A Matrix Model For An Energy Management System Based On Multi-Carrier Energy Hub Approach

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Abstract—**The INGRID FP7 European co-funded project studies several methodologies concerning hydrogen production and storage, aiming to provide services to electricity system operators for suitably balancing electrical supply and demand. In such a context, the problem of integrating different carriers into a single multi-hub optimiser represents a challenging topic for the research. This paper depicts the Energy Management System (EMS) of the plant which will be developed and built as a prototype of the INGRID system. The approach followed for the EMS design and development takes the cue from the matrix model presented in the rest of the paper, as well as the general optimisation problem formulation and the algorithm selected for its solution.**

Keywords-hydrogen solid-state storage; multi-carrier energy hub; matrix modelling; multi-objective optimisation.

I. INTRODUCTION

Last two decades have been characterized by the restructuring of vertically integrated energy systems towards liberalized markets, and by the increase of small distributed generation technologies and non-traditional energy carriers. At the same time, information and communication technology (ICT) equipment, like SCADA devices, data acquisition centres and control systems, have been the focus of development in order to provide better services for energy systems and devices. Furthermore, the growing awareness of the impacts of pollution has led to increased interest in sustainability, and environmentalism within governmental organizations, following the concept of sustainable development in order to increase "green" energy sources and reduce the emission of CO_2 in the atmosphere.

These changes in the energy systems, especially in electric power grids, are forcing the system operators, i.e., Distribution Service Operators (DSOs) and Transmission Service Operators (TSOs), to manage and operate their networks in new ways. Thus, it seems reasonable for future development on innovation within the existing infrastructure, to reuse it as much and as long as possible, by means of studying and designing new energy technologies and facilities. The INGRID FP7 European co-funded project [1]-[6] is studying several solutions concerning hydrogen storage, aiming to suitably balance electrical supply and demand. The proposed integrated approach for the INGRID system involves combining a solid-state high-density hydrogen storage system with advanced solutions for smart distribution grids, electrical power grids and methane pipeline networks. A concrete demonstrator will be implemented in Troia (Puglia, Italy), which will operate as an implementation and proof of concept of the overall INGRID system.

The possibility of planning and operating this kind of hybrid systems bridges both technical and economic demands, such as DSO requests, ancillary services, and, above all, price signals from energy markets.

In Section II, the structure of the INGRID system and its components are defined; in Section III, the concept of multi-carrier energy hub is introduced and adapted to the INGRID system structure; Section IV, depicts the proposed matrix model for the INGRID system and the related equations; Section V, is focused on the control algorithm chosen for the EMS implementation; in Section VI, the conclusions are given.

II. THE INGRID PROJECT SYSTEM

A. System structure and working conditions

The structure of the system proposed inside the INGRID Project is composed by a Renewable Energy Source (RES) power generation plant (PV and/or windmill), an Electric

Vehicle Recharge Station (EVRS), a Water Electrolyser (WE) with its AC/DC conversion device, a Fuel Cell (FC) with its DC/AC conversion device and an innovative Hydrogen Solid-state Storage System (HSS). This grid is connected to the Medium Voltage grid (MV, 20 kV) and the Low Voltage grid (LV, 0.4 kV). Figure 1 shows the block diagram of the system [5].

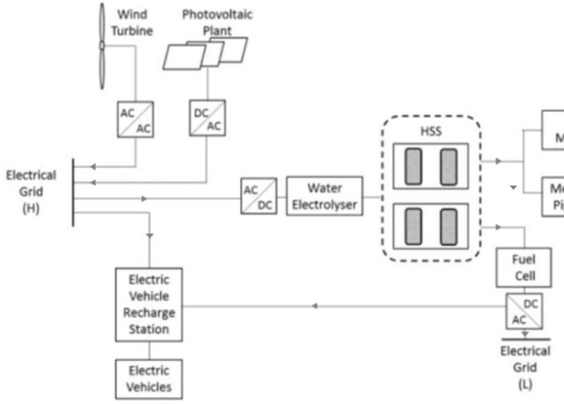

Figure 1. Block diagram of the INGRID system.

One of the most particular features of this system is the brand new hydrogen storage technology based on magnesium hydride, which offers several practical advantages: it adsorbs and desorbs hydrogen at a constant pressure, the high-temperature metal hydride and the low temperature metal hydride have similar dissociation pressures (a feature that allows the process to be self-regulating), and the hydrogen solid-state storage has the capability to store more hydrogen per mass unit than gas and liquid storage forms [17][18].

The WE can absorb electric power both from the MV grid and RES plant. The hydrogen produced by the WE may be sent either to the hydrogen market or to the methane distribution network (as considered in [19]), forming a so called “Open Loop” (OL). Otherwise, the hydrogen may be used to re-obtain electricity by means of the FC, in order to create a “Closed Loop” (CL). The EVRS can be supplied either from the internal RES plant, or directly from the MV grid or the FC generator; the EVRS is managed by an Intelligent Dispenser (ID). These power flows are outlined in Figure 1. The possibility of providing ancillary services directly to the LV grid, by means of the internal RES and/or the FC is being experimented.

A key aspect of the INGRID system is the close collaboration with the DSO for the general balance of the grid. For example, the DSO may request a power injection in the MV or LV feeder to facilitate their system operations. This could include delivering ancillary services, as well as balancing the consumption and generation of power, especially when the risk of power reverse flow occurs to the TSO network (very common in regions characterized by huge levels of RES production). In all these cases, an INGRID based plant would respond according to the availability of power and storage capacity, to fulfil the incoming requests, while keeping in mind its own strategic objectives. This goes beyond the already existing storage systems mainly composed of devices directly controlled by the network operators, and promotes a new form of collaboration and negotiation between the plant and the DSO, as well as the energy market.

B. *INGRID demonstrator*

The INGRID Project comprises the design and development of a demonstrator prototype, which is planned to be deployed in Troia (Puglia, Italy). The WE maximum rated power is equal to 1152 kW, the FC nominal power is 90 kW, the hydrogen storage capacity of the CL tank is equal to 25 kg of hydrogen, while the OL tanks has a total capability of 900 kg of hydrogen (450 kg in use, 450 kg as reserve). The CL storage system has better performances than the OL, because of its technological features, e.g., specifically the Phase Change Material (PCM) and the heat management unit, that allow higher efficiency if the stored energy is effectively used within few hours. Otherwise, the more capacious yet less efficient OL tanks can be used instead.

The prototype will be connected to a MV primary substation (150 kV/20 kV) and will absorb electricity from the electric grid as a flexible load from 0.365 to 1.2 MW. As a variable generator (0-90 kW), the plant will be connected to a low voltage power line. The main difference between traditional auxiliary storage systems, entirely controllable by the DSO, and the proposed one is that the INGRID system is intended to collaborate with DSO, rather than being directly commanded, to optimize its power consumption and generation according to several possible custom strategies, (e.g., to maximise the economical incoming of the plant, to minimise the carbon emissions, to follow the DSO profile, etc., or a combination of several strategies). For this reason, the multi objective optimisation can represent a promising approach to address the problem.

III. MULTI-CARRIER ENERGY HUB

As reported in the introduction, the development of modern energy systems is focused on defining hybrid structures involving various energy carriers. Therefore, this paper presents a hybrid and integrated multi-carrier energy system. The multi-carrier energy hub is defined as a “hybrid energy system which interfaces between energy producers, consumers and the transportation infrastructure” [7]. In Figure 2, an example of a possible multi-carrier energy hub is shown.

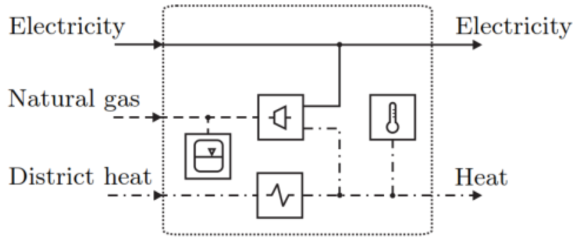

Figure 2. Example hub with gas turbine, heat exchanger, gas tank and heat storage [7].

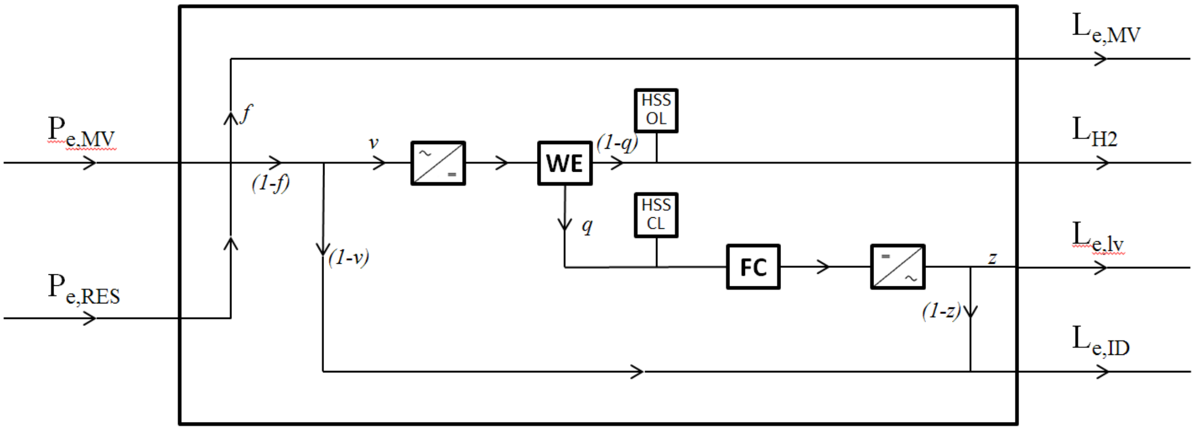

Figure 3. Flow chart of the proposed INGRD system.

$$\begin{bmatrix} L_{H_2} \\ L_{e,LV} \\ L_{e,ID} \\ L_{e,MV} \end{bmatrix} = \begin{bmatrix} (1\text{-}f)v\eta_R\eta_{WE}(1\text{-}q)c_F & (1\text{-}f)v\eta_R\eta_{WE}(1\text{-}q) & e_{OL} & 0 \\ (1\text{-}f)v\eta_R\eta_{WE}\eta_{FC}\eta_I zqc_F & (1\text{-}f)v\eta_R\eta_{WE}\eta_{FC}\eta_I zq & 0 & e_{CL}z \\ (1\text{-}f)\left[v\eta_R\eta_{WE}\eta_{FC}\eta_I(1\text{-}z)q+(1\text{-}v)\right]c_F & (1\text{-}f)\left[v\eta_R\eta_{WE}\eta_{FC}\eta_I(1\text{-}z)q+(1\text{-}v)\right] & 0 & e_{CL}(1\text{-}z) \\ fc_F & f & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} P_{e,MV} \\ P_{e,RES} \\ \dot{E}_{OL} \\ \dot{E}_{CL} \end{bmatrix}. \qquad (1)$$

G. Andersson et al. [7]-[11] have proposed a matrix modelling approach for the entire hybrid system, even with storage devices inside. Through this model, the conversion and storage stages of multiple energy carriers may be represented generally and comprehensively. Furthermore, the matrix-based approach is appropriate to use in the formulation of optimisation problems and allows easy implementation of complex optimisation algorithms. Accordingly, a model of the INGRID hybrid system using the approach briefly explained above (whose complete description is available in the referenced works) is proposed in the next section.

IV. MATRIX-BASED MODEL FOR INGRID SYSTEM

The system proposed by the INGRID Project can be modelled through the matrix-based approach introduced in the previous section: the final aggregate instantiation is a multi-carrier energy system that involves both electricity and hydrogen; this model also permits dealing with storage devices, and so it is perfectly suitable for the system purposes.

A graphical representation is depicted, in terms of a flow chart reporting all the devices working in the INGRID system, in Figure 3.

In this flow chart, the different "P_i" denote the input carriers of the system, which are the electric powers coming from the MV grid and RES internal to the plant; the different "L_j", in their turn, denote the output carriers considered as loads. These are: (i) the possible electric power injection in the MV feeder; (ii) the hydrogen flow toward the specific market, (iii) the electric power sent to the LV grid and (iv) the electric power used for supplying the EVRS through the ID. The WE and the FC are considered, respectively, with their AC/DC and DC/AC conversion devices. Eventually, the HSSs, for both OL and CL, are modelled by their own blocks.

The flow chart presents dispatching factors whenever a flow line splits in two different paths (cf. "*f*", "*v*", "*q*" and "*z*" in Figure 3). These factors allow the definition of the amount of energy sent to one process or another. All of them can assume a value between 0 and 1.

For instance, the factor "*q*" fixes how many kilograms of hydrogen per second flow in the OL or in the CL tanks.

The relationships between different energy carriers can be directly deduced by the flow chart and can be expressed through a matrix equation (1).

In this matrix model, each device is represented by its instantaneous efficiency "η_i"; the storage system contribution is represented by the parameters "e_{OL}" and "e_{CL}", that can be seen as the forward or reverse energy efficiencies of the whole storage system, depending on their working state:

$$e_{OL} = \begin{cases} -e^{+}_{OL} & \text{charging} \\ 1/e^{-}_{OL} & \text{discharging} \end{cases} \qquad (2)$$

$$e_{CL} = \begin{cases} -e^{+}_{CL} & \text{charging} \\ 1/e^{-}_{CL} \cdot \eta_{FC}\eta_I & \text{discharging} \end{cases} . \qquad (3)$$

These parameters will be multiplied by $\dot{E}_\alpha$ (where α = OL, CL) that corresponds to the internal flow of the device, assumed to be the time derivative of the stored energy.

The "c_F" coefficient allows the model to provide the possible plant configurations, depending on the DSO requests: (i) for the plant as a power consumer, and (ii) for the plant as a power producer when a possible power injection into the MV feeder is requested by the DSO. When c_F=1 and f=0, the entire system is supplied both by the grid and the RES plant; if c_F=0 and f≠0, the power produced by the internal RES plant is enough to supply the INGRID system and also to send power to the MV grid (e.g., if f=0.4, the 40% of the RES power is sent to MV grid and 60% is sent to the storage systems). Finally, the system equations for both the described conditions can be derived;

- if c_F=1 and f=0:

$$L_{H_2}= \left(P_{e,MV}+P_{e,RES}\right)v\eta_R\eta_{WE}\left(1-q\right)+\dot{E}_{OL}e_{OL} \tag{4.1}$$

$$L_{e,LV}= \left(P_{e,MV}+P_{e,RES}\right)v\eta_R\eta_{WE}\eta_{FC}\eta_I zq+\dot{E}_{CL}e_{CL}z \tag{4.2}$$

$$L_{e,ID}= \left(P_{e,MV}+P_{e,RES}\right)\left[v\eta_R\eta_{WE}\eta_{FC}\eta_I(1-z)q+(1-v)\right]+ \\ +\dot{E}_{CL}e_{CL}\left(1-z\right) \tag{4.3}$$

$$L_{e,MT}=0; \tag{4.4}$$

- if c_F=0 and f≠0:

$$L_{H_2}=P_{e,RES}\left(1-f\right)v\eta_R\eta_{WE}\left(1-q\right)+\dot{E}_{OL}e_{OL} \tag{5.1}$$

$$L_{e,LV}=P_{e,RES}\left(1-f\right)v\eta_R\eta_{WE}\eta_{FC}\eta_I zq+\dot{E}_{CL}e_{CL}z \tag{5.2}$$

$$L_{e,ID}=P_{e,RES}\left(1-f\right)\left[v\eta_R\eta_{WE}\eta_{FC}\eta_I\left(1-z\right)q+\left(1-v\right)\right]+ \\ +\dot{E}_{CL}e_{CL}\left(1-z\right) \tag{5.3}$$

$$L_{e,MV}=P_{e,RES}f. \tag{5.4}$$

V. MULTI-OBJECTIVE OPTIMISATION ALGORITHM FOR EMS STRUCTURE

By means of the proposed matrix-based model, the operating conditions of the INGRID system can be simulated and, thus, all the energy flows of each carrier of the system can be calculated. The INGRID EMS has to indicate the most suitable configuration of all the devices, sending an optimal working set-point to the local control units of each device.

The logic control criteria are defined by the EMS in order to meet one or more objectives, which are expressed by one or more functions depending on the operating conditions of the system. The most common objective functions [15], which the optimisation problems are referred to, are:

- the total generation cost of the whole supplied power;
- the energy losses in the grid;
- the total polluting emissions of the system.

This kind of problem can be solved with multi-objective optimisation, which optimises several objective functions simultaneously. In such a kind of problem, there is not a unique optimal solution, but a set of suitable solutions fitting the user's goals; these are approximated solutions that can be very near to the ideal solution of an optimisation problem.

Assuming that $f_i(\mathbf{X})$ are *k* different *objective functions*, the multi-objective problem is defined [16] as minimizing the vector of functions:

$$\mathbf{F(X)}=[f_1(\mathbf{X}), \ldots, f_k(\mathbf{X})]^T \tag{6}$$

which is subject to a set of *inequality constraints*, defined as:

$$g_i(\mathbf{X})\leq 0 \qquad i=1, \ldots, m \tag{7}$$

and a set of *equality constraints*, defined as:

$$h_j(\mathbf{X})=0 \qquad j=1, \ldots, p. \tag{8}$$

The *decision variables* are the numerical values which are expected to be chosen, as solutions, by the multi-objective optimisation. They are the independent variables of the objective functions and are used to minimise them; they are represented as the vector:

$$\mathbf{X}=[x_1, \ldots, x_n]^T \qquad \mathbf{X}\in\mathbf{\Omega}. \tag{9}$$

where $\boldsymbol{\Omega}$ is a n-dimensional vector space and represent the set of the feasible region of $\boldsymbol{X}$.

The INGRID system EMS relies upon the optimisation of a costs-benefit objective function [5] which refers to the purchase of electrical energy from the MV grid and to the sale of the produced hydrogen, the provision of ancillary services to the LV grid and the supply of the ID. A second fundamental objective function refers to the collaboration with the DSO: one of the goals of the system is following the power consumption profile requested by the DSO (which, in turn, is calculated by the DSO for overall grid system balancing) in order to achieve an economic discount on the energy acquisition price. Indirectly, this goal connects the contribution of the plant to the stability of the whole smart grid. A third possible objective function can involve the reduction of Greenhouse Gas (GHG) emissions, which is still under investigation.

Some of the problem's inequality constraints are fixed by the electrical power and hydrogen minimum/maximum rated values. Other constraints are related to the state of the storage devices, in order to avoid the production of hydrogen when the HSSs are not able to store it. The only equality constraint on the system is defined by the total produced hydrogen volume during the optimisation time horizon.

Such multi-objective optimisation can be resolved through heuristic algorithms [12]-[14], because of the non-linear nature of the objective functions. Previous works of the INGRID Project [5][6] have tested some heuristic algorithms, such as Generalized Reduced Gradient (GRG), Simulated Annealing (SA) and Tabu Search (TS) towards a simplified formulation of the optimisation problem, which have been used to deal with a mono-objective function related to the economic benefits for the system owner.

The appointed algorithm in order to manage the control issue of EMS is the Non-dominated Sorting Genetic Algorithm-II (NSGA-II) [13][14]. The algorithm is based on Pareto-dominance and Pareto-optimality, which are fundamental concepts in multi-objective optimisation. A solution $\mathbf{X} \in \Omega$ is said to be *Pareto-optimal* with respect to Ω if and only if there is no $\mathbf{X'} \in \Omega$ for which

$$\mathbf{v}=\mathbf{F}(\mathbf{X'})=[f_1(\mathbf{X'}), \ldots, f_k(\mathbf{X'})]^T \tag{10}$$

dominates

$$\mathbf{u}=\mathbf{F}(\mathbf{X'})=[f_1(\mathbf{X'}), \ldots, f_k(\mathbf{X'})]^T. \tag{11}$$

A vector

$$\mathbf{u}=[f_1(\mathbf{X'}), \ldots, f_k(\mathbf{X'})]^T \tag{12}$$

is said to *dominate* another vector

$$\mathbf{v}=[f_1(\mathbf{X'}), \ldots, f_k(\mathbf{X'})]^T \tag{13}$$

(denoted by $\mathbf{u} \preceq \mathbf{v}$) if and only if $\mathbf{u}$ is partially less than $\mathbf{v}$, i.e.,

$$\forall i\in\{1,\ldots, k\},\ u_i \le v_i \wedge \exists i\in\{1,\ldots, k\}: u_i<v_i. \tag{14}$$

Therefore, the Pareto-optimal Set, $\mathcal{P}^*$, is defined as:

$$\mathcal{P}^* := \{\mathbf{X}\in\Omega \mid \neg\exists\ \mathbf{X'}\in\Omega\ \mathbf{F}(\mathbf{X'})\preceq\mathbf{F}(\mathbf{X})\}. \tag{15}$$

Some recent papers [19]-[26] have proved that the NSGA-II is quite efficient, especially in the field of power distribution operation and planning.

This genetic algorithm separates and orders the population (the set of whole individuals) following a criterion based on non-dominance: individuals which are not dominated by any other individual are labelled with a higher rank; individuals that do not dominate any other individual have a lower rank. By means of a Binary Tournament Selection, individuals with the best rank are chosen to be the parents of the next generation. Following the analogy with the biological phenomena, crossover and mutation actions are performed on the selected elements, through a Simulated Binary Crossover and Polinomial Mutation [14]. Now, the parent and the child population are mixed and only the best N individuals are chosen for the next generation, where N is the population size. This is one of the most important features of the NSGA-II, called "elitism", which avoids possible losses of valuable solutions.

The algorithm results are an entire population of Pareto-optimal solutions. An important component of the EMS in INGRID will be its Decision Support System (DSS). This subsystem allows the set-point configuration of all devices of INGRID system to be chosen. Such a choice can be done either manually by a human operator who supervises the plant, or automatically by a decision maker algorithm which autonomously sets the operating configuration, choosing it from the feasible solutions provided by optimisation algorithm. The DSS will be designed once the demonstrator infrastructure is physically realised.

VI. CONCLUSIONS

In this paper, the problem of managing a multi-carrier energy hub has been discussed. The problem arises when other products, such as hydrogen, are used to store and later re-use the electrical energy flowing from the network, virtually decoupling the electrical side from the other. The concept analysed in depth, which will be implemented on a test site in the INGRID FP7 project, is a very promising approach for extending the concept of a multi-carrier energy hub to include other industrial intermediate products in process industry. This paper, in particular, has introduced the possibility to use multi-objective optimisation approaches to solve the problem in a more complete way, finding solutions that provide the fulfilment of other objectives than just the costs minimization. In the future, a comprehensive study will be performed on the economical sustainability of the entire system, exploiting the results of the implementation of algorithms over the multi-objective function optimisation.

ACKNOWLEDGMENT

This work is part of the INGRID project, co-funded by the European Commission within the FP7 Framework Programme. Authors thank the members of the INGRID Consortium as well as the European Commission for supporting any project dissemination activities. This work reflects only the authors' views. The Commission is not liable for any use that may be made of the information contained therein.

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