Multi-objective Optimization of Energy Hubs at the Crossroad of Three Energy Distribution Networks

Diego Arnone, Massimo Bertoncini,
Giuseppe Paternò, Alessandro Rossi
Research and Development Laboratory
Engineering Ingegneria Informatica S.p.A.
Palermo, Italy
e-mail: diego.arnone@eng.it, massimo.bertoncini@eng.it,
giuseppe.paterno@eng.it, alessandro.rossi@eng.it

Mariano Giuseppe Ippolito,
Eleonora Riva Sanseverino
Dipartimento di Energia, Ingegneria dell'Informazione e
Modelli Matematici (DEIM)
Università degli Studi di Palermo
Palermo, Italy
e-mail: marianogiuseppe.ippolito@unipa.it,
eleonora.rivasanseverino@unipa.it

***Abstract*—This paper provides a multi-objective optimization framework aimed at the management of a multi-carrier energy system involving both electricity and hydrogen. Using the concept of the multi-carrier hub, the proposed system has been modelled in order to define completely every energy flow inside the plant. After that, a heuristic multi-objective optimization algorithm, the Non-dominated Sorting Genetic Algorithm II, has been implemented for the energy management of the plant, taking into account simultaneously three different objective functions related to economic and technical goals. This optimization process provides the set point defining the working configuration of the plant for a daylong time horizon. The communication framework between the energy management system, the real plant and the monitoring tool has been developed too, using the Open Platform Communications (OPC) protocol for the data exchange. This has been presented along with the Decision Support System (DSS) provided by the optimizer and the Human Machine Interface (HMI) of the Supervisory Control And Data Acquisition (SCADA) monitoring the plant. All the presented applications are going to be deployed on a real plant demonstrator.**

Keywords-multi-carrier hub; multi-objective optimization; energy management system; OPC protocol; hydrogen storage.

I. INTRODUCTION

Today, multi-carrier energy hubs are a concrete reality for the energy distribution networks management, enabling the interconnection between these energy infrastructures by means of several energy devices able to convert, store and buffer various forms of energy. In the view of remodeling and restructuring energy infrastructures, especially electrical ones, multi-carrier hubs could represent an innovative and cutting-edge technology for the design and realization of a new hybrid, flexible and interoperable distribution grid framework.

The concept of multi-carrier hubs was introduced by G. Andersson and et al. [1][2], defined as "units where multiple energy carriers can be converted, conditioned and stored; such a system represents an interface between different energy infrastructures and/or loads". They faced the problem from many points of view, proposing a graphic model and a complete matrix model able to correctly represent every device in the system and its operation. This research laid the foundation for the systematic study of multi-carrier hub framework in several energy grid domains. In the last two years, many researchers have addressed the challenge of multi-carrier hub. Besides the modelling criteria, which are mostly based on G. Andersson studies, many authors faced the issues of the control and management of a multi-carrier hub. These tasks are very frequently addressed by means of heuristic optimization processes, e.g., multi-objective optimization [3], fuzzy logic systems [4], multi agent systems [5] or an effective combination of two of them [6]. Another significant topic related to the operational issues of a multi-carrier hub is the management of the dynamic behaviour of two or more energy carriers that must be controlled as a whole inside the multi-carrier structure. Most of these studies focused on the interaction between electricity and thermal energy, because of the great difference between the time scales of these energy carriers [7][8]. Finally, some studies proposed a widespread usage of the multi-carrier hub concept over a city/district level in order to create a unique interoperable energy distribution network by connecting different energy infrastructures through two or more multi-carrier hubs properly located [9][10].

The present paper proposes an Energy Management System (EMS), based on a multi-objective optimization process, which is able to perform the management, scheduling, control and monitoring tasks of a multi-carrier system. This system involves two energy carriers, electricity and hydrogen, and interconnects a Medium Voltage (MV) electrical distribution grid, a Low Voltage (LV) electrical distribution grid and the methane/natural gas network for hydrogen delivery. It also integrates Renewable Energy Sources (RES) in the management of electrical power flows. The structure of such a system roughly consists of a Water Electrolyser (WE), connected to the MV grid and able to produce hydrogen, an innovative Hydrogen Solid-state Storage System (HSS), installed on two different channels, and a Fuel Cell (FC), connected to the LV grid, that absorbs hydrogen from one of the HSSs. The research performed on this system is part of the European co-funded INGRID project (7th Framework Programme) [11][12]. In Figure 1, the block diagram of an INGRID system instantiation is shown.

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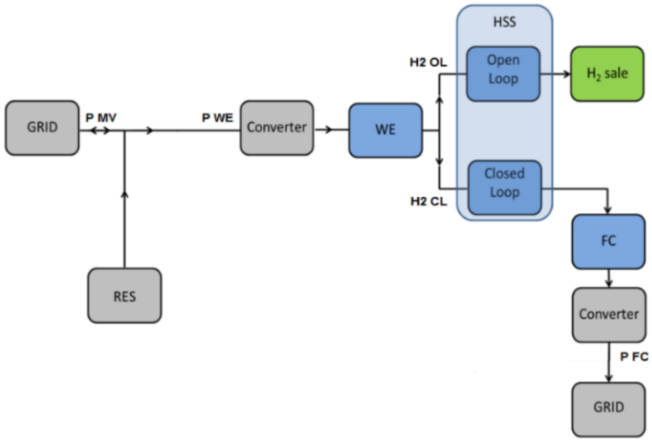

Figure 1. INGRID plant block diagram detailed with electricity and hydrogen flows.

The present paper is structured as following. In Section II, the INGRID system structure and operation are described and analyzed. In Section III, the energy management framework and its optimization process are depicted, along with the Objective Functions (OFs) and constraints. Section IV shows the communication framework and the EMS interaction with the monitoring tools, whilst Section V shows the optimization results and the EMS Graphic User Interface (GUI). In Section VI, the conclusions are given.

II. INGRID PROJECT SYSTEM

A. *INGRID project*

The INGRID project aims at contributing to balance supply and demand of different energy carriers. The main goal of this project is to handle the very large amount of power generated by RES systems, installed on MV distribution grid, by absorbing electric power, which is used to produce and store hydrogen [11]. In this way, an INGRID plant can prevent grid technical issues and power reverse flow phenomena. The electric energy absorbed by the WE is converted in hydrogen that is stored into two different storage systems belonging to two different channels: the Open Loop (OL) channel, in which the hydrogen is stored and then sent to the methane pipeline network, and the Closed Loop (CL) channel, in which the stored hydrogen is employed to supply the FC. The FC, in its turn, generates electric power for LV balancing services.

The EMS here proposed is tailored on the INGRID project demonstrator, which is being deployed, set up and will operate in Troia (Puglia, Italy).

B. *INGRID EMS overview*

The EMS of the INGRID system consists of several different components.

The core of the EMS is the Energy Supply and Demand Matcher (ESDM), which is in charge of scheduling tasks over 24 hours, performed by means of the optimization process. The flexibility of the optimization allows the user of the plant to properly choose even a shorter time horizon. It provides the power absorption and generation profiles for all the devices inside the system.

The data related to the forecasted power profiles of RES production and the prevision of price profiles are evaluated by a simulation tool that provides the EMS with these initialization data. Moreover, in order to meet the balancing strategy of the Distribution Service Operator (DSO), the grid operator sends to the EMS a suggested power consumption profile for MV grid and a suggested power generation profile for LV grid before the optimization process.

The EMS is also responsible of the monitoring of the entire plant by means of a specific tool developed in WinCC® [13] environment. The monitoring tool consists of an integrated HMI, that collects all the equipment operational parameters, as well as the alarms, and a communication framework which adopts the OPC protocol [14]. In Section IV, the monitoring tool is depicted.

At the end of the optimization process, a DSS allows the human operator to interact with the EMS and choose the most suitable working configuration for the plant. The DSS therefore selects a fixed number of optimized solutions and provides the user with a Graphical User Interface (GUI) through which these solutions can be displayed, compared and then adopted. These tools are shown in Section V.

III. MULTI-OBJECTIVE OPTIMIZATION FRAMEWORK

A. *Non-dominated Sorting Genetic Algorithm II (NSGA-II)*

The optimization process is implemented by means of an evolutionary algorithm, the Non-nominated Sorted Genetic Algorithm II (NSGA-II) [15][16]. Such an algorithm allows to simultaneously optimize two or more objective functions simulating the biological phenomenon of the evolution. The NSGA-II offers good performance in terms of convergence, as well as scalability, as it is shown by adding a new third objective function to the original optimization framework. The total complexity of the algorithm is $O(mN^2)$, where m is number of the objective functions and N is the size of the considered population.

This algorithm has been already tested and acknowledged in previous studies on the field of smart grid and electrical network management [17][18][19]. Moreover, its efficacy has been evaluated by comparing it with previous studies [20] that have addressed INGRID plant optimization task by means of mono-objective heuristic optimization processes, such as Tabu Search and Simulated Annealing.

Such a kind of optimization process offers a set of solutions, which is the population front resulting from the last generation. The DSS will help the user of the INGRID EMS to properly choose the most suitable solution.

B. *EMS optimization*

The optimization carried out by the ESDM module aims at scheduling all the electric power and hydrogen flow profiles inside the plant while optimizing two or more objective functions which are strictly related to the operational conditions of the system equipment.

The three INGRID system parameters selected for being optimized by the NSGA-II are the hydrogen flow in OL channel, the hydrogen flow in CL channel and the electric power generated by the FC. It worth noting that the sum of OL

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and CL hydrogen flows defines the power consumption of the WE through the efficiency of this device. In this way, all the significant parameters of the plant are managed, since OL hydrogen flow is directly linked to the State of Charge (SoC) of the HSS installed in this channel and thus to the hydrogen produced to be sold. Similarly, the CL hydrogen flow is responsible of the SoC of the HSS in the CL channel, which in its turn provides the generation availability of the FC. The complete definition of these physical quantities, achieved by implementing the multi-carrier hub model [21], allows to set three objective functions strictly related to them.

The first objective function is based on economic criteria. It addresses the maximization of the daily revenues deriving from the sale of hydrogen to the hydrogen market and balancing services to the LV grid. It can be defined by roughly considering the purchase cost of the input energy carriers, i.e. electricity from MV grid, and a sale price of the output energy carriers, i.e. electricity to LV grid and hydrogen to its proper market:

$$OF1=\sum_{i=1}^{24} - \begin{Bmatrix} \left[\left(P_{e,WE}(t_i)-P_{e,RES}(t_i)\right)c_{grid}(t_i)\right]+ \\ -\left[L_{H2}(t_i)p_{H2}+L_{e,LV}(t_i)p_{ANC}(t_i)\right] \end{Bmatrix} \quad (1)$$

where:

- $P_{e,WE}$ is the electric energy consumption of the WE during a time step, [kWh];
- $P_{e,RES}$ is the electric energy generated by the internal RES system during a time step, [kWh];
- L_{H2} is the amount of produced hydrogen to be sent to the H2 market during a time step, [kg];
- $L_{e,LV}$ is the electric energy produced by the FC injected into the LV grid during a time step, [kWh];
- c_{grid} is the energy purchase price from MV grid, [€/kWh];
- p_{H2} is the hydrogen sale price, [€/kg];
- p_{ANC} is the electrical energy sale price to the LV grid for balancing services, [€/kWh].

The second objective function is instead related to the smart grid philosophy adopted by the INGRID system: one of the most significant goal is to support DSOs on coping with power flows imbalances mainly caused by the huge amount of power produced by RES installed on MV distribution grid. In order to avoid RES generation curtailments, a very expensive and deplorable practice, the DSO estimates a power consumption profile that fits its technical contingencies and should be followed by the INGRID system. The EMS is therefore asked to accomplish this goal without constraining system operation to a fixed power value: actually, the WE is not forced to absorb the electric power suggested by the DSO, but its power consumption depends on the optimization strategy, that takes into account DSO. This has been implemented by means of a technical objective function aiming at minimizing the distance between the DSO power profile and the real power absorption of the INGRID system:

$$OF2=\sum_{i=1}^{24}\left[\frac{\left(P_{grid,MV}(t_i)-P_{DSO}(t_i)\right)}{1000}\right]^2 \quad (2)$$

where:

- $P_{grid,MV}$ is the total power absorbed from the MV grid, [kW];
- P_{DSO} is the power consumption suggested by the DSO, [kW].

This objective function as been designed as a numeric quadratic index in order to address suitably the distance between the two power profiles.

The evaluation of daily economic revenues takes also into account the level of compliance of the INGRID plant with this curve: if the plant manages to satisfy DSO within a small range around the suggested profile, a price discount for energy purchase is considered.

In this paper, a third objective function is introduced in order to manage the power injection of the FC in the LV distribution grid. As seen above, the request of a power profile, either a generation or a production one, is not considered as a constraint but as a suggested behaviour to fulfil network operators strategy. LV power profile is evaluated to exploit the availability of the INGRID CL storage system for, e.g., balancing services and for electric vehicle recharge programs. This third objective function is shaped as the second one, being a numerical index that stands for the distance between the power generation request and real power produced by the FC:

$$OF3=\sum_{i=1}^{24}\left[\frac{\left(P_{FC}(t_i)-P_{LV,dem}(t_i)\right)}{1000}\right]^2 \quad (3)$$

where:

- P_{FC} is the power produced by the FC available for LV balancing services, [kW];
- $P_{LV,dem}$ is the power demanded by DSO, [kW].

For the sake of simplicity, the constraints of the optimization problem are just described. These constraints are mainly inequality ones. They are related to the maximum and minimum rated power of the WE and FC, the maximum and minimum hydrogen flow of the OL and CL channels, the capacity of the two HSSs. Other technical constraints are due to the power variation limits imposed by the WE and FC. Actually, the delta power between two time stamps cannot be larger than a fixed value. Finally, the new hydride technology of HSSs needs particular conditions and procedures for the absorption and desorption tasks, which are taken into account by means of operational constraints.

As already stated, the requests of power profile at the MV and LV grid interface are not handled as equality constraints but by means of two different objective functions, so these profiles are followed according to the optimization criteria. This is one of the most innovative concept proposed by the INGRID project.

IV. Communication Framework And Monitoring Tool Integration

In this section, the communication framework among the EMS, the monitoring tool and the real plant devices are outlined. In Figure 2, all the modules of this framework and their interconnections are shown.

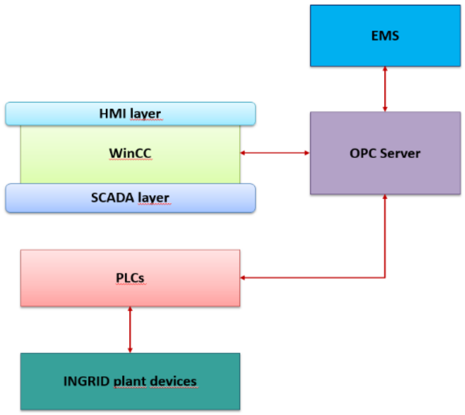

Figure 2. INGRID communication framework.

The OPC server has a central role in this structure since all the data are exchanged through the OPC protocol. In order to start the optimization process for the desired time horizon, the EMS reads the initialization data and the current plant configuration from the server. The data pertaining the device are synchronized to the Programmable Logic Controller (PLC) of each device inside the plant, and is also employed for the monitoring tasks handled by WinCC®. In its turn, the EMS performs the optimization and provides the system with the set points for the each time stamp over the entire time horizon. These set points, chosen from a continuous domain, are written in the OPC server and then are used by the monitoring tools, as well as from the PLCs of the real plant as an input for the real devices.

The optimization framework is able to cope with deviations of the real plant configuration from the set points suggested by the EMS or with errors in forecasted data. In this case, the optimizer performs a new optimization in real-time, starting from the data of the current configuration and/or the new forecasted profiles; the time horizon can be set considering only the remaining hours of the day.

The monitoring tool is a component developed on purpose for the INGRID project, which collects and integrates all the set points, operational parameters and the alarms regarding the plant equipment. In Figure 3, its HMI is shown. The HMI is part of the SCADA of the plant, which can be used for the general control of the plant. The EMS, by means of the DSS, can access the SCADA to perform its optimization. Human intervention is always prioritised, as it can be expected.

The HMI is currently implemented as a demo, since the OPC server is interfaced by simulation drivers.

V. RESULTS AND GRAPHIC USER INTERFACE

As mentioned in the previous sections, the optimization process schedules the set points of the plant equipment for a user defined time horizon. These set points are selected by the algorithm in order to achieve the best values of the OFs, thus the suggested plant configuration should allow high economic revenues, a good MV profile following and a good LV profile following. Nevertheless, the algorithm provides an optimized solution front, made by a number of suitable solutions equal to an entire population. Each of these solutions implies different values of the OFs, so it is important to properly choose the best solution that fits the user's current goal.

A DSS has been realized in order to ease this task: it automatically selects the three solutions that allow to reach the best value of the first OF (OF1 best), the best value of the second OF (OF2 best) and the best value of the third OF (OF3 best). They are clearly outlined by the GUI of the optimizer application, shown in Figure 4. This GUI displays some initialization data and the starting plant configuration, all the optimized energy flow profiles inside the plant for the three solutions selected by the DSS, the price profiles and the forecasted profiles of RES. The real plant data are not available yet, since the demonstrator plant is still under construction; so, the initialization profiles and the starting plant configuration are supposed among those representing a possible and effective operating condition.

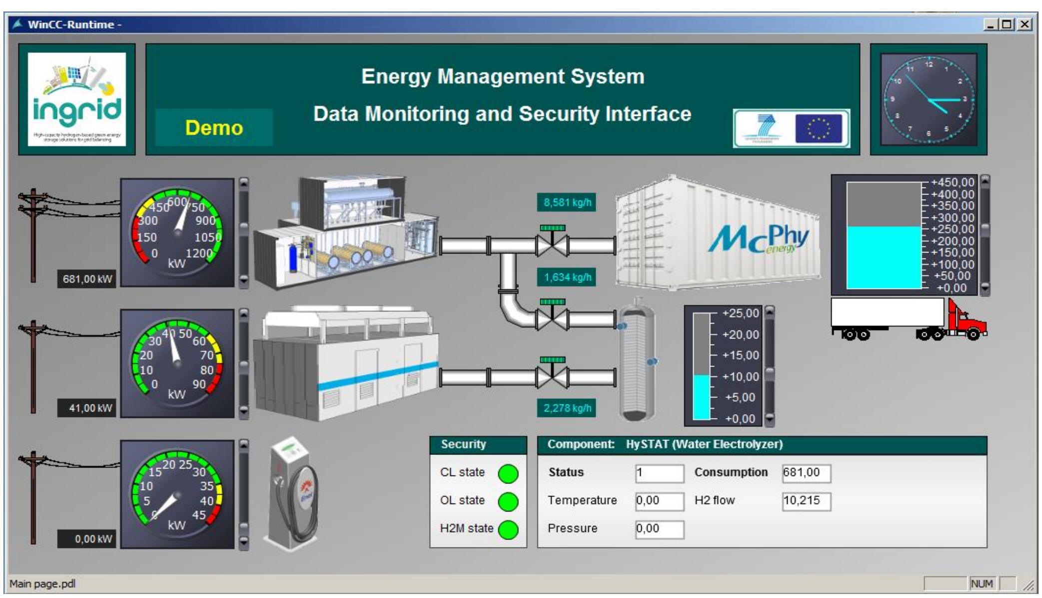

Figure 3. The HMI of the SCADA of the plant developed in WinCC® environment.

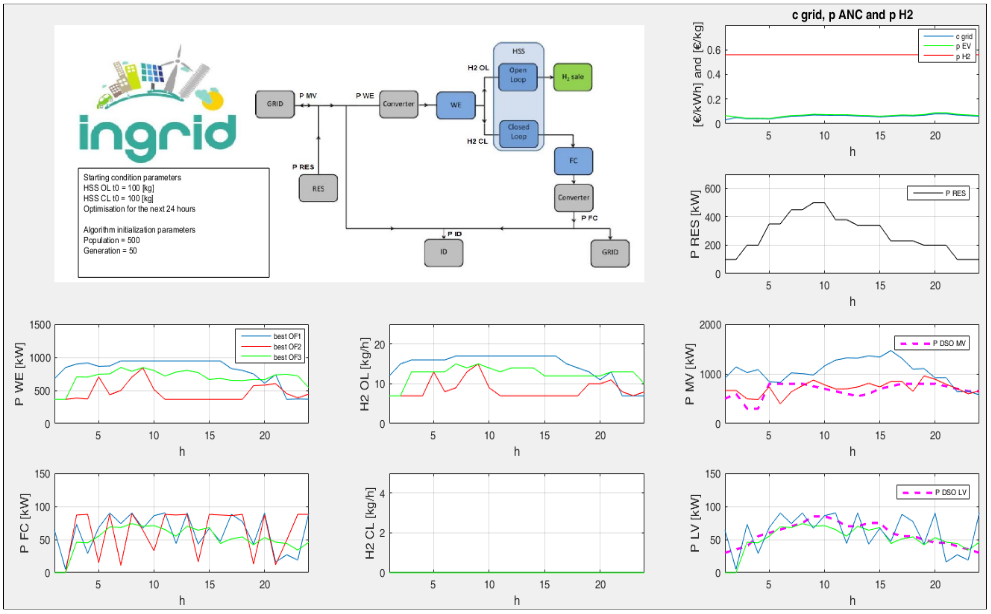

Figure 4. The Graphic User Interface (GUI) of the optimizer application developed in MATLAB® environment.

In particular, the last two rows of the GUI show the power consumption of the WE (P WE), the hydrogen flow on OL channel (H2 OL), the hydrogen flow on CL channel (H2 CL) and the power produced by the FC (P FC). All these data are provided for the OF1 best solution (blue lines), OF2 best solution (red lines) and OF3 best solution (green lines).

The last two charts of the last column show the graphic comparison between the two power profiles requested by the DSO, both for MV and LV grid, as well as the actual power absorption by the INGRID plant from MV grid and the power injected on LV grid. For the sake of clarity, they are shown again in Figure 5. It is possible to notice how INGRID plant manages to approximately follow the requests of the DSO. It worth noting that the best adherence to the MV profile request is achieved by means of the OF2 best solution, whilst the best adherence to the LV profile is achieved by means of the OF3 best solution. In these two graphs, the OF2 best curve (red) and the OF3 best curve (green) are compared to the OF1 best curve (blue), in order to show how OF1 best solution does not allow to respond to DSO profile suggestions (purple).

The human operator of the plant, once examined these solutions, has to choose the one that fits better the current operational contingencies of the plant. Depending from economic advices or grid technical issues, the human operator can be oriented on adopting a solution instead of another one. On this purpose, the DSS provides the user with a GUI that allows to choose one of the proposed solutions, making it the current desired plant configuration. In Figure 6, this GUI is shown. Using this interface, the user can accurately analyze the power profiles of the WE and FC, selecting them from the pop-up menu, for the three solutions selected by the DSS. The numerical values of the three OFs are displayed, too. Once selected the desired solution, the user is asked to click on the "OK" button to make it effective and to send all the configuration data to the OPC server to be synchronized to the PLCs controlling the plant devices.

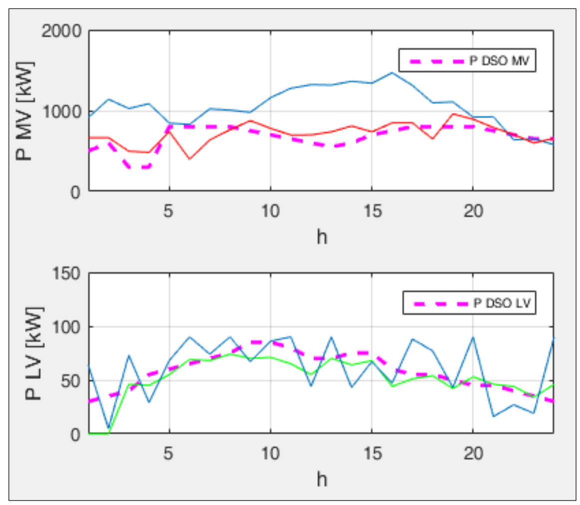

Figure 5. The graphic comparison between: MV grid DSO profile and INGRID plant power consumption for OF2 best solution; LV grid DSO profile and INGRID plant power generation for OF3 best solution.

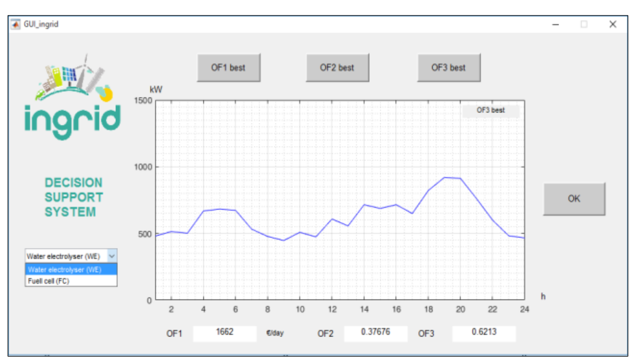

Figure 6. Graphic User Interface (GUI) of the DSS developed in MATLAB® environment.

VI. Conclusion and Future Work

This paper proposes the EMS for a multi-carrier energy system that involves both electricity, as well as hydrogen and interconnects three different energy distribution networks, providing them flexibility and balancing services.

The first part of the present study addresses the structure of the proposed system and the concept of multi-carrier hub. After that, the EMS structure is explained, along with all its modules. In particular, the optimization framework and its multi-objective algorithm are shown and analyzed. This multi-objective optimization process provides very good results and allows to implement very complex management criteria driven by different objective functions. In future studies, this kind of approach can be used for the optimization tasks of other smart grid or microgrid implementations, e.g., for the management of a district level and/or a building level power flows scheduling.

The last two sections explain how the data obtained by means of the optimization process are exchanged by this application and the plant equipment and how they are employed for defining the real plant configuration, as well as for monitoring purpose. The OPC protocol has been chosen in order to ease the communication with the industrial devices. Today, other protocols, such as IEC61850 and OpenADR, are under investigation for allowing a more flexible negotiation framework between the figures asking for a service, like the DSO in this study, and the systems in charge of fulfilling them.

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