet the energy needs of the microgrid while minimizing its impact on the grid. Tables 3 and 4 summarize various noteworthy configurations, allowing energy self-consumption to be promoted and a high renewable energy coverage rate. As a result, a better match between supply and demand is observed. As an interesting result, the predictive strategy allows the management of the batteries to be improved. Using such a strategy, energy is injected to the grid and extracted from the grid at more favourable times (than with the non-predictive approach).

In addition, the combination of photovoltaic solar panels and a vertical-axis wind turbine has proven to be a viable energy mix option for residential buildings located in the south of France. Clearly, adding a wind turbine to the building produces a greater flexibility in the management of energy resources. However, the savings one can achieve by shifting some domestic loads from on-peak (or part-peak) to off-peak periods are limited.

### Table 3: Noteworthy configurations. Configurations 1 and 4: predictive strategy. Configurations 2 and 5: non-predictive strategy, for a grid threshold set to 70%. Configurations 3 and 6: non-predictive strategy, for a grid threshold set to 30%.

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<th>Configuration</th>
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<th>( E_{bat} ) [kWh]</th>
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### Table 4: Noteworthy configurations. Configurations 1 and 4: predictive strategy. Configurations 2 and 5: non-predictive strategy, for a grid threshold set to 70%. Configurations 3 and 6: non-predictive strategy, for a grid threshold set to 30%.

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</table>
2. CONTROL AND OPTIMIZATION OF ENERGY PRODUCTION SYSTEMS

The second thematic axis is about controlling and optimizing energy production systems. So, in this section of the document are presented works dealing with (1.1) assessing the solar resource, from images provided by a sky imager, for the management of CSP plants, (1.2) developing a supervision tool for solar photovoltaic facilities, (1.3) developing a MPPT charge controller for lead-acid batteries, dedicated to low-power photovoltaic applications and (1.4) managing multi-energy district boilers equipped with thermal storage systems.

2.1. Solar resource assessment for the management of CSP plants

Context

In recent years, solar power generation has developed fast. This can be explained by state subsidies, new technologies and the potential of solar power for large-scale deployment: in six hours, deserts in the world receive as much energy as the annual consumption of the world population. Two main technologies based on solar energy are currently available: solar photovoltaics (solar PV) and Concentrated Solar Power (CSP). Although the total capacity installed for electricity production using PV technologies is clearly higher than the one using CSP technologies, CSP plants can be easily equipped with storage systems and, as a result, power generation can be more flexible than in PV plants. This will be a key point in the development of the CSP sector. However, despite a promising future, a lot of challenges have to be addressed to make such technologies competitive against conventional (but more polluting) technologies. That is why this scientific domain, in which PROMES-CNRS is involved, is expanding strongly. The work presented here is part of the European project CSPIMP (Concentrated Solar Power efficiency IMProvement). Its aim is to improve plant efficiency by developing better procedures for steam turbine start up cycles and maintenance activities as well as proposing advanced plant control schemes. Among the different challenges pointed out by this research project, the solar resource assessment and forecasting are essential tasks since they would allow a better real-time management of the solar field, and thus reduce the maintenance activities, while improving the expected benefits. As a result, a solar resource assessment and forecasting tool has been developed for the management of CSP plants, in particular the parabolic trough power plants of Acciona Energia.

Materials and methods

First, a study of the way in which solar radiation and the atmosphere interact has been carried out. The main conclusion is that DNI (Direct Normal Irradiance) can be decomposed into a determinist component (the clear-sky DNI) and a stochastic component (the clear-sky index). This is the starting point in the assessment and forecasting of the solar resource. So, we have focused first on assessing and forecasting the clear-sky DNI. Such a task has required the development of a tool for the detection of clear-sky DNI data. Such a tool takes advantage of the low intraday variability of atmospheric turbidity in order to decide if a new DNI measurement is “clear sky” or not. We have considered two experimental sites: Perpignan and Golden, in the USA. In case of a clear sky, the plant operator can optimize its degree or latitude and the plant can be operated in an optimal way. Otherwise, in case of a cloudy sky, the operator is often willingly overestimating the clear-sky DNI in order to prevent possible damage to the plant. In that case, a precise evaluation of the clear-sky DNI is necessary so as to control the risks and operate as close as possible to the optimal operating conditions. That is why a model of the clear-sky DNI has been developed. Such a model is based on both the atmospheric turbidity coefficient proposed by Ineichen in 2002 and the last known clear-sky situation. Once the operator is able, at every moment, to know or estimate the clear-sky DNI, its intraday forecasting is convenient, in particular with the aim of anticipating the impact of a moving Sun on DNI. The forecasting methodology is identical to the estimation methodology.

Regarding both the analysis of the cloud cover and forecasting of the clear-sky index, a sky imager has been used. Resorting to this device is the consequence of a detailed study dealing with the specific needs in the project and the existing technical solutions in industrial vision. During the project, we have developed three PSI (PROMES Sky-imager). The first PSI has allowed the ELIAUS group to become familiar with the problematics and constraints related to the assessment of the solar resource using a sky imager. This first PSI is still in operation.
The second PSI is a failure because it does not provide any answers to the limitations of the PSI 1. As a result, it has been replaced by the PSI 3 which is able to produce HDR (High Dynamic Range) images (Figure 2).

With such a device, one can detect highly exposed clouds and, in the end, evaluate the luminous gradient in the circumsolar area. In particular, this gradient impacts the optical performance of the solar field.

Its assessment could allow the operator to estimate in a precise way the real amount of solar energy collected by the receptor and, consequently, improve its production.

So, the PSI 3 is a multifunctional device, helpful in the management of a CSP plant. Based on such an analysis, Acciona has decided for a PSI 3 for the CSP plant of Palma del Rio II, in Andalusia (Spain) (Figure 3).

Using the pictures taken by the PSI 1 and 3, various algorithms dedicated to cloud detection and cloud motion estimation have been developed. Regarding the detection of clouds, most of the existing solutions have difficulty with thin clouds and the circumsolar area. Indeed, thin clouds are detected as clear sky and the circumsolar area is detected as a cloud, resulting in a bad estimation of the cloud cover and a bad intraday forecasting of DNI. To solve this problem, a cloud detection algorithm has been developed. This algorithm is based on clear sky images generated using a formulation of the sky luminance distribution specially developed to solve the problem of the circumsolar area. Finally, a study dealing with estimating the cloud motion has been initiated. We have decided for a block-matching algorithm and a spatial and temporal filtering process, in order to evaluate the mean cloud motion. Based on that, the intraday forecasting of DNI, using a sky
imager, has been initiated. So, an easy determinist model based on the cloud fraction has proven to be able to be more accurate than a persistent model from a horizon of 23 minutes.

Results

Using the clear-sky DNI model, based on both the atmospheric turbidity coefficient proposed by Ineichen in 2002 and the last known clear-sky situation, the mean absolute error is lower than 40 W/m², over the tested period (one year for both the Perpignan and Golden sites). Regarding the clear-sky DNI forecasting, the mean quadratic error is about 20 W/m², for a forecasting horizon of 30 minutes. Concerning the intraday forecasting of DNI, using a sky imager, the mean quadratic error is about 180 W/m², again for a forecasting horizon of 30 minutes. It is about 190 W/m² using a persistent model (for the same horizon). Such a result is modest but encouraging because there are a lot of areas for improvement. Now, the main problem to solve is related to the stray reflections taking place into the optical system. Indeed, these reflections deteriorate the quality of the HDR images, misleading most of the developed algorithms. Once this problem will be solved, it will be possible to increase the filter density and, as a result, the image dynamic range. So, the Sun will be observed without saturating pixels, a new algorithm for the detection of clear-sky situations will be developed, and the luminous gradient in the circumsolar area will be studied with precision. In addition, activities related to the intraday forecasting of DNI will continue. In a medium- and long-term perspective, possibilities related to the measurement of GHI (Global Horizontal Irradiance), DNI, and DHI (Diffuse Horizontal Irradiance) using images provided by the PROMES Sky-Imager have to be evaluated. Carrying out a study dealing with stereoscopic vision is also considered in order of being able to determine the altitude of the clouds and realize a spatial forecasting of DNI. A step forward in the optimization of the parabolic trough power plant will be to adapt in real time the flow rate of the heat transfer fluid, based on the distribution of DNI on the solar field.

2.2. Supervision tool for solar photovoltaic facilities

Context

Due to various changes in the feed-in tariff for photovoltaic (PV) electricity, such electricity is more and more expensive. As a consequence, the payback period for solar PV facilities is getting longer and longer. An efficient supervision system can contribute to limit the production losses, optimize performance, and reduce the payback period. The study presented here, as part of the PRIMERGI (Programme de Recherche, Ingénierie et Maintenance pour les Energies Renouvelables et leur Gestion Industrielle) project, has focused on developing, testing and implementing a data acquisition system dedicated to solar PV facilities connected to the electricity grid. Using the collected data, a fault detection approach has been developed. It is dedicated to the management and supervision of such facilities. So, using this approach, the photovoltaic production can be evaluated in real time.

Materials and methods

Two photovoltaic facilities, the first one in Perpignan (PROMES-CNRS) and the second one in Toulouse (LAAS-CNRS, Laboratoire d’Analyse et d’Architecture des Systèmes), have been considered in this study. In Perpignan, the PROMES-CNRS facility is composed of three photovoltaic fields, connected thanks to five inverters. Its power is 14.5 kWp. Since 2012, LAAS-CNRS has in Toulouse a building dedicated to energy optimisation and ambient intelligence. Ambient intelligence refers to electronic environments that are sensitive and responsive to the presence of people. The building is equipped with three photovoltaic fields of 720 m², for a total power installed of 100 kWp. Inverters are equipped with acquisition systems. Using data collected in Perpignan and using Matlab, a model has been developed for estimating the sunlight received by a tilted photovoltaic field from GHI (Global Horizontal Irradiance). The energy analysis of both the Perpignan and Toulouse facilities has allowed evaluating performance as well as the operating losses. These studies have highlighted that one can consider the current-voltage curve (or I-V curve) of the PV generators, which is an important source of losses, as an evaluation tool. So, the proposed fault detection approach is based on using the acquisition system for power measurements and analysing the current-voltage curve.

Results

Regarding the sunlight model, in case of a partly cloudy sky, the mean relative error is lower than 20%. In case of a totally cloudy sky, the error is higher. Thanks to the different analyses we have carried out, a complete and efficient fault detection methodology has been developed. Using this methodology, the PV production can be optimized. The user is informed in real time in case of a fault, including its type and localization. Shading, inverter or acquisition system failures, and the activation of one or more by-pass diodes can be detected.
2.3. MPPT charge controller for lead-acid batteries, dedicated to low-power photovoltaic applications

This research and development activity has dealt with implementing charge controllers for low-power applications in remote sites. Lead-acid batteries are still widely used due to their low cost and ease of manufacture. Despite these advantages, disadvantages are equally remarkable: a short life and a high sensitivity to incorrect operation (in comparison to Li-ion batteries). In other words, the life of a lead-acid battery is significantly related to charging and discharging parameters. Therefore, it is mandatory to have available devices that will ensure the proper charging of a battery and are able to restore it, if sulfation occurs (in case of a deep discharge). These devices are called "charge controllers" or simply "chargers". The main goal of the work has been to increase the life span of lead-acid batteries and improve the efficiency of the electrical conversion chain. To reduce the charging time, it is recommended to use current pulses in the final stage of the load (80 to 100%). The pulsed current reduces the ionic imbalance (in the charge pulse current, diffusion optimizes the distribution of ions in the electrolyte volume and the current density increases). The dissipation of heat lowers the temperature in the battery, slows the growth of grains in the active material and decreases the development of the corrosion layer during cycling. This leads to an increase in life span. In the pursuit of the maximum power point, the P & O (Perturb and Observe) algorithm has been used. The architectures used are Buck, Boost or Buck-Boost architectures. Experimental results have shown yields above 80% for an electrical conversion chain not fully optimized at the moment.

2.4. Predictive management of multi-energy district boilers

Context

Because reducing the consumption of fossil energy, and the associated greenhouse gas emissions, is mandatory, Cofely GDF-Suez (now ENGIE) tries to optimize the performance of its multi-energy district boilers. These plants are connected to local heat networks for thermal energy distribution (heating and hot water). They use wood and gas or fuel oil as combustible. Usually, the boiler units are not well sized and, as a result, one could optimize performance thanks to a better use of renewable energy. Such an optimization can lead to a better match between demand and heat supply. Clearly, Thermal Energy Storage (TES) is an interesting option in the search for an optimized operation of the wood boilers equipping the plants. Indeed, at a reduced rate of productivity, their energy efficiency is low. In addition, wood boilers are not able to respond to sudden changes in power. As a consequence, adding a hot water tank to a multi-energy district boiler equipped with one or more wood boiler units seems to be a good option to smooth its daily operation. However, the storage and release processes have to be managed in a good way, based on immediate and future energy needs and the status of the boiler units. That is why Cylergie, the research and development centre of Cofely GDF-Suez, has united with PROMES-CNRS with the aim of developing a tool dedicated to the design and predictive management of thermal storage tanks.

Materials and methods

First, the operation of a multi-energy district boiler has been modelled. The proposed model is generic and, as a result, easy to adapt to different plant configurations. In order to investigate the main factors leading to thermal losses, a model describing the thermal stratification process that takes place in the hot water tank has been developed and validated using experimental data. A parametric study has allowed the impact on the thermal losses of the main geometric and meteorological characteristics to be evaluated. Let us remember that efficiency is related to the ability of a hot water tank to keep the thermal energy initially stored. So, in order to minimize the thermal losses, the tank has to be well insulated. Then a design (sizing) tool, based on a sequential management strategy, has been developed. Such a strategy allows the operation of the boiler units, as well as the quantity of energy to be stored or released, to be defined at each time step, according to the power demand ($P_{net}$), the characteristics of the boiler units, and the volume of the tank. This phase of the work has allowed the development of a tool for the design (sizing) of thermal storage tanks likely to be added to multi-energy district boilers. The tool is currently used by Cylergie to evaluate the impact of TES. Various energy and economic criteria have been defined. Finally, a management strategy based on model predictive control has been proposed. Using such a strategy, an objective function, expressed from both the wood power ($P_{wood}$) and the gas power ($P_{gas}$), is minimized. At each time step, a forecasting tool has been applied. The strategy, the power demand has to be forecasted over the next 24 hours. As a result, a forecasting tool has been developed. It is based on the concept of time series and uses a wavelet-based multiresolution analysis as well as feedforward artificial neural networks. Such an analysis allows a signal of high variability to be decomposed into approximations (i.e. low-frequency coefficients) and details (i.e. high-frequency coefficients) using a bank of filters composed of low-pass and high-pass filters. The main idea behind such an approach is to replace the forecasting of an original time series whose variability can be high by the forecasting of its wavelet coefficients (of lower variability).
Each coefficient is forecasted using an artificial neural network and the inverse transform allows the signal to be rebuilt. The proposed strategy is robust and efficient. It is able to reject the disturbances and modelling errors (Figure 4).

Figure 4: Block diagram of the predictive strategy proposed for the management of multi-energy district boilers equipped with thermal storage systems.

Results

Both the sequential and predictive strategies have been applied to a multi-energy district boiler located in Cernay, a northeast city in France (in the Bas-Rhin region). Table 5 summarizes the performance of such strategies. Taking the performance of the multi-energy district boiler without energy storage as a reference, the predictive strategy is clearly the best. The results highlight that, whatever the strategy, adding to the plant a thermal storage tank, if it is well designed, is economically viable. The consumption of fossil energy is minimized and, as a result, the same remark applies to the greenhouse gas emissions. Table 5 highlights that adding to the plant a 200 m$^3$ tank managed using the sequential strategy allows a significant economic gain (480 k€) during its 24-year operating period. The wood coverage rate is higher than 90%. In addition, thermal energy storage allows the decrease in the wood coverage rate to be limited, in case of an increase in the power demand. Using the predictive strategy, the tank is better used and, considering the same volume, the payback period is lower than when using the sequential strategy. The global economic gain is reduced of about 140 k€ over the 24-year operating period of the plant.

Table 5 Performance of the sequential and predictive strategies proposed for the management of multi-energy district boilers equipped with thermal storage systems (Cernay, Bas-Rhin).

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Référence</th>
<th>Séquentielle</th>
<th>Prédicitive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal volume of the tank [m$^3$]</td>
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<td>200</td>
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<tr>
<td>Cost of the tank [k€]</td>
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<td>98</td>
</tr>
<tr>
<td>Payback period [year]</td>
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<td>4.07</td>
<td>3.29</td>
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<tr>
<td>Global economic gain [k€]</td>
<td>n/a</td>
<td>478.67</td>
<td>615.21</td>
</tr>
<tr>
<td>Wood coverage rate [%]</td>
<td>86.12</td>
<td>93.76</td>
<td>95.88</td>
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<tr>
<td>Wood coverage rate [%] with Pnet + 10%</td>
<td>75.65</td>
<td>82.27</td>
<td>85.52</td>
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<tr>
<td>Wood coverage rate [%] with Pnet + 20%</td>
<td>61.01</td>
<td>65.36</td>
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</table>
3. CHARACTERIZATION OF COMPONENTS AND MATERIALS

The third thematic axis is about characterizing components and materials. So, in this section of the document are presented works dealing with (1.1) characterizing optic fibers in radiative environment and (1.2) characterizing dielectric materials, using the thermal step method, dedicated to photovoltaic applications.

3.1. Characterization of optic fibers in radiative environment

3.1.1. Evaluation of commercial optic fibers

The ELIAUS group works with the French space agency (CNES) on the evaluation of commercial optic fibers. Undertaken studies permit to identify relevant devices, as well as their optimal operating wavelengths, to work in a radiative environment. Through successive contracts, this lasting collaboration allows the constant development and upgrade of the experimental setup that measures Radiation-Induced Attenuation (RIA) in tested fibers. These fibers can be chosen in response to a specific need of an ongoing space project or selected amongst the various components available on the market in a prospective logic. Samples are either bought or obtained free of charge, in exchange of irradiation results, via partnerships with fiber manufacturers, distributors or end users. Over the concerned period, optic fibers from Draka (Prysmian Group) have been characterized. Experimental measurements obtained from the beginning of the activity are now gathered in an online database (http://radfiber.univ-perp.fr) called RadFiber. Since its public opening in June 2015, 56 login requests coming from 45 establishments have been received. The list includes laboratories, institutes, and national or international companies. By now, eleven commercial fibers have been irradiated through 18 spools; maximum dose reaches 495 Gy; dose rate domain ranges from 2.98 to 10 Gy/h; certain fibers have been tested at multiple temperatures (-50, 17 and 60 °C); database contains 198242 RIA entries.

3.1.2. Development of a distributed optic fiber dosimeter

Following the ANR call for proposal RSNR (Recherche en Sûreté Nucléaire et Radioprotection), the ELIAUS group received in May 2013 a positive answer for carrying out the DROÏD project. This 260 k€ project, in collaboration with LPMC (Laboratoire de Physique de la Matière Condensée, University of Nice, France), aims at developing a distributed optic fiber dosimeter. This dosimeter will not use a scintillating fiber whose principle does not allow for the localization of the irradiated section. It will be based on the fiber Radiation-Induced Attenuation (RIA), read by optical reflectometry which in essence realizes a distributed localized measurement. The dosimeter is illustrated by Figure 5.

![Figure 5: Distributed optic fiber dosimeter.](image)

Preliminary calculations aimed at estimating the dosimeter sensitivity have demonstrated the necessity to develop a fiber much more radiation sensitive that typical fibers dedicated to telecommunications. To reach this goal, a bibliography on the radiation response of optic fibers has been achieved. The purpose of this work was to establish links between, on one hand, fiber composition and fabrication parameters and, on the other hand, the RIA. 137 papers have been selected, analysed and synthesized in a 20-page report. This document ends by defining 4 fiber compositions. For the first irradiation campaign of the project, LPMC has proposed to select from their list of already fabricated fibers those whose composition was the most likely to induce a high RIA. Eleven spools have been delivered to PROMES-CNRS and then prepared for the irradiation campaign that took place at the ONERA (in Toulouse). At the end of it, the large amount of data has required software development in order to quickly compute the RIA for each fiber sample. Data analysis has revealed the following points. Regarding the development of a sensor presenting some fading (i.e. a partial annealing of radiation-induced defects), the first campaign has permitted to identify two fibers potentially interesting thanks to their high RIA (about 0.01 dB/m after 0.1 Gy at a wavelength of 850 nm). Concerning the avenue without fading, it has been observed that the five fibers containing phosphorous (P) (which is an element able to inhibit fading) have all shown significant annealing after the irradiation stop.
Developing a fading free sensor thus requires incorporation of more phosphorous into the silica matrix. The second campaign will then focus on several types of fiber manufactured with high P concentrations. The operation of the dosimeter requires an accurate modelling of the sensor radiation response as a function of dose rate, temperature and optical power carried by the waveguide. A first step in the modelling process is to determine an adequate experimental procedure intended to reap data containing rich enough information to assure modelling success. To do so, from the knowledge of the radiation effects on glasses, several fake data sets have been generated to reproduce the behaviour of an optic fiber irradiated by ionizing rays. These data have then permitted to proceed with classical tests and explore various simulation scenarios.

3.1.3. Optic fiber sensor based on Raman effect for the measurement of high temperatures in radiative environments

For about 10 years, EDF R&D has been working on qualifying chains to measure temperatures via an optical fiber interrogated by a Raman remote access facility. Today, using such distributed measurement finds interest in the nuclear domain thanks to the spatial resolution improvement of the remote access facility. In the framework of a CIFRE Ph.D., started in April 2014, EDF R&D and PROMES-CNRS lead studies with multiple objectives: determining the key parameters impacting the temperature measurement by Raman effect in a high temperature and radiative environment, defining the measurement system (type of optic cable, fiber coating, etc.) for this environment, and proposing a method to calibrate the remote access facility. It has been firstly assessed that the temperature Optic Fiber Sensor (OFS) should withstand a gamma dose rate of 0.6 Gy/h during 12 months (total dose of about 5 kGy) at 350 °C. New estimations, deduced from calculations with MCNP simulation software, precise that the sensor must undergo a total dose of 20 kGy (considering the primary gamma rays from N16 as well as the secondary rays). A first test took place on the Saphir platform of the Saclay CEA. The high dose rate of the Linac source has allowed reaching a total dose of 1 kGy on an OFS at room temperature. The experience feedback has shown that RIA has totally darkened the various tested fibers for a total dose less than 1 Gy at room temperature. A second test has been achieved on the Mega irradiation source of ONERA (Toulouse). The low chosen dose rate and the simultaneous high temperature heating of the OFS have permitted to get close to the real operating conditions. Results have demonstrated that RIA is too low to be quantified at high temperature up to a total dose of 0.2 kGy. The next irradiation campaign is designed to reach 20 kGy at high temperature.

3.2. Characterization of dielectric materials dedicated to photovoltaic applications

The objective of this study is to develop a new technique for the characterization of charges trapped in dielectric passivation materials deposited in a thin layer on the surface of photovoltaic cells. Dielectric thin films are commonly used in the manufacture of photovoltaic cells in crystalline silicon. These layers are needed to enhance the cell conversion efficiency by reducing the activity of recombinant defects which are present on the silicon surface. The aim via this passivation step is to increase the collection of carriers photogenerated by incident radiation in the silicon by increasing their lifetime. In PROMES-CNRS, dielectric thin films (nitride or silicon carbide, silicon oxide hydrogenated SICN:H) are deposited on the front and/or rear faces of photovoltaic cells using chemical deposition techniques assisted by plasma. They allow removing the silicon surface defects either by reducing the density of interface states (by chemically saturating dangling bonds) or by pushing the carriers (electrons or holes) away from the surface by field effect. In this work in progress, we focus on this second phenomenon. The field effect is induced by the presence of structure defects leading to positive or negative fixed charges. This field effect is necessary to achieve a better photovoltaic efficiency. We propose to use the thermal step method. This method is non-destructive and able to detect charges in volume. It is based on measuring and analysing a capacitive current generated by the propagation of a temperature wave in the material to be characterized.

The obtained results are compared with C-V measurements. To this end, we have deposited a metal electrode on the dielectric layer and get a Metal-Insulator-Semiconductor (MIS) structure (Figure 6). Preliminary results are encouraging and highlight the pertinence of the proposed approach for the characterization of dielectric materials dedicated to photovoltaic applications.

Figure 6 : The copper pad of the heat sink and the conductive tip (left), a sample placed on the radiator (right).