Energy Management in a Smart Grid-integrated Hydrogen-based Storage

Electric Grid balancing when integrating large-capacity Renewable Energy sources

Diego Arnone, Alessandro Rossi, Massimo Bertoncini
Engineering I. I. S.p.A.
Palermo and Roma, Italy
diego.arnone@eng.it, alessandro.rossi@eng.it,
massimo.bertoncini@eng.it

Diana Moneta
Ricerca sul Sistema Energetico S.p.A.
Milano, Italy
diana.moneta@rse-web.it

Rosario Proietto
Onyx Technology S.r.l.
Roma, Italy
proietto.rosario@gmail.com

Giuseppe Tondi
ENEL Distribuzione S.p.A.
Roma, Italy
giuseppe.tondi@enel.com

Carlos García-Santiago
Tecnalia
Miñano, Spain
carlosalberto.garcia@tecnalia.com

***Abstract*—The integration of plants for the distributed production of electric energy from renewable (especially solar and wind) sources into the electric grid has become an increasingly complex task over the last years because the amount of "green" energy nowadays injected into the grid is sometimes comparable to the energy supplied by traditional thermal plants. This introduces a strong variability, a partial unpredictability and a significant dependency from the location, three of the main features that characterize the energy produced by photovoltaic plants and wind turbines. This paper introduces a high level description of an innovative system that integrates high-capacity hydrogen-based storage into the grid with the aim of contributing to the grid balancing and to the improvement of the power quality. A concrete demonstrator is being designed and will be connected to a properly selected primary substation where most of the power lines connected to the medium voltage bus bar are active because they are connected to many photovoltaic plants and wind turbines.**

Keywords-energy management system; hydrogen-based storage; integration of renewable energy sources; grid balancing.

I. INTRODUCTION

Thanks to a growing environmental awareness as well as to many government directives and incentives, the distributed production of energy from renewable sources is rapidly expanding. The amount of "green" energy nowadays injected into the grid is in some places comparable to the energy supplied by traditional thermal plants. In order to obtain an efficient Renewable Energy Sources (RES) injection into the grid in terms of stability and power quality, both transmission and distribution grids need a certain level of "smartness", because RE is characterized by non-controllable variability, partial unpredictability and locational dependency [1]. So, the integration of photovoltaic plants and wind farms into the grid entails the need to provide proper solutions to a wide range of problems not entirely new to the network but still more critical. The huge amount of RE can negatively affect the efficiency of classic fossil fuel-based generators and reduce their lifetime because it forces them to operate in not optimal and continuously changing conditions to balance load and overall supply.

Today, Distribution System Operators (DSOs) must compensate RE output fluctuation, grid faults, conventional generation outages, load variation with more flexibility consisting in conventional generation flexibility (e.g., "unit commitment" techniques), demand/response, energy storage (e.g., batteries, hydrogen production and storage, water pumping, etc.) and grid-friendly RE generation. In this context, the INGRID FP7 European co-funded project [2][3][4] is studying several solutions, which this work, still in progress, is part of. In order to balance power supply and demand by empowering the grid flexibility, the proposed solution may either shift the electricity adsorption or modify the energy injected into the grid. These methods must be applied in the context of a strict cooperation with the distribution system operator. Our integrated approach involves combining a solid-state high-density hydrogen storage system with advanced solutions for smart distribution grids, which monitor and control a large number of RES. In the vision of the INGRID project, when a huge amount of energy produced by RES injected into the distribution grid reaches a critical level in terms of balancing, power quality, grid stability and so on, this amount of green energy (or part of it) may be transformed and moved on a different energy vector, e.g., hydrogen, syngas, Full Electric Vehicle (FEV)

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mobility, or simply injected into the grid again, by providing proper ancillary services. The brain of the proposed solution is the Energy Management System (EMS).

The remainder of the paper is organized as follows: in Section II, an overview of the related works is provided; in Section III, the INGRID System is described; in Section IV, more details are provided about the role played by the EMS; in Section V, the EMS optimisation problem is modelled as well as the solution that is being investigated to address it; in Section VI, the conclusions are given.

II. Literature Review

Many research projects and initiatives are focused on proposing new approaches and solutions to balance energy supply and demand when renewable sources are integrated into the electric grid. Recently closed EU co-funded FP7 projects, like SEESGEN-ICT [5], INTEGRIS [6] or HiPerDNO [7], aim at designing and implementing new solutions for EMS, in particular through communication networks improvements. Other research works, like the recently ended MIRABEL project [8], propose an approach on a conceptual and infrastructural level that allows energy distribution companies to balance the available supply of renewable energy sources and the current demand in an ad-hoc fashion. Moreover, many research works concerning optimization strategies for EMS have been published. As reported in [9][10][11] the optimization strategy is based on a proper objective function that may be a profit function or a losses function. However, despite a considerable amount of research undertaken in ICT-based EMS, significant research challenges do exist in terms of improving sustainability, reliability and cost-efficiency of energy supply. Of course, in order to cope with these challenges, significant changes towards an ICT-empowered Smart Energy Grid are required. Moreover, the expected transition to Smart Grids requires deep technological transformations and huge financial investments. This involves enhancing and upgrading existing infrastructure, implementing new systems and improving integration throughout the ICT operating environment.

In general, very partial and fragmented solutions have been proposed so far. A comprehensive yet fully integrated contextual data model is missing, as well as a suitable intelligence in the processing of the captured information; all of these aspects will be fundamental for proactively predicting the energy production and accordingly fine tuning the energy produced and transmitted into the grid.

Current EMSs are lagging behind due to their low integration level among the different subsystems, like power grid, RE sources, storage system, etc., which prevent EMSs to effectively accomplish their task of mitigating the intermittent energy supply from RE sources through balancing activities offered by storage systems.

III. The INGRID System

The INGRID system will strictly collaborate with the Distribution Management System (DMS). That collaboration will allow either to adsorb or to inject active or reactive energy considering both DSO indications and results coming from each subsystem.

When needed, the INGRID system may indirectly adsorb the electricity produced by RES based plant outside INGRID system by means of an electrical connection to the grid. Moreover it may directly adsorb/supply electricity if an internal RES (iRES) based plant inside INGRID system is taken into account.

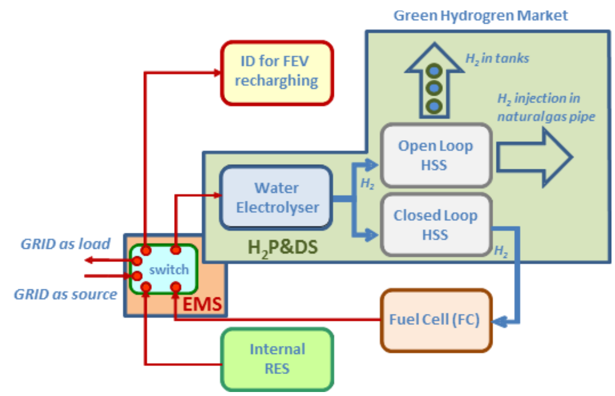

Figure 1. Graphical representation of the INGRID System.

As depicted in Figure 1, the adsorbed electricity is used to supply a Water Electrolyser (WE) to produce hydrogen which may be either stocked in an innovative solid-state storage system by exploiting a patented magnesium hydrides-based technology, or directly injected into existent methane pipeline (if feasible). The hydrogen, stored in high capacity but conventionally sized tanks, can be sold in the green H_2 market (open loop) or can be used to supply a Fuel Cell (FC) that, according to the specific strategy adopted by the System, converts it again in electricity (closed loop). This electricity is either injected into the grid or used by the charging stations of an innovative green urban mobility system [12] whose management system is named Intelligent Dispenser (ID). Grouping all the subsystems in two main categories, i.e., loads or sources, the INGRID EMS, addressed by this paper at a very preliminary stage, is the ICT-based component in charge of monitoring and controlling the power flows from sources to loads.

TABLE I. Possible energy connections

		Loads			
		Grid	*AUX*	*ID*	*H_2P&D*
Sources	*Grid*	no	yes	Yes	Yes
	iRES	yes	yes	yes	Yes
	FC	yes	Yes	Yes	No

In Table 1, a schema of the possible electric connections inside the plant is reported, where AUXiliary equipment (AUX) is considered as well.

In order to perform a real-time demand/supply balance according to a specific strategy (e.g., economic sustainability), the EMS must exchange information about energy requests and offers, costs and prices, constraints and degrees of freedom, with all the System sub-units that will be equipped with proper management systems. For instance, the Hydrogen Production and Distribution System (H_2P&DS)

will control hydrogen production, manage its storage, accept purchase orders, supervise and manage the tanks delivery and its injection into the gas distribution network. But, it also will predict its own power adsorption in the future hours and communicate this adsorption profile to the EMS that, in its turn, will decide if and to what extent the required power adsorption profile will be followed. In general, the EMS receives (sends) from (to) each subsystem a load or generation trend intended as a graph of power vs time. The time (horizontal axis) is divided in different "time slots" where the EMS, in accordance with a certain optimisation strategy, defines the power level (vertical axis) of each subsystem, i.e., the set-point of each component, its electrical connections and widely the plant configuration.

The System that is being currently designed will be instantiated in a concrete 39 MWh energy storage facility that will be deployed and will operate in Troia (Puglia region, Italy). As a variable passive load (0 - 1200 kW), the plant will be connected to a middle voltage feeder of a primary substation (150/20 kV/kV). As a variable generator (0-90 kW), the plant will be connected to a low voltage power line.

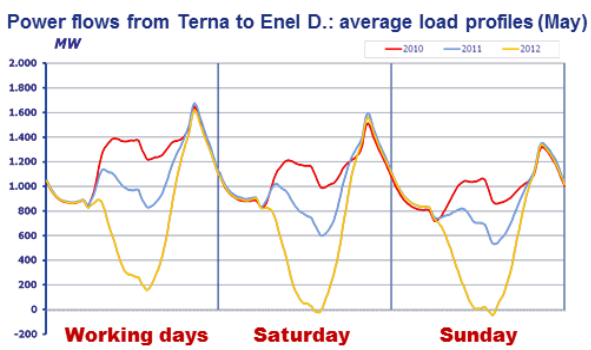

Figure 2. Exchange profile from Terna to Enel Distribuzione in Puglia region.

The primary substation has been identified among the ones having an high value of power reverse flow, calculated as the number of hours in one year in which the phenomena occurs. The curves in the Figure 2 represent the power requested by the distribution network managed by Enel Distribuzione in the Puglia region, to the transmission and transport grid, managed by Terna, the unique Transport System Operator (TSO) in Italy. The diagram shows the effect of the growing distributed generation from 2010 to 2012. The curves are lowered along years reaching a value of zero (in 2012, the local RES generation balanced the local adsorption) and even a reverse flow during the low load days occurred.

IV. THE ROLE PLAYED BY THE EMS

The EMS is the core of the INGRID system defining the energy adsorption/supply of the INGRID components. Energy Management Systems can be found in a number of different applications, since this generic denomination can be adopted whenever some kind of management must be applied to energy (e.g., mobile devices, data centres, FEVs, smart buildings, etc.).

In the Smart Grid domain, the concept of EMS-Family has been recently proposed [13]; it includes different types of EMS for generation plants, for TSOs, for DSOs, for substations, for micro-grids and final energy consumers. All these systems are coordinated by a global EMS that can be considered as the Smart Grid brain. The system described in this paper is in charge of dispatching electric power flows among the different sub modules of the overall infrastructure by significantly contributing to grid balancing, while ensuring the economic sustainability by selling hydrogen and providing FEV charging services.

The proposed EMS will be based on the concept of a closed-loop feedback control process. The feedback cycle starts with the collection and monitoring of relevant data from the interested sources that reflect a fine-grained state of the whole system. A comprehensive contextual information model will fully describe the whole status of the involved parties, i.e., the Green Energy Storage (GES), the grid or the Green Urban Mobility System, as well as factors which affect the decisions for energy dispatching, i.e., price of both energy and hydrogen, historical energy demand, etc. Structuring and reasoning about the collected data will be done during the subsequent analysis phase which will include machine learning methods and semantic contextual information extraction, business intelligence and statistical methods, consumption forecasting and distribution rules.

The analysis phase will originally combine and integrate intelligent processing technologies, e.g., basic and advanced statistics, data mining, complex event processing (CEP), predictive analytics, etc., to plan all the power flows internal to the plants and towards the grid as well as the hydrogen tanks transfers into the green hydrogen market.

Applying CEP techniques in the domain of the Smart Grid will allow to detect relevant events from the distributed and heterogeneous data sources and to analyse their impact in real time. Based on the results coming from the analysis, the EMS will take a decision about how to reach a desirable state, often taking into account opposing goals, involving also external factors, such as local policy for a risk analysis about reliability of the whole energy system.

Finally, in order to accomplish all the decision task balancing the energy flows, the EMS must monitor each of the overall system sub-modules, i.e., the WE, the Hydrogen Solid-state Storage (HSS), the FC, the ID and its scheduling system, the local RES production and related predictions as well as all the request coming from the DSO (e.g., through the DMS), the price of energy, the price of hydrogen, etc.,

The full feedback process can follow two approaches where, according to the requirements of reliability and/or to risk policies, a human intervention can be required or not, enabling the EMS system to follow either fully automatic or semi-automatic paradigm by requesting the human intervention in order to achieve the desired goal. So, human operators will be able to question, and possibly, to override the decisions. Similarly, the knowledge will be incremental, learning from past successful and unsuccessful decisions taken by the system, as well as from issued human advices.

V. THE EMS OPTIMISATION PROBLEM

The optimisation problem is related to the maximisation of an objective function. In this case revenues and costs have to be taken into account and a profit function is considered, as fully described in [14], and just reported here.

$$\sum_{i=1}^{N}\{P_{WE-HSS-OL}(t_i)\cdot\Delta t\cdot K\cdot\eta\cdot p_{H_2}\cdot w_1+P_{IDdemand}(t_i)\cdot\Delta t\cdot p_{EV}(t_i)+$$
$$+\beta\cdot P_{FC}(t_i)\cdot\eta\cdot\Delta t\cdot p_{EV}(t_i)\cdot w_2+(1-\beta)P_{FC}(t_i)\cdot\eta\cdot\Delta t\cdot p_{ANC}(t_i)\cdot w_2$$
$$+[P_{RES}(t_i)\cdot\Delta t\cdot c_{grid}(t_i)-P_{IDgrid}(t_i)\cdot\Delta t\cdot c_{grid}(t_i)-(P_{WE-HSS}(t_i)\cdot\Delta t\cdot$$
$$\cdot c_{grid}(t_i)]\cdot[1-\alpha\cdot d_{\%}^{-}] \quad (1)$$

The WE power level at a generic instant is represented by P_{WE-HSS} where $P_{WE-HSS-OL}$ is the part dedicated to the open loop. $P_{IDgrid}\Delta t$ is the energy adsorbed by the grid to supply the ID and is the part of the overall required energy ($P_{IDdemand}\Delta t$) sold at the price p_{EV}. βP_{FC} represents the FC power dedicated to the ID, while $(1-\beta)P_{FC}$ is related to the ancillary services. p_{ANC} represents the related incentive, c_{grid} the electricity price, P_{RES} the RES power. K is a conversion parameter from electrical energy to H_2 quantity, η is the round-trip efficiency, w_i are technical weights and $d_{\%}^{-}$ is the incentive granted by the DSO for following its profiles.

The first part of the function represents the possible revenues from electricity supply and hydrogen production, whereas the second one is related to the incurred costs. Some weights are used to take into account technical constrains.

Moreover, that function has to be maximized considering different technical constraints as the maximum FC power, the advised range of the WE power level, the capability of the HSS system and so on. As an example, the constraint related to the storage capability is reported below:

$$0\le HSS_{CL-state}\,(t_i-1)+P_{WE-HSS-CL}(t_i)\cdot\Delta t\cdot K_1\cdot\eta-P_{FC}(t_i)\cdot\Delta t\cdot$$
$$\cdot K_2/\eta\le HSS_{CL-capacity} \quad (2)$$

where $HSS_{CL-state}$ and $HSS_{CL-capacity}$ represent the closed loop HSS charge state and its capability, respectively.

Considering the complexity and nonlinear trends, three different algorithms are being implemented to solve the optimisation problem: two heuristic algorithms, Simulated Annealing and Tabu Search, and the nonlinear programming method Generalised Reduced Gradient. By means of these algorithms, the EMS will control a subset of the input variables defining an optimal plant configuration for each considered time slot (Δt) in a wide time horizon (N*Δt).

VI. CONCLUSION AND FUTURE DEVELOPMENTS

The proposed solution is a variable and controllable load/generator, whose cooperation with the DSO will support the electric grid balancing, following the adsorption or generation profiles sent periodically. The development of new incentive models to support such a flexible system, the management of the hydrogen production and sale and energy supply to electric vehicles will help to accomplish this task.

The system potentiality in real conditions will be tested by a prototype connected to a feeder of a primary substation where a power reverse flow occurs, since the renewable energy produced exceeds the adsorbed one. The proposed solution will be as much general and versatile as possible, allowing the adoption of different optimization approaches.

The results achieved by applying the proposed algorithms will be processed and released soon and will help to evaluate the economic sustainability of the proposed solution.

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