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DEVELOPMENT OF A SMART SIMULATOR FOR SMALL-SCALE SOLAR CHP SYSTEM IN THE BUILT ENVIRONMENT

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ABSTRACT

In this work a hardware-in-the-loop simulator of a novel micro combined heat and power system is discussed and its potential presented. The plant under investigation consists of a concentrated Linear Fresnel Reflectors solar field, a 2kWe/18kWt Organic Rankine Cycle unit and an advanced latent heat thermal energy storage tank equipped with reversible heat pipes.

Because of the complexity of the integrated system, various control strategies are requested for its optimized operation. However, the evaluation of the different control logics and optimizations in real-time can be complex due to technical and reliability issues. Hence, a hardware-in-the-loop simulation framework based on Matlab/Simulink has been developed and validated to assess the dynamics operation of the different subsystems with varying control strategies and set-points. As an example of the validation procedure, the use of the simulator is illustrated by means of the switch among the different operation modes of the plant with varying ambient conditions. The scientific approach proposed can be extended to any function block of the developed controller.

Keywords: renewable energy, energy systems for power generation in urban environment, micro combined heat and power system, hardware-in-the-loop, operation control, smart energy management

NONMENCLATURE

Abbreviations

CSP	Concentrated Solar Power
HIL	Hardware-In-the-Loop
LFR	Linear Fresnel Reflector
LHTES	Latent Heat Thermal Energy Storage
mCHP	Micro Combined Heat and Power
OM	Operation Mode
ORC	Organic Rankine Cycle
PLC	Programmable Logic Controller

1. INTRODUCTION

Among the key instruments to reach the challenging targets defined by the Paris Agreement, renewable energy technologies are considered the ones with the greatest potential. Because of its availability worldwide, solar energy represents the most promising and clean energy for future power generation. In particular, use of solar energy in decentralized energy systems is foreseen as a valuable alternative to substitute thermal and electric power generation from fossil fuel.

Despite the interesting potential of micro-cogeneration at residential level [1], nowadays the structural expansion of decentralized mCHP systems is still limited and their control rather complex. Moreover, when coupled with unpredictable renewable energy sources, such as solar, the short and long-term fluctuations entail challenging dynamic effects to deal with. To reduce such variability and extend the operation

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of the systems, different storage energy technologies can be adopted. Nevertheless, the proper control of the system is fundamental to optimize the operation of the different sub-systems with varying ambient conditions and user needs.

Among the different integrated systems to efficiently convert solar energy into generated power, Concentrated Solar Power (CSP) plants coupled with Organic Rankine Cycle (ORC) systems are considered one of the most competitive at large scale [2]. At small-scale, instead, their adoption is still limited so far mainly because of economic feasibility [3]. At present, many researchers studied them. For example, Taccani et al. [4] tested a small-scale cogenerative solar ORC, powered by parabolic trough collectors, achieving a gross electricity efficiency of 8%. Manfrida et al. [5] numerically investigated the performance of a PTC-ORC, finding an overall solar-to-electricity efficiency of 3.9% over a week period. Bouvier et al. [6], instead, studied and tested the performance of a single-cylinder expander coupled with a 46.5 m^2 double-axis PTC solar field, obtaining a power output of 1.3 kWe and a solar-to-electricity efficiency of 3%. Eventually, in a previous work [7] some of the authors of the present paper developed a mathematical model of an innovative mCHP system for residential applications and evaluated its performance with varying ambient conditions for a whole year.

All the above mentioned studies revealed the paramount importance of an adequate control logic and management of the integrated systems to better exploit the collected solar energy and increase the conversion efficiency of the plants. However, due to the system complexity, the use of powerful development tools becomes crucial to reduce the design time, the related cost and to minimize the probability of errors. Generally speaking, developing and testing physical prototypes can be very expensive. To minimize such costs, two approaches are commonly adopted, namely simulation and hardware-in the-loop (HIL). These two strategies can be jointly adopted in order to achieve good results in short time. In particular HIL technique reduces the time of control algorithm development in the real control system, since physical phenomena can be simulated and developers can concentrate only on control algorithm performances [8].

In literature, Huang et al. [9] and Griese et al. [10] addressed the use of HIL to evaluate various optimizations respectively for building controls and for the operation of an energy system consisting of a biocatalytic methanation reactor, a photovoltaic park, a regenerative fuel cell and short-term storage units.

In this work, the authors developed a hardware-in-the-loop simulator of a novel micro combined heat and power system and presented its performance by illustrating its use for the selection of the different operation modes of the plant with varying ambient conditions.

2. METHODOLOGY

2.1 The integrated plant

The plant under investigation consists of: (i) a 146 m2 solar field based on Linear Fresnel Reflectors producing heat at temperatures in the range 250-280°C; (ii) a 2kWe/18kWt regenerative Organic Rankine Cycle plant; (iii) a 3.8 tons advanced PCM thermal storage tank equipped with reversible heat pipes. The plant has been designed by the consortium of several Universities and

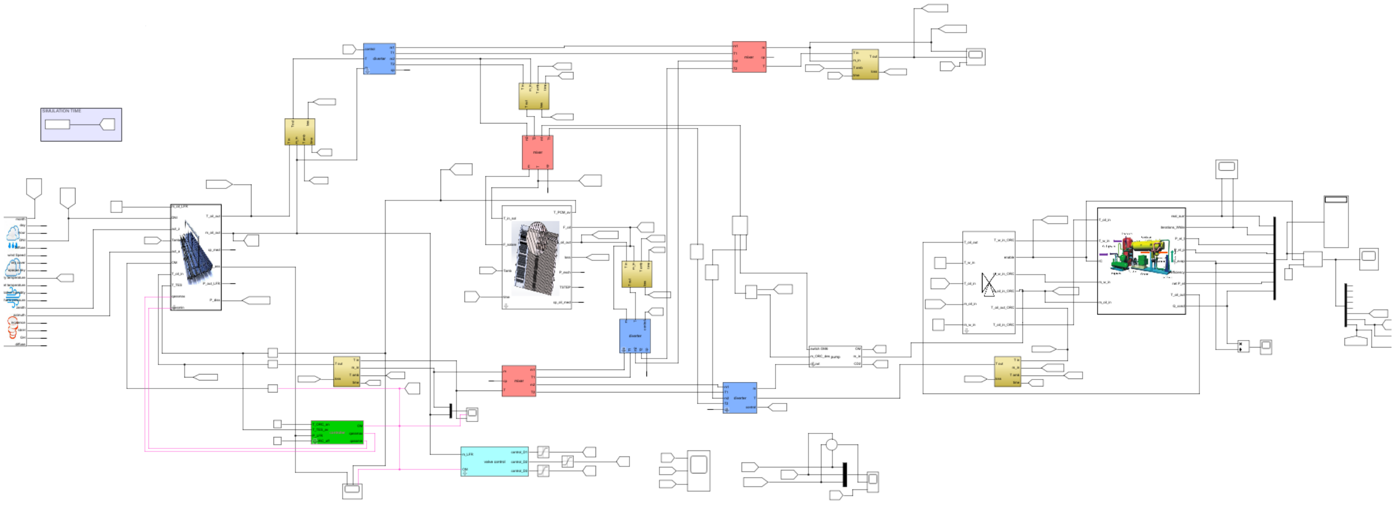

Fig 1 The model of the integrated plant in Simulink

industrial organizations under the EU funded Innova MicroSolar Project [11]. It has been installed in the city of Almatret (Spain) coupled to a residential building and it is going to be tested in the next months. Further details about the plant can be found in [12].

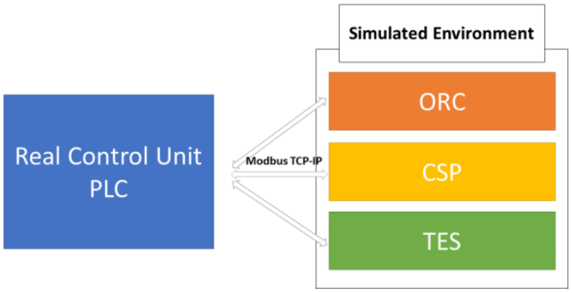

Fig 2 scheme of the HIL approach

2.2 The model

The dynamic simulation model of the prototype plant has been developed in Matlab/Simulink. Energy+ database has been used for weather data in terms of solar radiation and ambient temperature for the city of Lerida in Spain (close to the plant location).

The model includes the following main components: (i) the LFR solar filed; (ii) the micro ORC plant and (iii) the latent heat thermal energy storage (LHTES) tanks equipped with reversible heat pipes. Ad hoc subroutines have been developed in Matlab, as extensively reported in a previous work [7]. Figure 1 reports a scheme of the integrated plant model in Simulink.

The Matlab/Simulink blocks have been developed with the aim to interact with the real control system running on an external Programmable Logic Controller (PLC). In the real system architecture the central control unit interacts with the control units of the different subsystems using a Modbus TCP-IP communication as reported in Figure 2. The central control unit acts as master agent and it is responsible to monitor the overall system, actuate the system-level control procedures and and assure the safety of the global plant. Hence, the Matlab/Simulink blocks have been developed to emulate the subsystems control units or a part of them: they implement a slave modbus communication and expose the same logical input/output as in the prototype plant.

A sofware-based synchronization strategy has been implemented to assure the data consistency between the simulated model and the real controller. This allows to decrease the control cycle time of the PLC respect to the normal setup, making the test phase really faster compared to a real scenario.

Therefore, the central control PLC can be directly connected to the PC where the Matlab/Simulink simulation runs and the control strategies checked and potentially optimized using a simulated environment.

3. RESULTS AND DISCUSSION

Depending on the solar radiation and the state of charge of the LHTES the integrated plant works according to different operation modes. Indeed, the diathermic oil from the solar field flows to the LHTES and/or directly to the ORC, depending on its temperature and on the amount of power collected at the receiver as reported in Table 1. On the contrary, when the power produced by the solar field is low or zero and the average TES temperature is within a given operating range (TORC,on = 217 °C and TORC,off = 215 °C), the thermal energy of the TES can be used to run the ORC unit and assure its operation for a maximum of 4 hours with no sun.

Table 1. Operating conditions for the different OM of Innova Microsolar plant model

OM	Description	Operating conditions
OM1	LFR supplies ORC	T_{oil}=210°C
OM2	System off	-
OM3	LFR supplies PCM storage	$T_{oil}=T_{PCM,av}+10°C$
OM4	LFR supplies PCM storage and ORC	T_{oil} =210°C if $T_{PCM,av}<200°C$ else $T_{oil}=T_{PCM,av}+10°C$
OM5	PCM storage supplies ORC	oil flow rate 0.22 kg/s
OM6	PCM storage and LFR supply ORC	T_{oil}=210°C from LFR and total oil flow rate 0.22 kg/s

Figure 3 shows the plant operation in terms of thermal and electrical power output and operation mode for a typical summer day.

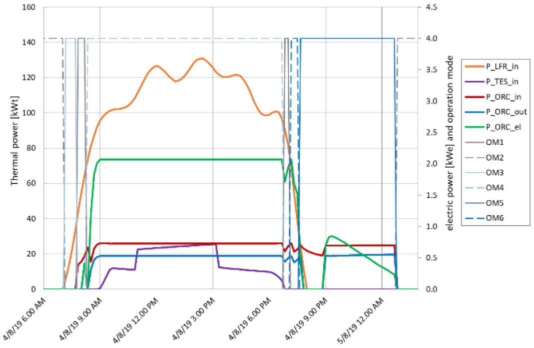

Fig 3 plant operation in a typical summer day

Then, the HIL framework has been tested on the same instantaneous hours of Operation Modes as for the Matlab/Simulink simulation model. Hence, the performance of the HIL approach has been compared with respect to the real scenario and also with the simulation model in terms of computational time for 2 typical weeks of operation (winter and summer) as reported in Table 2. A time step of 10s has been considered and simulations run on a PC with Intel®Core2 Quad8330 processor.

Table 2. Comparison between HIL simulator, real scenario and Matlab/Simulink simulation model

	Time (January) [min]	**Time (August) [min]**
HIL simulator	124.38	154.31
Real Scenario	10080	10080
Matlab/Simulink simulation model	5.64	7.37

Less than three hours, indeed, are needed to test the real control system instead of a full week without considering any system downtime or other mechanical or hydraulic problems that could even extend such period. At the same time, the Matlab/Simulink simulation model takes 20 times less computational time than the HIL approach. The longer amount of time of the HIL architecture respect to the simulation model is mainly due to the following two factors: firstly the communication overhead introduced by TCP-IP modbus and secondly the minumum cycle time of the PLC-based control unit. As a consequence, the more efficient way to proceed is to perform a first design phase of the control strategy in the simulated environment and only later with the HIL framework in order to finely tuned the control algorithms.

4. CONCLUSIONS

This paper aims at presenting a HIL simulator for optimization of integrated systems operation. The HIL simulator emulates the performance of an innovative mCHP system, as designed and built by a consortium of universities and companies within the EU funded project Innova Microsolar. Both controller and major plant components have been included in the framework to ensure that the dynamic operation of the different subsystems is correctly represented. The approach adopted to synchronize the simulated model and the real controller of the plant is described and, as an example, the switch among the different operating modes is illustrated. The presented approach can be extended to any other functional block of the controller and adopted to define the best optimization strategies of the plant.

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