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Technical Report TA User Project

Smart Energy Grid Optimization with Multi-Agent Distributed Predictive Control

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Abbreviations

AMPC	Adaptive Model Predictive Control
BMPC	MPC-based controller for negotiation
CL	Closed Loop
DER	Distributed Energy Resource
DSM	Demand Side Management
ESS	Energy Storage System
MIQP	Mixed Integer Quadratic Programming
MMPC	Microgrid Model Predictive Control
MPC	Model Predictive Control
OL	Open Loop
PCC	Point of Common Coupling
PV	Photo Voltaic
QP	Quadratic Programming
RES	Renewable Energy Source
RMSE	Root Mean Square Error
SOC	State Of Charge
TES	Thermal Energy Storage

Executive Summary

Microgrids are the advanced trend of power networks for the future energy management to have reliable and energy efficient systems. This research addresses the problem of energy management in a typical microgrid through an MPC approach. Although, there are numerous strategies to improve the energy consumptions trend in the building sector, recent uses of demand side management (DSM) is proven to be a considerable way for achieving thermal and electrical energy saving. The main contribution of this research is to provide a comprehensive framework, based on a distributed Model Predictive Control (MPC), to minimize/maximize the cost/benefit of the microgrid while preserving user comfort. In detail, the research proposes two different scenarios to reach the goal exploiting the same hardware equipment of the lab and also software simulation. The optimization problems are formulated as mixed integer quadratic programing (MIQP) and quadratic programing (QP). MATLAB is used to solve the optimization problems to find the optimal solutions and also for the simulation of some missing components. Finally, experimental results show the accuracy and economic advantages of the proposed methods.

1 General Information of the User Project

User Project Title: Smart energy grid optimization with multi-agent distributed predictive control
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Host Infrastructure: ICCS-NTUA
Access Period: 16/07/2017 to 29/07/2017 and 24/11/2017 to 05/12/2017
User Group Members: Luca Ferrarini, Le Anh Dao, Soroush Rastegarpour, Alireza Dehghani Pilehvarani

2 Research Motivation

The need of integrating renewables to combat the global warming and gas emissions, while increasing the level of comfort of an increasing number of users in the world, is causing operational and behavioral challenges for the generating units, the electric system as well as the user attitude towards energy issues.

The strategy to tackle this problem is to reduce electricity losses and congestions by ensuring the energy demand as near as possible to producers. This idea gives the opportunity not only to save large amount of electricity losses in transmission, sub transmission and distribution grids, but also to reduce the congestion of grids, which comes to enhance the capacity of grid without infrastructural investment. Distributed and diffuse generations with the exploitation of renewable sources are practical means in center of governors' attentions in many European countries, which has been paving the way towards the microgrid concept. In order to manage efficiently the microgrid, suitable control startegies should be put in place through the exchange of signals among the many actors of a microgrid, thus giving rise to the smart microgrid concept.

In the proposed approach, a smart microgrid contains storage devices, smart buildings (i.e. energy flexible buildings, where the flexibility is induced by advanced control) and renewables (mainly PV, wind and hydro). Optimization approaches and algorithms are developed exploiting as decision variables the charge and discharge of the storage and the flexibility of the energy consumption. The cost function of the optimization problem is defined as a compromise between contrasting objectives, namely the minimization of the energy bill for the end user, the maximization of the profit for market operators, maximization of own production of energy, minimization of changes in the energy exchange profile in the day-ahead market. All the main economic and technical constraints are included inside the optimization problem in order to improve costs and power quality.

The above scenario is sketched in Figure 1. In our approach an hourly variation of electricity price is also considered, as well as costs related to devices operation, penalties related to trading activities with the markets as well as uncertainties in the system (e.g. RES production, end-users' demand profile). The complexity of considered problem pose an essential need for an advance optimization algorithm that can handle large amount of constraint and different cost function terms.

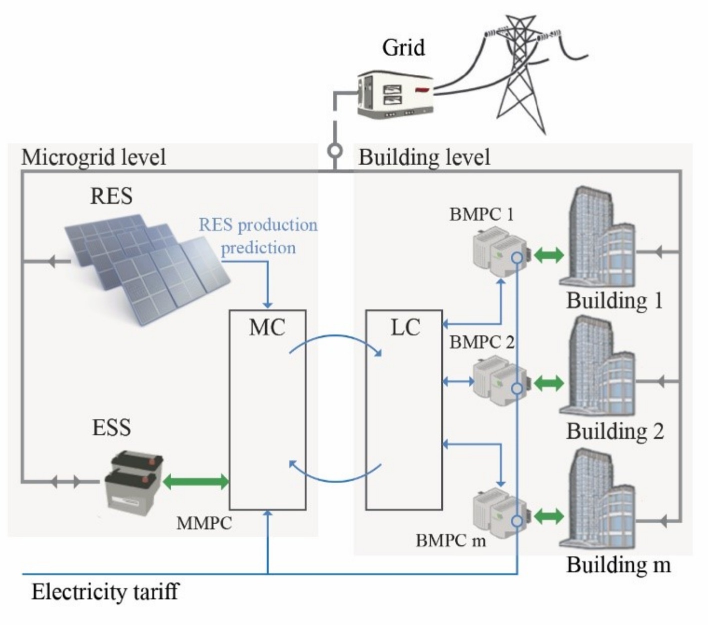

Figure 1: Compact layout of the considered microgrid and control system. A single switch connects the grid to the building (load), the ESS and the distributed RESs.

On the other hand, due to the growing energy demand in residential buildings, thermal energy control and overall power consumption reduction has drawn attention in microgrids and has become a hot research topic. Development of an energy management system to modify consumer's energy consumption patterns is a substantial solution toward this problem. Although, there are numerous strategies to improve the energy consumptions trend in building sector, recent uses of demand side management (DSM) is proven to be a considerable way for achieving thermal and electrical energy saving. DSM concept refers to all the actions which make a change in power demand behaviour in demand side, including shaping end user electricity consumption by modification of efficiency in heating devices, exploiting additional equipment and advanced controllers. Hence, recently there has been a growing interest towards Energy Storage Systems (ESS), particularly thermal energy storage (TES). TES gives the possibility to shape the demand profile in an economic way based on dynamic electricity tariff, by storing energy in thermal term during off-peak hours.

2.1 Objectives

As explained above, in this research we propose to adopt distributed MPC for energy management in a typical microgrid. In the following the main objectives are listed:

- Study and design of a new optimization algorithms for micro grid energy management
- Smart microgrid modeling with renewable sources, storage and smart buildings
- Optimal load flow through the microgrid
- Price-based demand response optimization
- Different scenarios, optimization cost and control settings are tested in simulation environment.
- Assess the direct benefits of this architecture compared to actual grid management policies and power dispatching algorithms through experimental implementation.
- Realization of distributed MPC approach

2.2 Scope

The report explains the scenarios that are tested in the lab which includes the theoretical explanation and the results. In both scenarios MPC technique is used to have the optimal solution for energy management for the considered microgrid. MPC is a popular control technique for large scale systems that can handle explicitly multiple constraints in the optimization problem. Additionally, another main advantage of MPC is use of prediction of the system future evolution starting from the current system state. On the other hand, strong computational requirements of MPC make its industrial application problematic to apply for large scale systems.

The distributed MPC approach can easily tackle this problem by dividing the system into some subsystems, each one endowed with its controller (agent) that can decide locally subsystem's control actions. In this way, we reduce the computational effort for each agent, and also improve reliability, scalability, etc. Actually, distributed model predictive techniques are seldom used in the electricity framework, and with limited formalization and generalization [1, 2, 3]. The proposed topology and control algorithms are verified in experiments in this project to demonstrate the feasibility.

3 State-of-the-Art/State-of-Technology

The increase in the cost of energy produced with conventional fossil fuels, not to mention the growing concern for the environmental problems related with their usage, has fostered the interest in alternative energy sources, such as Renewable Energy Sources (RES). Besides being cleaner, these energy sources can often be placed in the vicinity of the end users, thus reducing the energy losses related to electricity transmission. This entails a radical change in the structure of the energy system, where the electricity network includes many small and distributed generators, as opposed to few large generators. The concept of microgrids appears to be a promising solution to properly address this type of scenario. A detail definition of microgrids is still under discussion; however, microgrids can be seen as relatively small electricity networks, that can include any type of distributed energy resources, as well as consumption and storage elements operated in coordination to reliably supply electricity. As a consequence, different technical problems in national distribution grid are facilitated by solving them locally in individual microgrid. Microgrids can be connected to the grid at the distribution level through a Point of Common Coupling (PCC) or operated in “islanded” mode, where they do not use electricity supplied by the main grid.

Briefly, some of main advantages of microgrids can be mentioned as:

- Peak rebate which is a result of ICT technologies and optimization techniques
- Drastic reduction in fossil fuel use as a result of peak rebate and loss reduction
- Significant decrease in end-user blackout as a result of precise load forecasting and also efficient action in happening blackouts.
- Decreasing the investment for grid expansion as a result of load balancing
- Cost minimization for end-user and maximizing profit for RES producers in the context of high uncertainty on RES [4]

Besides of mentioned advantages, microgrids presents also some technical challenges in protection and control as follows [5, 6]:

- Economical and reliable operation of microgrids under the context of uncertainty on consumption, RES production as well as market price cause.
- Voltage and frequency control is critical in islanded microgrids as it is disconnected from the main grid.
- Seamless transition grid-connected and islanded modes.
- Protection coordination, fault current distribution as well as voltage control due to bidirectional power flows in microgrids integrated to DERs.

To obtain high performance in microgrids, besides the use of control technique, studies has suggested optimal use of ESSs and conventional DERs and deployment of demand response as two main sources of control [7 and the references therein]. In common between them is capability in changing power profile, by this way microgrids can compensate any physical imbalance and even enable participation into different power markets [4, 7, 8, 9]. While ESSs and DERs follow strictly requests from a controller as long as their technique constraints are satisfied, demand response program typically, in another way, is operated indirectly via inducing consumers through two main categories – Incentive Based Program and Price Based Program.

Accordingly, the development of optimal control solutions for microgrids has been the objective of several recent research endeavors, employing, e.g., heuristic algorithms [10, 11, 12, 13]. One particularly exploited methodology in this context is Model Predictive Control (MPC), which is well suited to deal with the large amount of constraints that have to be imposed in real time and the tight performance requirements associated to these systems (see [7, 14, 15] and references therein).

Basically, MPC based methods can be classified into three categories that are centralized, decentralized and distributed. As the matter of fact, the use of centralized scheme may not be able to apply in practical due to the large size of the system that raise significant problems in computation, communication burdens, reliability as well as scalability. These mentioned problems motivate the development of non-centralized scheme (i.e., decentralized and distributed schemes) that utilize multiple (predictive) controllers that carry out their calculations in separate processors. Distributed approaches can be divided into cooperative and non-cooperative schemes. Opposed to non-cooperative one where the local controllers have different, possibly conflicting objectives with or without considering all possible behaviors of the neighboring subsystem, the local controllers in cooperative methods optimize the same global cost function [16].

Regarding the control scheme, centralized scheme, distributed scheme and various settings of these two are considered in this specific field of study including [17, 18, 19]. In particular, the centralized control scheme has been studied in [11] where as the model of all involved components are supposed to known by the centralized controller. Even though the load model is not known by the centralized unit but only the size of the controllable load, it is not trivial to estimate this information in general during prediction horizon due to the dynamic of the controlled system (e.g., heating and cooling systems). Not to mention the scalability, computational burden, failure of single unit issues, etc., in the centralized scheme. More recent works have put more attention on the distributed MPC and hierarchical control schemes such as [18,19]. In [19], a two-layer control scheme based on MPC operating at two different timescales has been studied whereas the higher level following the centralized scheme to compute the set-points for the microgrid's component in the low-level controller. In this paper, some details on the markets (e.g., imbalance charge, difference in purchasing and selling tariffs) are neglected and the flexible load is not here considered. On the other hand, [18] employed a sequential distributed MPC on energy management problems in the microgrid, however some details are missing including the presence of RES, non-linear model of the ESS, difference in purchasing and selling tariffs.

4 Executed Tests and Experiments

In this project, the proposed control approaches are executed in MATLAB, which is then connected to the dedicated server to be implemented in real components. We propose to use two different distributed control approaches (cooperative and non-cooperative) for the energy management inside microgrid regarding MPC technique. The following sections provide general picture of the system, test plan, setup and procedure for proceeding the test.

4.1 System Description

4.1.1 Consensus based distributed MPC approach

The setting of the considered microgrid consists of 3 parts that are utility grid, the load (or (microgrid low-level layer) and the group of ESS, RES (microgrid high-level layer). Therefore, we propose a vision to the system to divide the microgrid into two layers with a hierarchical control to integrate the day-ahead market interactions down to control at user level. The overall control architecture is depicted in Figure 2.

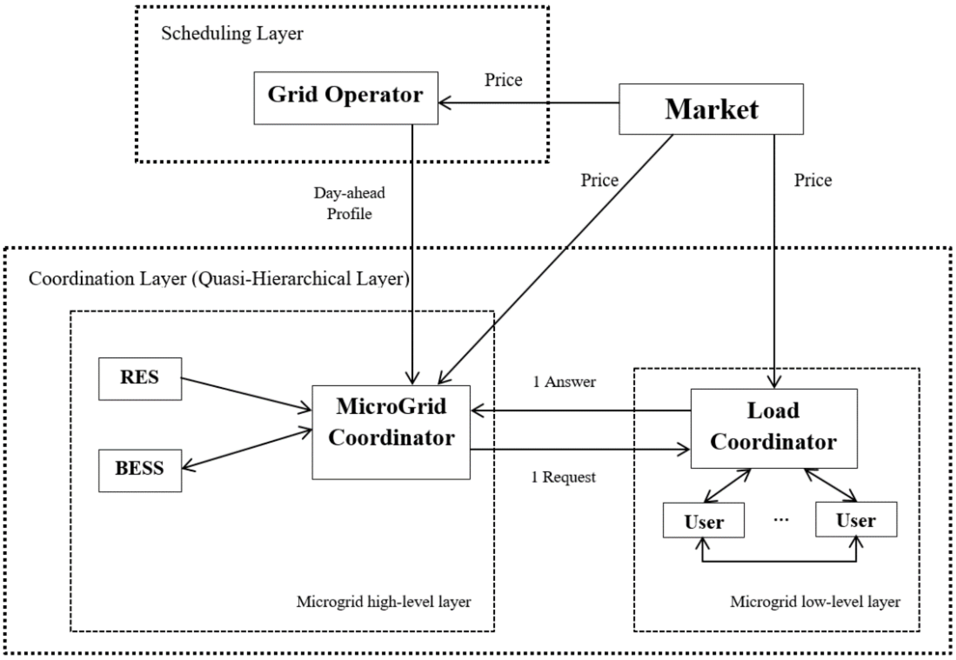

Figure 2:Proposed scenario for consensus based distributed MPC approach

In the proposed vision, the two layers are high-level layer and low-level layer. In the high-level layer which consists of solar panels, Energy Storage System (ESS) and utility grid, the ESS is controlled by a microgrid coordinator (MC). Microgrid coordinator (MC) is responsible to manage the microgrid energy flow to have an optimal operation regarding its constraints and objective in a cost-effective way to minimize the cost and maximize the benefit.

On the other hand, the low-level layer manages a group of residential thermal buildings through a load coordinator (LC). Each building is equipped with a controller to regulate the temperature, energy cost and also involving in the market when it is needed. In fact, LC behaves as an aggregator that *(i)* initially receives the request to change load profile from MC and then dispatches this information to the load controllers, *(ii)* receives the response from load controllers, *(iii)* computes (optimally) and distributes new load power profiles as a part of the proposed distributed algorithm, and iterates until an agreement is reached. More specifically, each building is equipped with a MPC-based controller for negotiation (denoted as BMPC) that works with the same sampling time as MMPC. As for communication between microgrid and Load level, at the beginning of each time instant, BMPC receive a request (i.e., maximum change of total local consumption) from microgrid. Then, following the iterative distributed MPC with a coordinator framework, the level of change for each of them is established by way of an interaction and negotiation process among the local controllers.

4.1.2 Non-cooperative distributed MPC approach

In this context, model predictive control approaches have been used for controlling of both load (a radiant-floor building) and energy management system of a complex real configuration of a grid-connected microgrid and energy market.

The proposed microgrid includes both electrical and thermal energy storage. Although using a thermal energy storage (TES) can have beneficial effects on energy saving, it makes the system much more complicated in terms of prediction and control.

One of the major problem in this control scheme is the nonlinear time varying behaviour of thermal storage due to the strong effects of return water flow rate on the tank dynamics. The main idea is to use a non-cooperative distributed adaptive MPC in order to minimize the energy consumption and maximize the comfort level in demand side. In this case, water flow rate and water temperature of the tank can vary freely to provide the adequate thermal energy for room heating system. An energy management system will be considered to manage the power distribution between grid and renewable resources to decline costs.

4.2 Test Plan

4.2.1 Consensus based distributed MPC approach

Three different experiments are planned during two separated period of the research stay. The first and second test focus on evaluating the overall algorithms during summer and winter period. On the other hand, the third one is tested during winter and the focus in on the distributed algorithm on the microgrid lower level. A bit more detail on these experiments are described as follows:

1) Ec1 experiment: Test the performance of the overall control architecture with PV during summer period in a sunny day and good prediction error (RMSE [%] is around 3.5%) and with no feedback from the measured PCC power to the microgrid coordinator (Open loop – OL).
2) Ec2 experiment: Test the performance of the overall control architecture with PV during winter period in a cloudy day with high prediction error (RMSE [%] is around 3.5%). There is feedback from measured PCC power to the microgrid coordinator (Closed loop – CL).
3) Ec3 experiment: Test the performance of the proposed control with focus on building level by choosing proper weights in low-level layer to increase the role of the load coordinator (LC) to support the microgrid in tracking promised power.

The basic setting of parameters in the planned experiments (Ec1, Ec2 and Ec3) will be reported in the next chapter of results and conclusion.

4.2.2 Non-cooperative distributed MPC approach

This test plan can be divided into the following points:

1) En1 experiment: Test the performance of the overall control architecture with PV during a sunny day without PV estimator.
2) En2 experiment: Test the performance of the overall control architecture with PV during winter period with bad weather and higher prediction error without PV estimator.

4.3 Standards, Procedures, and Methodology

Here are the procedures for the experiments:

1) Test and measure the charging and discharging efficiency of the battery.
2) Test and measure the resistive loads and figure out the principles of load control
3) Figure out the principles of the proposed control algorithm in MATLAB
4) Test the connection between MATLAB and the server for reading and writing
5) Calculate the scaling factor for the simulated components to be compatible with the real ones.
6) Calculate the data transfer delay and consider it in our control algorithm and select the suitable sampling time for the overall system
7) Read the load and PV power measurement from the server
8) Predict the PV power over the control horizon
9) Calculate charging and discharging battery power to fulfil the objectives of the microgrid
10) Calculate load energy consumption regarding the requested demand from the microgrid coordinator
11) Save the results in MATLAB data base
12) Go to step 7
13) Obtain and save the results

4.4 Test Set-up

4.4.1 Experimental facility description

The core of the test facility is a microgrid that comprises a PV generator, a small Wind Turbine, battery energy storage, controllable loads and a controlled interconnection to the local LV grid. The battery unit, the PV generator and the Wind Turbine are connected to the AC grid via fast-acting DC/AC power converters. The converters are suitably controlled to permit the operation of the system either interconnected to the LV network (grid-tied), or in stand-alone (island) mode, with a seamless transfer from the one mode to the other.

However, in our experiments, only gried-tied single phase microgrid has been employed including the following units:

1. A 13.5 kWh Lead-acid storage system, formed by a series of 30 cells. 2 V, 250 Ah. The ESS is connected to an inverter capable of providing ±3.3 kW.
2. 15 kW resistors, 1 kW lamps, 0.5HP motor and 2.5 kVAR inductive load.
3. 11 monocrystalline PV panels with 110Wp, 12 V for each one. The PV plant is equipped with an inverter capable of providing 1.1 KW nominal power.

The devices are fully controllable and/or measurable through a Supervisory Control and Data Acquisition (SCADA) which is implemented using a PLC (Programmable Logic Controller) system with Labview-CoDeSys software. In detail, the following features are available through SCADA system:

1. Measurements on the AC and DC side of the inverters
2. Environmental measurements (irradiation, wind speed etc..)
3. Control of the storage system
4. Load profile programming

A schematic diagram of the single phase microgrid system together with SCADA system is depicted in the figure below (Figure 3). While Figure 4 presents a photo of the actual installation of the microgrid.

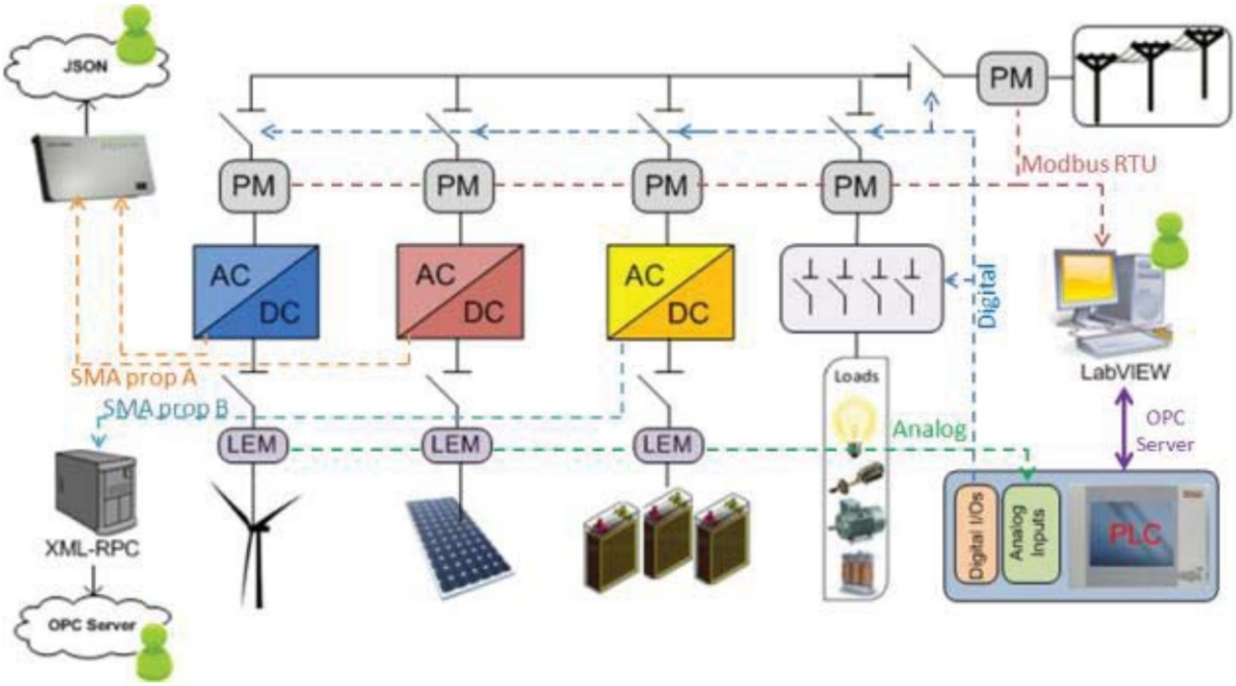

Figure 3. The single phase microgrid monitoring and control infrastructure

Figure 4. Actual installation of the single phase microgrid

4.4.2 Consensus based distributed MPC approach

The overall configuration of the test is shown in Figure 5 containing three parts which are: the controllers, the real and simulated equipment . The simulated part and control algorithm are implemented in MATLAB and the control commands are sent to the hardware components through a dedicated software interface. Moreover, all the measurements such as loads and PV power are saved and available in a dedicated server which is accessible from MATLAB through a network. Specifically, due to the lack of the residential buildings, this type of components is simulated in the PC and its control commands are sent to the emulated module which is a resistive load in the lab.

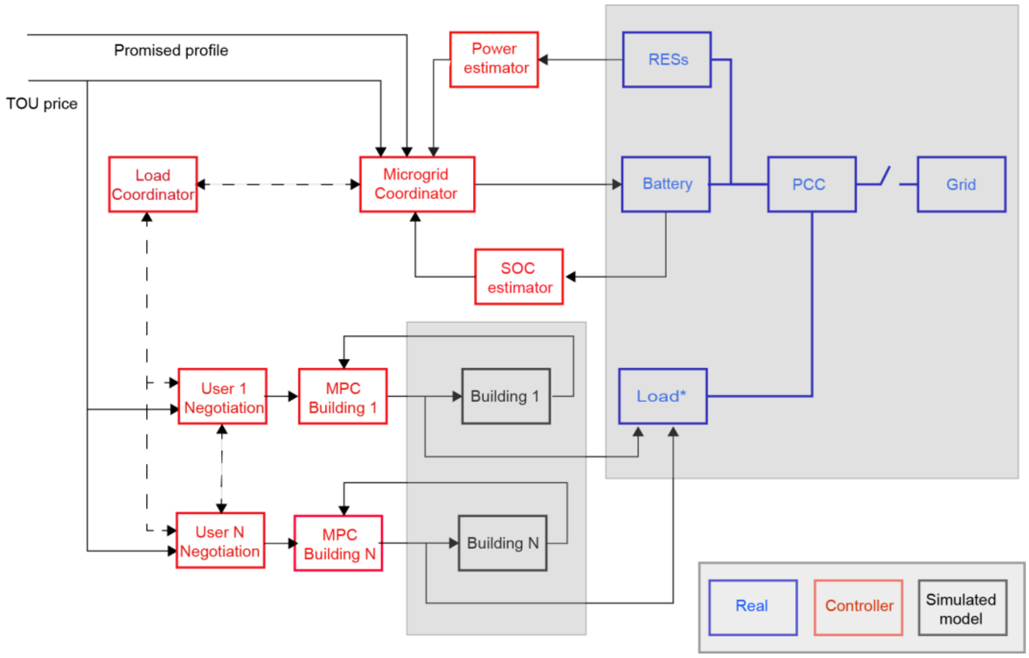

Figure 5:The overall configuration of the experimental test

The main task of the test setup was related to the connection between Matlab and the developed software available in the lab. In summary, the following connection was developed during the research stay:

1. Querying from the database the data of PV production, Load power, ESS power, Grid power and voltage and frequency measured at different points of the network.
2. Reading State of charge of the ESS and also its frequency and writing the command for ESS and Load power through an interface written by python code with the hardware.
3. All the data transferring between machines tasks are performed using UDP or TCP/IP connection

4.4.3 Non-cooperative distributed MPC approach

Due to the fact that real thermal buildings are not available, we emulated these components by using the controllable loads in the laboratory. At the end, the overall configuration and of the experimental test is illustrated in Figure 6.

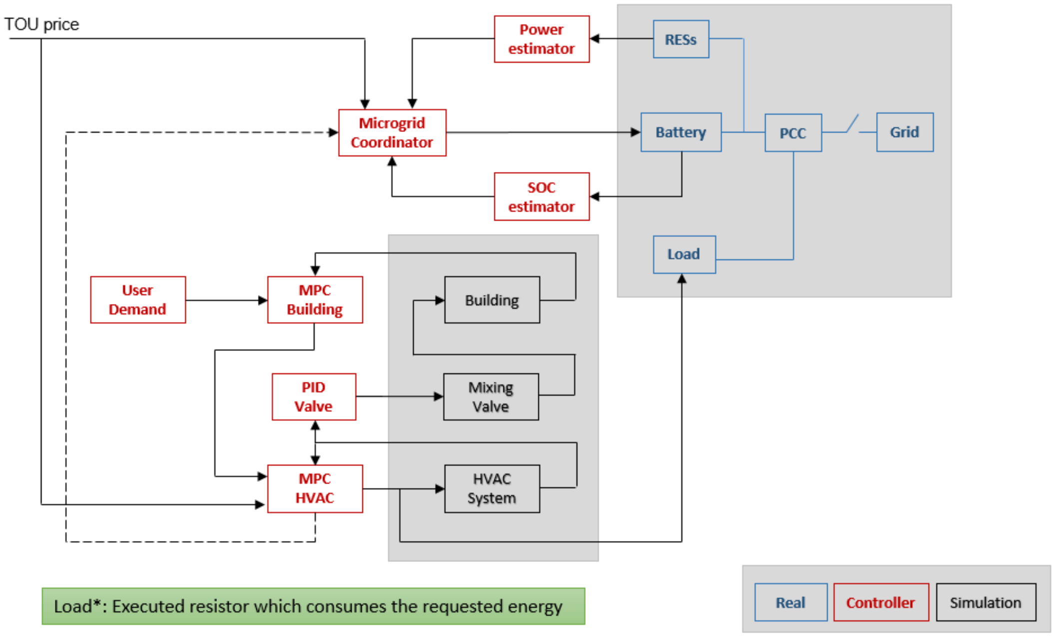

Figure 6: Overall configuration of the experimental test

two different test cases have been conducted based on different weather condition and also with/without PV estimator. Each test case is a 5 hours experiment in which 20% of the total battery capacity is considered as the available electrical energy storage and also thermal storage and building are simulated in Matlab simulation environment.

4.5 Data Management and Processing

To save and manipulate the data we have two space that are dedicated server in the lab and also internal memory of the PC that runs MATLAB for the algorithms. For data processing, there are some commercial and non-commercial software and in this research we use MATLAB solvers to solve optimization problems.

5 Results and Conclusions

5.1 Consensus based distributed MPC approach

For the tests the following components and settings are used:

- Utility grid: as a main source of energy
- Battery: 13.5 KWh with 500 watts charging/discharging limitation bound
- Electricity tariff: ranges from 7.5 cents/KWh to 13.7 cents/KWh
- Number of iterations for negotiation phase is 100.

Other information is reported in Table 1.

Table 1: Experimental parameters of Ec1, Ec2, Ec3

Experiments	Ts [minutes]	P^b_{max}[W]	SOC^b_{min}[%]	SOC^b_{max}[%]	Test Period	Test time
Ec1	20	500	85	97	Summer	1-5 pm
Ec2	15	500	75	87	Winter	1-5 pm
$Ec3$	5	250	86	89	Winter	9-11 am

where Ts is sampling time of the system in experiments, P^b_{max}, SOC^b_{min}, SOC^b_{max} are maximum charge and discharge power, minimum state of charge, maximum state of charge of the ESS, respectively.

In Ec2, Ec3, the users are divided into two groups of benefit priority (i.e., focusing on the monetary minimization) and comfort priority (i.e., focusing on the temperature setpoint tracking) and two different set-points that are $21\,°\,C$ and $21.5\,°\,C$. On the other hand, in Ec3, all the users are set as benefit priority users.

1) Ec1 experiment

In this experiment, users' consumption profile is set to a constant value which can keep the buildings' temperature to track perfectly the temperature setpoints and this profile is known by MMPC. The initial temperature of each building is set to be equal to its setpoint. A higher ESS capacity with respect to the one mentioned in **Error! Reference source not found.** is also chosen in this test. The results for Ec1 is depicted in Figure 7.

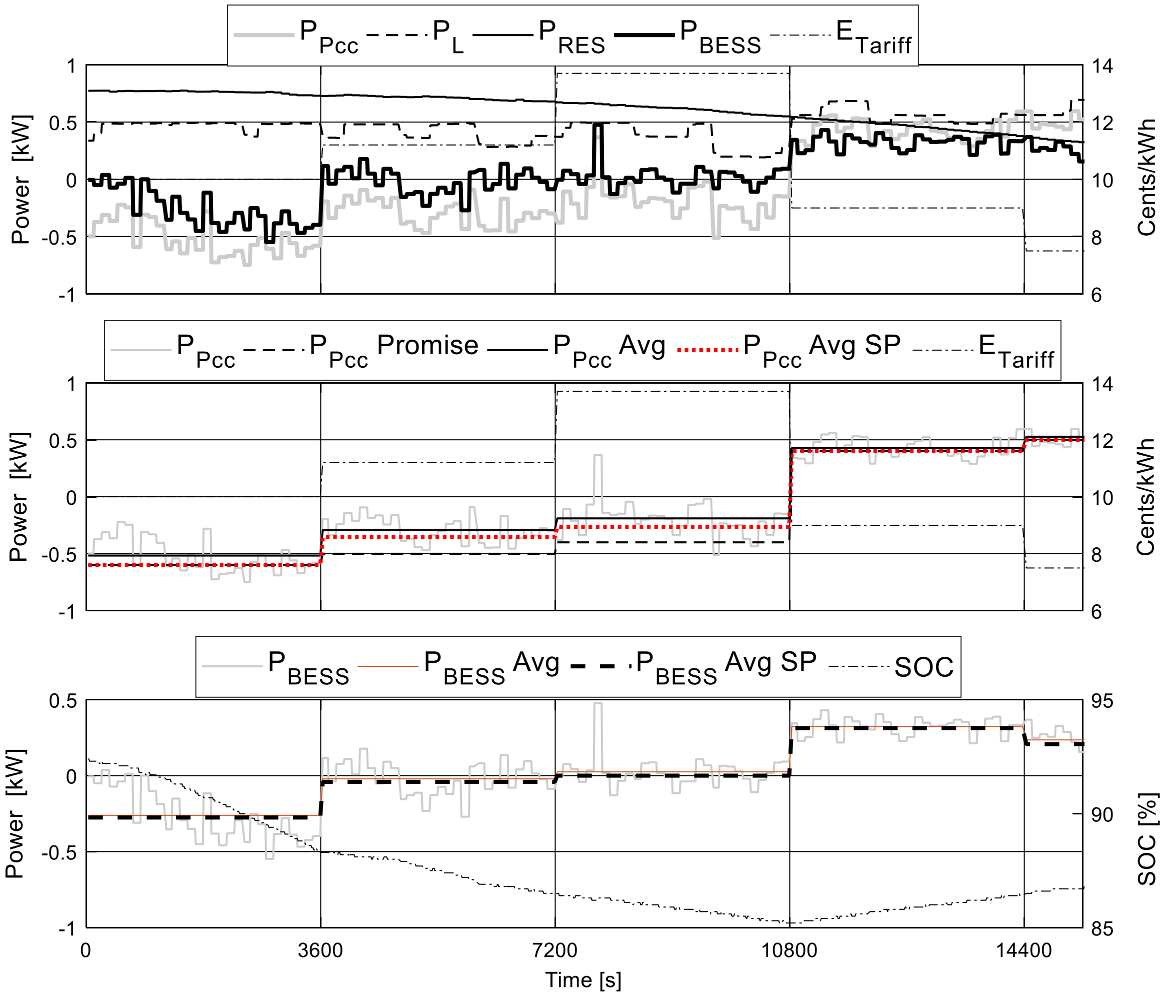

Figure 7: Result of the first experiment (Ec1), subplot 1: power flow through all the involved components, subplot 2: PCC actual (1-min average), actual (1-hour average), setpoint and reference power, subplot 3: ESS actual (1-min average), actual (1-hour average),

As can be seen from Figure 8, the setpoint of total power flow through PCC follows quite closely to the reference power profile. However, the actual PCC differs by a larger margin due to the RES prediction error, control error in both ESS and load side. This behavior highlights the necessity of further investigation on feedback PCC power measurement to the microgrid coordinator which will be addressed in the experiments Ec2 and Ec3.

2) Ec2 experiment

The similar setting of Ec1 is applied to Ec2 during winter period and a bad weather day which cause a higher error in RES generated power prediction. This test is 4 h long and starts at 1 pm (Greece time). The system is here operated in CL with respect to PCC power. Another modification of Ec2 with respect to Ec1 is introduction of the MPO which provide a better value for the reference power with respect to the one in Ec1.

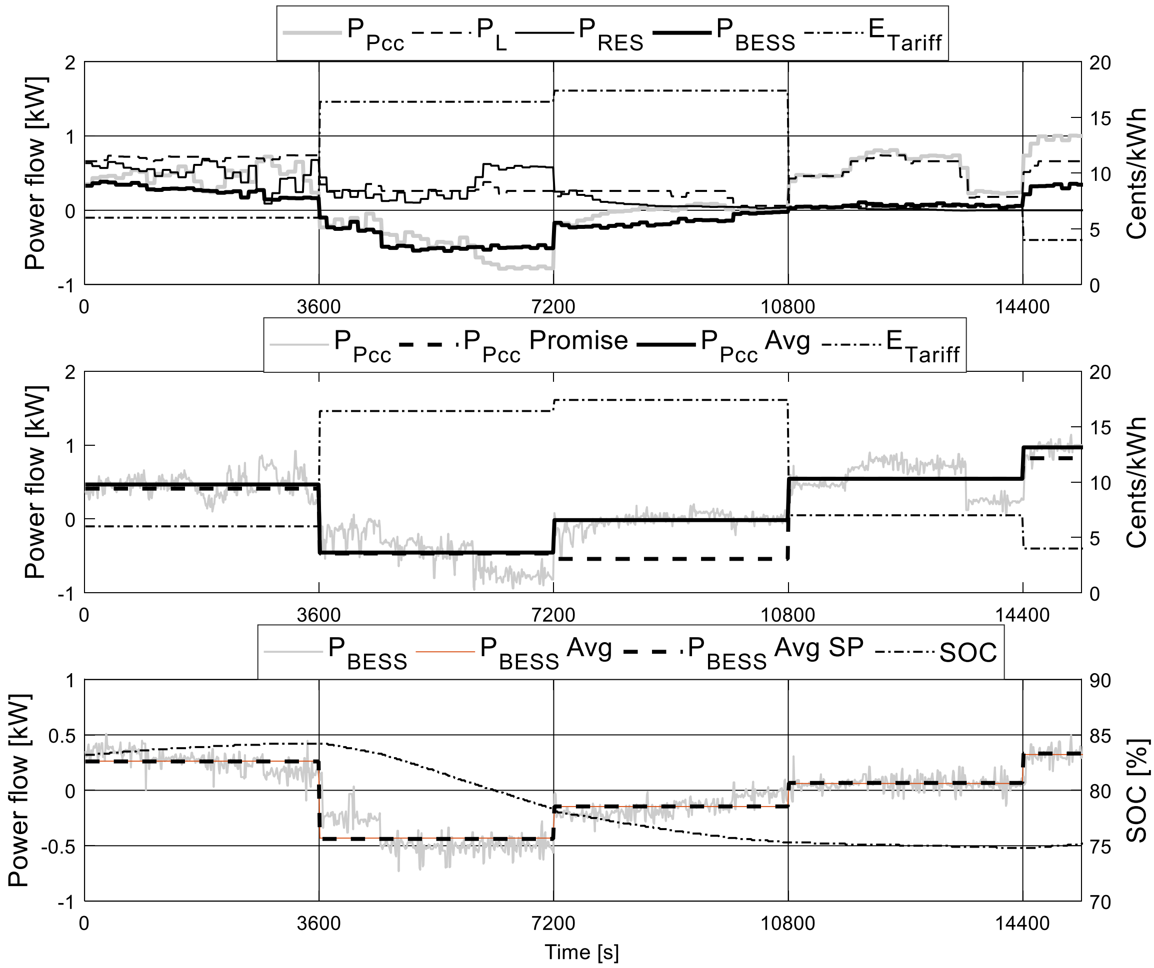

Figure 8: Result of the second experiment (Ec2), subplot 1: power flow through all the involved components, subplot 2: PCC actual (1-min average), actual (1-hour average), setpoint and reference power, subplot 3: ESS actual (1-min average), actual (1-hour average)

Another source of prediction error is introduced by considering different initial load consumption profiles in MPO and in MMPC. In fact, in the MPO, the microgrid consider same load consumption prediction as in Ec1 while in the MMPC the load consumption prediction is declared by the users. Even the presence of various prediction and control errors, the setpoint of total power flow through PCC track very well the reference power and so for the PCC actual power since the feedback of PCC power measurement is considered in MMPC. As shown in Figure 9, the microgrid tends to export electricity during peak period and import electricity during off-peak hours which could bring them monetary benefit.

3) Ec3 experiment

This experiment focuses on evaluating the building level. In this test, a smaller battery size (SOC is reduced by three times and maximum power is reduce two times with respect to the one in **Error! Reference source not found.**), high weight for tracking promised PCC power profile in MC and low weight for temperature tracking, high weights for tracking the request from microgrid coordinator in all the MPC building are chosen.

The purpose of these consideration is to increase the role of the LC and the BMPCs in supporting the microgrid to track promised profile and also increasing the confliction between users since all of them are flexible in changing their consumption. Without affecting the goals of the experiments, the length of the test is shortening to 2 hours and all other term related to time factors (e.g., sampling time, changes of tariff) is reduced 3 times shorter.

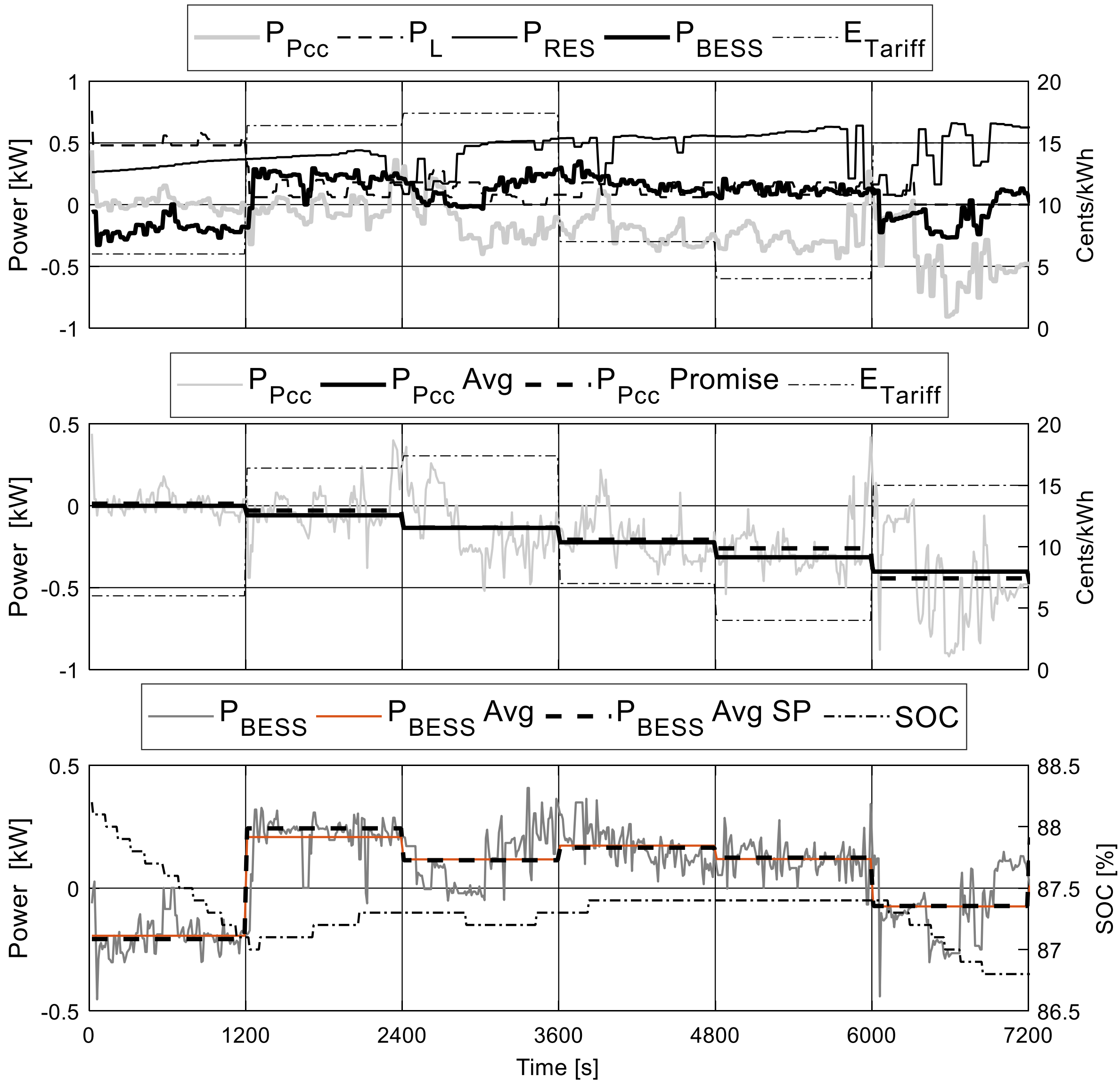

Figure 9: Result of the third experiment (Ec3), subplot 1: power flow through all the involved components, subplot 2: PCC actual (1-min average), actual (1-hour average), setpoint and reference power, subplot 3: ESS actual (1-min average), actual (1-hour average).

While in all other experiments and simulation, we will consider the same value of Q_j for all the users, this experiment instead evaluates our algorithm with Q_j being different numbers which show the difference in the roles of each user in the consensus based approach. Values of 8, 4, 2, 1 are chosen for Q_j of user 1, 2, 3 and 4 respectively and the temperature setpoint of all users is 21°C. The actual PCC power can still track very well the reference power as in Ec2 thanks to the ESS and especially the users' flexibility. The modification of the planned consumption cost the users their comfort, however, as far as the users can exploit the thermal inertial in the buildings good performances for temperature tracking can be foreseen as depicted in Figure 10. In this experiment, the maximum number of iteration recorded is 37 and the negotiation phase takes maximum 8.3 second correspondingly.

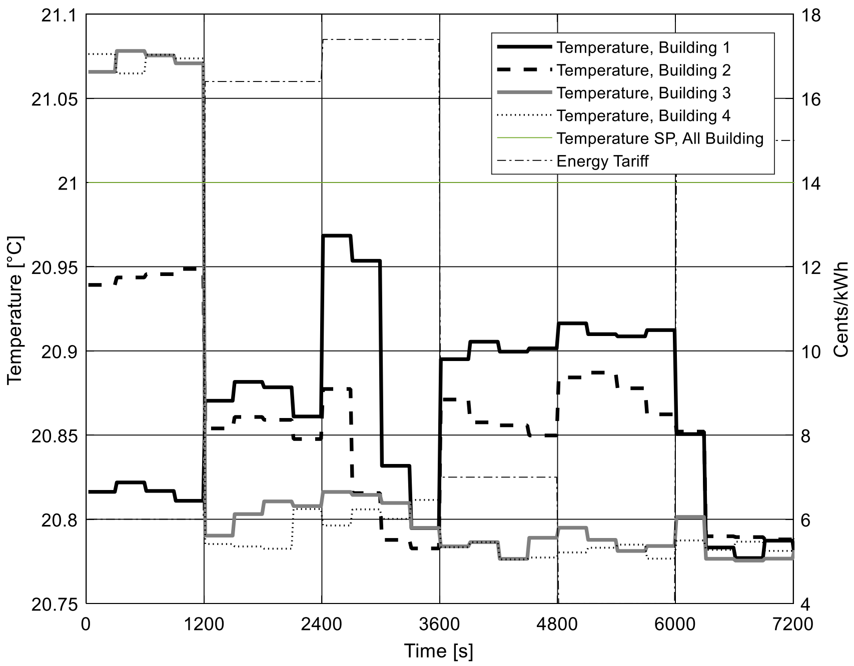

Figure 10: Temperature in each building during 2-hour experiment Ec3.

Regarding power quality of the microgrid, the measured voltage and frequency of the grid and the battery inverter are measured are reported in Figure 11. The results show an acceptable power quality during the operation of our experiment as *(i)* the frequency stays around 50 (Hz) with maximum deviation is 0.06 (Hz) and *(ii)* the voltage (RMS value) is from 223 to 234 (V) which account for maximum 3 % deviation from the nominal value of 230 (V). Notice that the same figure for Ec1 is not here presented due to lacking data, however the similar or even better power quality can be expected from Ec1 in the same condition of the local network in Ec2 since the power variation of PV generated power, load and ESS are less than the ones Ec2 especially.

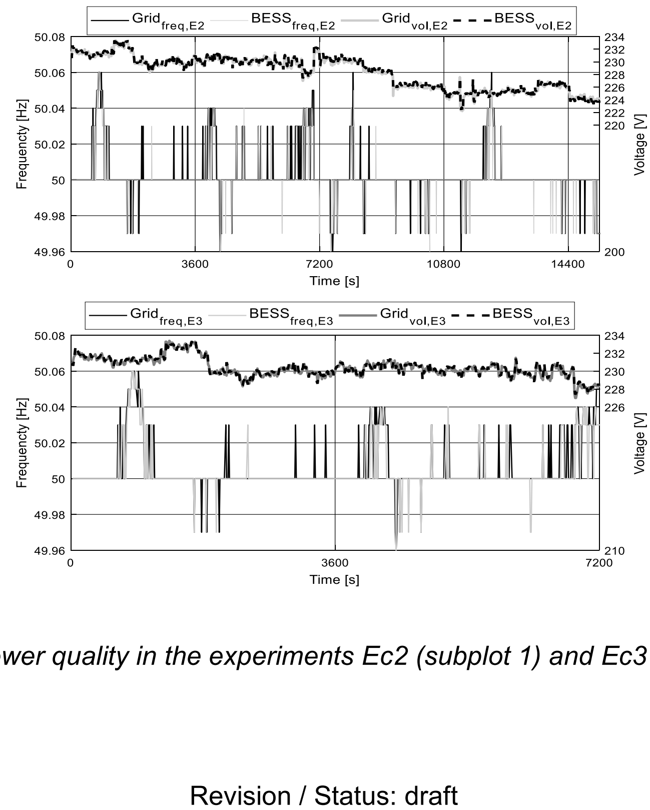

Figure 11: Power quality in the experiments Ec2 (subplot 1) and Ec3 (subplot 2)

Table 2: Experimental and Simulation results

ID	E_b **	E_{RES}	E_u
Unit	Wh	Wh	Wh
E1	65.5	2552	1798
E2	-251.3	937.5	1677
E3*	116.6	852.8	335.5
E2_simul	-279	937.5	1653

(*): Shorter simulation period is considered in Ec3.
(**): Positive values mean charging and vice versa

Where E_b is energy flow through ESS, E_{RES} is energy produced from RES and E_u is energy consumed by users.
Based on the data in Table 2, the simulation results of Ec2_simul and Ec2 are close to each other that shows the accuracy of the method in practice.

5.2 Non-cooperative distributed MPC approach

For the test, the following components are used:

- Utility grid: as a main source of energy
- Battery: 13.5 KWh with 500 watts charging/discharging limitation bound
- Electricity tariff: ranges from 5 cents/KWh to 35 cents/KWh

The test period is 5 hours from 11 a.m. to 4 p.m. with 10 minutes sampling time. It is considered that it is a winter case simulation for the users in a sunny day. The user's requests are divided into two different set-points that are $21^\circ C$ and $23^\circ C$.

The main novelty of our approach is in the application side by using a variable water flow rate technology instead of using constant flow rate for the thermal energy storage Figure 12.

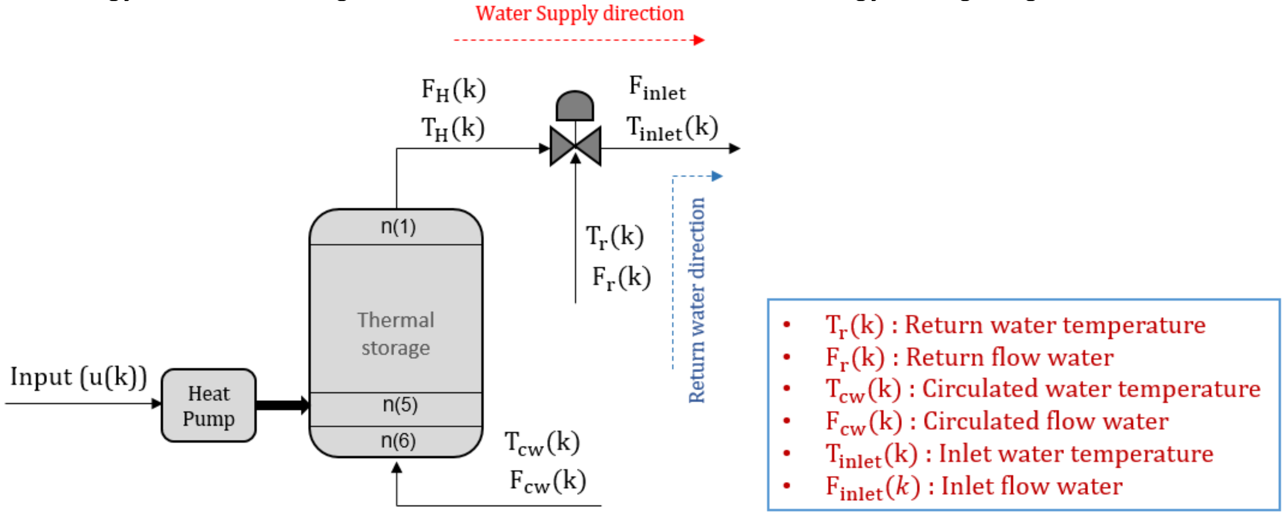

Figure 12:Structure of thermal energy storage connected to the mixing valve

The considered system divided to two different sub-layers: The first one is demand side management system including radiant floor building, HVAC system (Heat-Pump technology) and a mixing valve between tank output and return water of the building. The second layer dedicated to the energy resources management system with Energy Storage System (ESS), Thermal Energy Storage (TES) and Renewable Energy Sources (RES).

The first sub-layer employs an Adaptive Model Predictive Control (AMPC) which was developed from a well-known iterative distributed algorithm (MPC2). On the other hand, The MPC optimization problem in the second sub-layer is formulated as a fixed horizon Mixed Integer Quadratic Programing (MPC1). The propose control scheme has been shown in Figure 13.

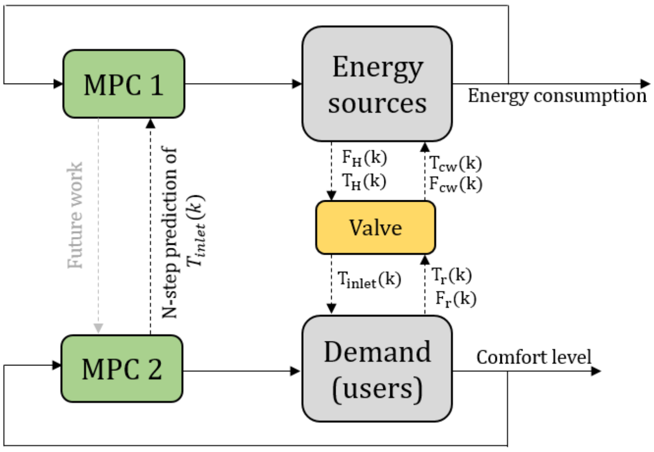

Figure 13: Distributed MPC structure

Figure 14 and Figure 15 show that the minimum required thermal energy for the room heating system (the blue line in Figure 14) is always provided by TES (red line in Figure 14) and also the comfort level is always preserved (Figure 15) for both experiments En1 and En2.

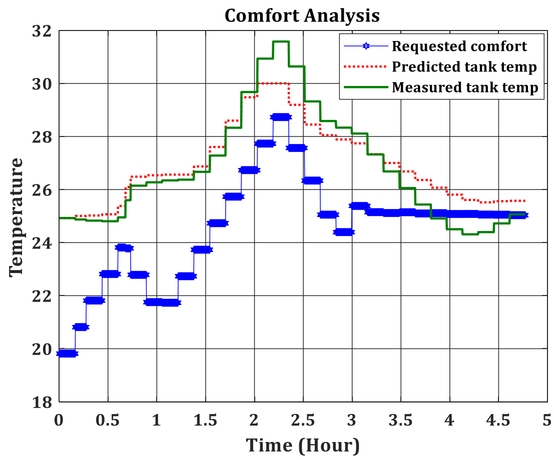

Figure 14: TES temperature vs. inlet water temperature

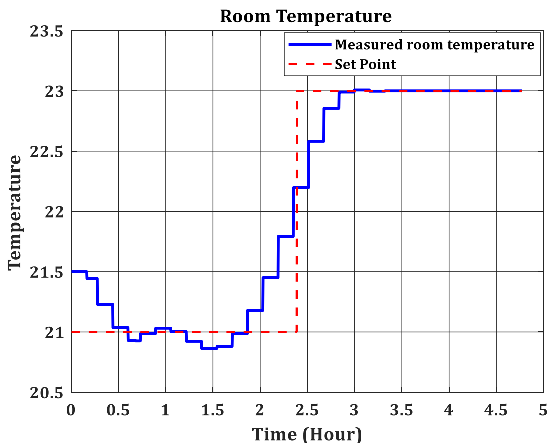

Figure 15: Room temperature

According to different weather conditions and, consequently different PV production, two experi-

ments, namely En1 and En2, have been conducted.
En1 experiment. As it has been shown in Figure 16, the proposed distributed adaptive MPC can economically distribute power among all generators and storages while satisfy comfort condition. Figure 18 shows the charging and discharging procedure of energy storages based on electricity price tariff.

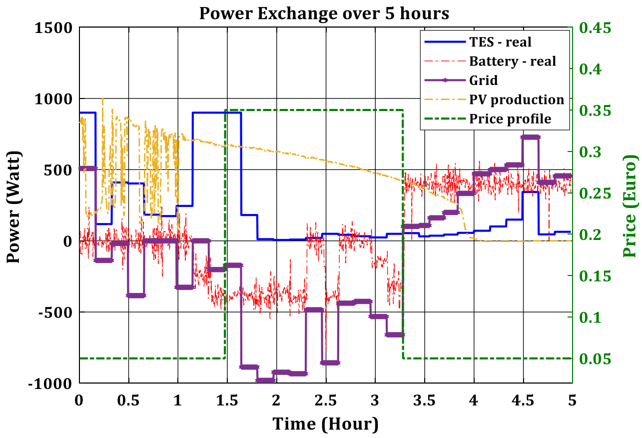

Figure 16: Power exchange

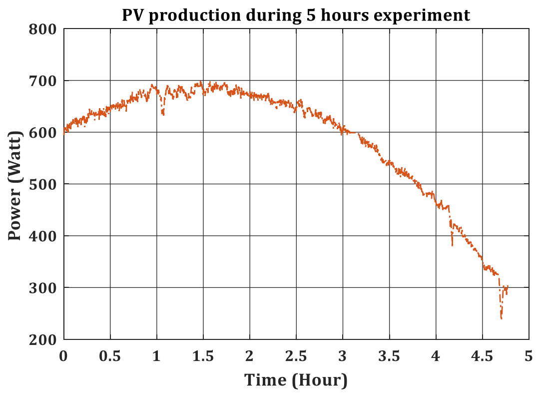

Figure 17: PV panel production during 5 hours experiment

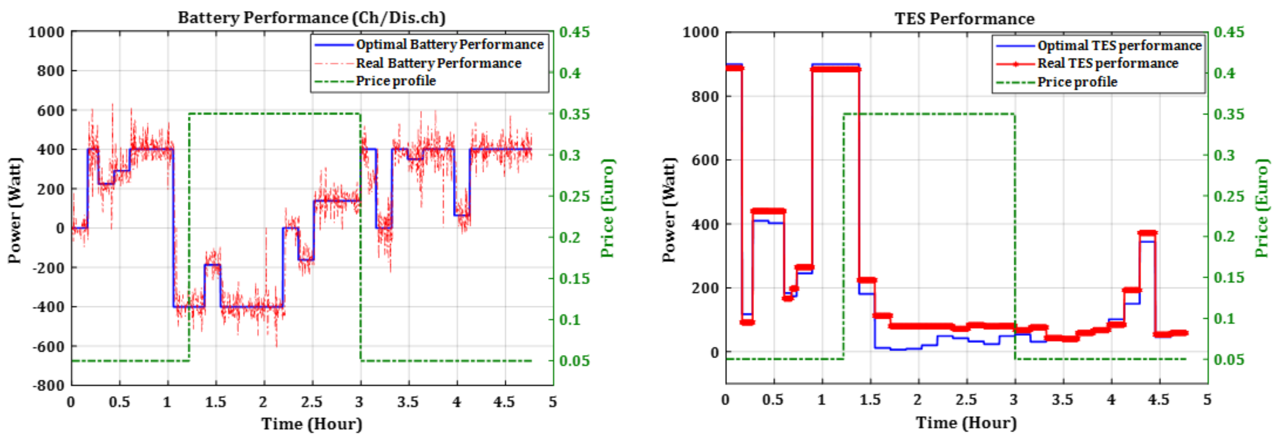

Figure 18: Charging and discharging procedure of energy storages

En2 experiment. In this analysis, a cloudy day is considered when the PV production is fluctuating and in turns its estimation is difficult. The results of this experiments have been shown in Figure 19, Figure 20 and Figure 21.

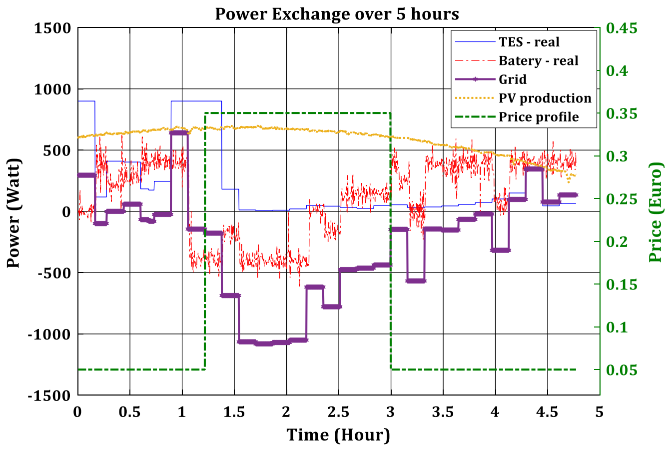

Figure 19: Power Exchane

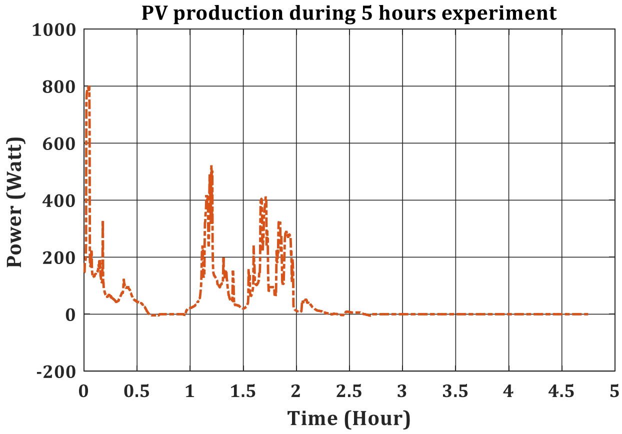

Figure 20: PV panel production

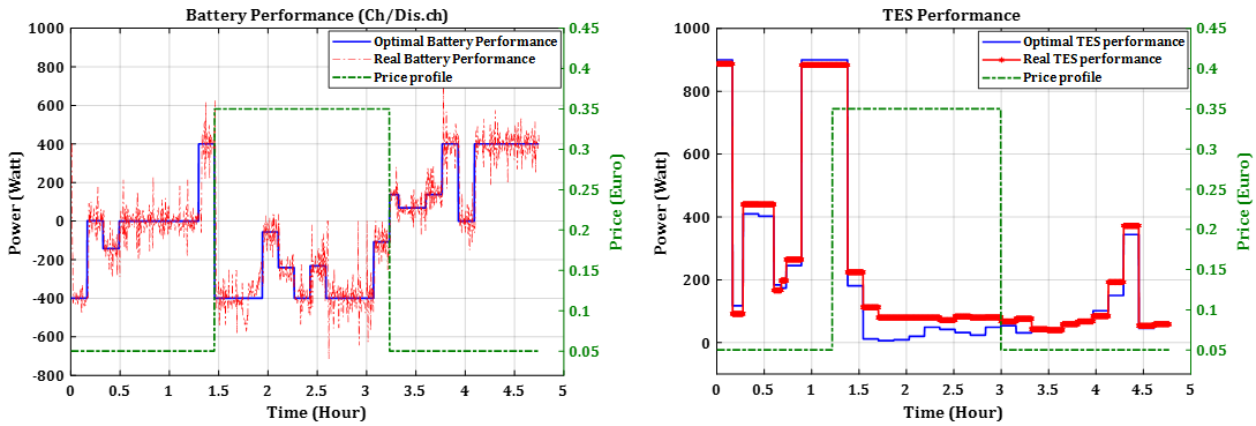

Figure 21: Charging and discharging procedure of energy storages

5.3 Conclusion

In this project, the experimental validation activities of the distributed microgrid MPC algorithms are presented. The microgrid consists of storage system, PV panels, resistive loads, and grid connection. We proposed two distributed MPC approaches for energy management of a microgrid that were implemented and tested in NTUA testing facility. In addition to the experiments, simulations are performed in order to strengthen the analysis of the microgrid control architecture and understand which aspects could be possibly improved. In particular, an interesting issue foresees the combination of the two approaches which uses the thermal energy storage and consensus based approach to manage the energy resources which is beneficial for both users and microgrid. In addition, further improvement can be made on iterative negotiation between high-level and low-level layers.

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6 Open Issues and Suggestions for Improvements

Although the obtained results show enough accuracy of the proposed method, this work can be a starting point of future research in this field.

6.1 MC-LC iterative negotiation

In this work, the negotiation between MC and LC takes place once, which means 1 request and 1 answer and no more. To have better solutions, extension of the work to an iterative negotiation would result in more accurate solutions. In this way, a hierarchical control would be another topic for the future works.

6.2 Consumer grouping

For now, we considered that all users have the same priority and in negotiation phase they can freely exchange data between themselves. Due to large residential and commercial areas which have established priority connection between some of them, the idea of neighbourhood could play a role in negotiation phase. Therefore, considering the common interests of the users, we can make different groups of users which users in each group can have some benefits of their group-mates and they will consider these advantages in their negotiation procedure. Managing groups is a challenge task in this topic but some advantages of being in a group like sharing resources or batteries make this topic an interesting one.

6.3 Pricing mechanism

In this research, the pricing mechanism considered the same for whole system. To distinguish between users' neighbours and non-neighbours a pricing mechanism could highlight this relation between users and could be a topic for future researches.

7 Dissemination Planning

Given the positive results, we are planning to prepare and submit two different journal papers, one more focused on consensus-based distributed MPC approach and one on non-cooperative distributed MPC approach. The publisher will be most likely IEEE in both cases.

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9 Annex

9.1 List of Figures

9.2 List of Tables