Model Predictive Control of Energy Systems with Hybrid Storage

Felix Rafael Segundo Sevilla, *Member, IEEE,* Chan Park, *Member, IEEE,* Valerijs Knazkins *Member, IEEE* and Petr Korba *Member, IEEE*.

***Abstract*—In this work an algorithm to control the power flow of an electric power system with two integrated energy storage systems is investigated. The power system under consideration consists of a conventional distribution feeder that supplies the power to satisfy the customers' demand, a set of photovoltaic (*PV*) panels that also contribute to the power generation, one unit of Lithium-Ion battery storage for the intra-day use and a combined power-to-gas (*PtG*) and gas-to-power installation that converts the power excess in the summertime into hydrogen and injects power back to the system in the wintertime.**

The proposed control algorithm is based on model predictive control tailored for the energy system under investigation. To demonstrate the performance of the proposed control, a set of synthetic *PV* and demand profiles representing future conditions in Switzerland were created and used as input data to the system model. The synthesized generation and consumption data span a whole year of operation.

A number of detailed simulations performed in the framework of the study reported in this paper demonstrate the effectiveness of the proposed control algorithm and provided invaluable insights into the optimum operation of the complex integrated power system.

***Index Terms*—Energy storage systems, electric power system, optimal power flow, model predictive control, self-consumption, power-to-gas.**

I. Introduction

THE large-scale utilization of fossil fuels for over a century to generate electricity to satisfy the ever growing energy demand has resulted today in the form of severe environmental issues clearly visible by most of the major economies also known as G-20; greenhouse gas emissions in alarming levels, abrupt climate changes, and human illnesses related to the atmospheric pollution.

As a first step towards finding an admissible solution to these problems, the leading economies have already invested a lot of capital in their infrastructure to incorporate considerable amounts of fossil-free generation such as wind and solar into their existing power networks. It is noteworthy mentioning that China, the United States of America, and Germany have made the most significant contribution to the electrical energy paradigm shift. Based on this trend, it is foreseen that the green energies will continue increasing worldwide in the years to come. In Europe the politicians have implemented objectives such as the "20-20-20", which is a short-term goal with milestones aiming at the increase of energy efficiency and reduction of the greenhouse emissions [1]. Similarly, Switzerland in parallel to the European Union (EU) objectives, has created a long-term plan known as the "Energy Strategy 2050" that has similar goals as in the EU "20-20-20". One of the key objectives in the Swiss vision is decommissioning the nuclear power plants and their replacement with fossil-free energy, in particular with the solar energy [2].

Although increase of these carbon-free energy sources are a key part of the solution towards the environmental healing, they are intermittent sources that can produce considerable amounts of electricity when environmental conditions are favorable (the high level of irradiation during the summer days and strong winds during the night) or produce very little otherwise. Excess or lack of electricity generation in large amounts can jeopardize the reliability of the system, cause the frequency and voltage deviations exceeding the allowed operating limits, and activate system protections that could potentially lead to lack of electric supply.

The intermittency of the power derived from the renewable energy sources can be solved by including an energy storage system which will absorb the excess electric power and inject it back into the system during the peak demand.

There are readily available different technologies that make the fossil-free energies more versatile and flexible; for instance reducing variability of the renewable sources and providing frequency and voltage support to the grid. In Switzerland, the federal government invests considerable resources and efforts in the future grid, creating the Swiss Competence Center for Energy Research and Future Swiss Electrical Infrastructure (SCCER-FURIES) where all the research centers and educational institutes contribute to reaching the goals of the Energy Strategy 2050. The investigation of new control strategies for distributed generation and the feasibility of energy storage systems presented in this paper is also part of the strategic goals of SCCER-FURIES.

In this paper, two different energy storage system technologies are combined, namely, battery and hydrogen technologies. It has been proved that the use of different energy storage technologies can satisfy a major range of applications, improving the lifetime of the single components [3], [4]. The optimal use of hybrid energy storage systems (*ESS*) requires the development of a controller, which takes into account all the constraints. Therefore a sophisticated algorithm to control the interaction of the elements in the test system is presented in this paper.

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F. R. Segundo Sevilla, C. Park, V. Knazkins and P. Korba are with the Power Systems and Smart Grid Lab at the Zürich University of Applied Science ZHAW in Switzerland (e-mails: {*segu, park, knaz, korb*}*@zhaw.ch*).

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II. Energy Storage Systems (*ESS*)

A. Battery Energy Storage Systems (BESS)

The battery storage technology is a mature and versatile discipline. Nevertheless, this paper is concerned with the use of a Lithium-Ion *BESS*. The main focus is placed on the energy flow considerations; the chemical description of *BESS* devices is outside the scope of this work and therefore is omitted. This particular technology has gained popularity thanks to the improvements in its relatively longer cycle life, lighter weight and higher voltage production in comparison with the traditionally used lead-acid technology. A typical *BESS* installation consists of 3 main parts: battery module itself, power electronics converter enabling the energy conversion of DC to AC at the required frequency and battery management system allowing the charging and discharging the battery in an optimal way [5]. Choosing the proper installed capacity and the rated power of the *BESS* to maximize the operational value is itself an important engineering task. An effective sizing algorithm for *BESS* can be found in [6].

B. Hydrogen Storage System (Power-to-Gas)

In terms of maximizing the efficiency, transforming electricity into other physical forms such as gas is obviously not the optimal path. The transformation process is always accompanied by unavoidable conversion losses (from power to gas), losses in the storage, and further reverse conversion losses while transforming the gas into electricity. Nevertheless, conversion of the electricity into hydrogen appears to be a feasible option, particularly considering the high energy density of the hydrogen. Transforming electricity into hydrogen is broadly known as power-to-gas concept and is considered to be suitable for storing electricity for long time periods, to solve congestion problems on the power networks or even store energy if the price in the electricity market is not profitable. Combined power-to-gas and gas-to-power installations are composed of an electrolyzer, a fuel cell and a storage system, which typically can be a tank or even the conventional natural gas pipe network. The hydrogen can be used for mobility, in the chemical industry or burned for the generation of electric power that can be fed back to the electric network [7].

III. Formulation of the problem

The system under consideration is depicted in Figure 1, including only one storage system can be found in [8]. In this figure the arrows indicate the admissible direction of the power flow. The test network consists of a domestic demand, which is modeled as the lumped load. It is assumed that in the vicinity, *e.g.*, on the roofs of the houses and buildings, there are photovoltaic (*PV*) panels that act as an intermittent energy source depending on different factors, such as time of the day and weather conditions. Another component of the system is a lithium-ion battery. The battery serves as a storage system and is installed in the vicinity as well, providing energy to the demand at nights and when the energy from the solar panels is insufficient to supply the total demand. In addition, there exists a power-to-gas installation, which is also used as storage system to produce hydrogen in summer when the number of sunny days is excessively high. The installation transforms the stored gas back to electricity to contribute with the demand in winter or during cloudy days to a certain extent. To realize the *PV* potential to a fuller extent, the *BESS* is charged absorbing energy from the *PV* panels when the consumption of the demand is less than the *PV* generation. The relationship among the various components in Figure 1 is described below.

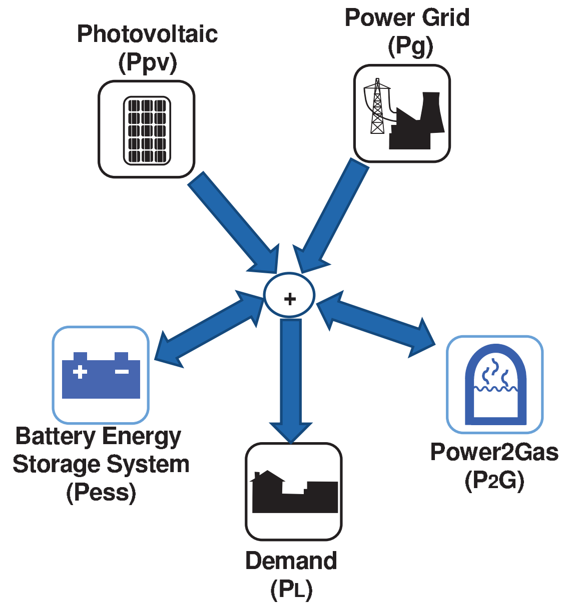

Fig. 1: Test system with hybrid storage; battery and power-to-gas

a) The total power consumption or demand (P_L) at the time instant k is equal to the contribution from the power grid (P_g), the PV panels (P_1), the discharged power of the *BESS* to the system (P_d), and the power from the accumulated hydrogen stored in the power-to-gas installation (G_{2p}).

$$P_L(k) = P_g(k) + P_1(k) + P_d(k) + G_{2p}(k) \tag{1}$$

b) The photovoltaic panels (P_{pv}) supply energy to the system demand (P_1), contribute to charge the *BESS* (P_c) and produce hydrogen through the electrolyzer (P_{2g}) mostly during the summer, as indicated in Figure 1.

$$P_{pv}(k) = P_1(k) + P_c(k) + P_{2g}(k) \tag{2}$$

c) The battery (P_{ess}) absorbs the power from the PV panels (P_c) and discharges (P_d) to provides power to the system demand.

$$P_{ess}(k) = P_c(k) - P_d(k) \tag{3}$$

d) The power-to-gas installation (P_{P2G}) transforms power from the PV panels into hydrogen (P_{2g}) in summer and supplies power to the grid (G_{2p}) transforming the hydrogen back to power in winter or during cloudy days to supply the demand

$$P_2G(k) = P_{2g}(k) - G_{2p}(k). \tag{4}$$

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e) By Kirchoff's law, the sum of currents (and thus the sum of active powers) injected in a node has to be zero.

$$0 = P_g(k) + P_{pv}(k) + P_{ess}(k) + P_2G(k) - P_L(k). \quad (5)$$

A. Dynamic model of the system

The dynamic model of the system described on Figure 1 has two state variables and is described below.

$$\begin{aligned}\hat{x}_1(k+1) &= A_1\hat{x}_1(k) + \tfrac{1}{Q_1}\left(\eta_1 P_c(k) - 1/\eta_1 P_d(k)\right)\\ \hat{x}_2(k+1) &= A_2\hat{x}_2(k) + \tfrac{1}{Q_2}\left(\eta_{2a} P_{2g}(k) - 1/\eta_{2b} G_{2p}(k)\right)\end{aligned} \quad (6)$$

where $\hat{x}_1(k)$ is the state of charge of the battery $SoC(k)$ and $\hat{x}_2(k)$ is the level of hydrogen stored in the tank $H(k)$. A_1 and A_2 are the gains of each of the storage systems, and in this study are numerically equal to 1. η_1, η_{2a} and η_{2b} are the battery, power-to-hydrogen, and hydrogen-to-power conversion efficiency coefficients, respectively. In this work the efficiency coefficients were set to 90% for the *BESS*, 70% for the power-to-gas and 60% for the gas-to-power conversions, respectively. Q_1 and Q_2 are the energy storage capacities for the battery and the hydrogen tank, respectively. The system has 5 inputs defined as follows: $u_1(k)$ is the actual active power from the *PV* panels supplied to the load (P_1), $u_2(k)$ is the charging power of the storage system (P_c), $u_3(k)$ is the power supplied from the storage system to the demand (P_d), $u_4(k)$ is the power transformed into hydrogen (P_{2g}) and $u_5(k)$ is the hydrogen transformed back to the active power and fed back to the system (G_{2p}).

Introducing the new variable $\hat{x}(k) = [\hat{x}_1, \hat{x}_2]^\intercal$ and based on the relationships from equation (1) to equation (5), the following equations are defined [9]:

- $y_1(k) = P_L(k) - P_1(k) = c_1(P_g(k) + P_d(k) + G_{2p}(k))$, such that $y_1(k) = a_1\hat{x}(k) + b_1u(k)$, where $a_1 = [0,0]^\intercal$ and $b_1 = [c_1, 0, c_1, 0, c_1]$. From the definition of $y_1(k)$, it can be noticed that minimizing $\sum c_1^2 P_1(k)^2$ is equal to minimizing $\sum(P_L(k) - y_1(k))^2$.
- $y_2(k) = P_{pv}(k) = c_2(P_1(k)+P_c(k)+P_{2g}(k))$, such that $y_2(k) = a_2\hat{x}(k) + b_2u(k)$, where $a_2 = [0,0]^\intercal$ and $b_2 = [c_2, c_2, 0, c_2, 0]$. Self-consumption from the photovoltaic panels P_{pv} can be assisted by minimizing $\sum(c_2(P_{pv}(k) - y_2(k)))^2$.
- $y_3(k) = P_{ess}(k) = c_3(P_c(k)+P_d(k))$, $y_3(k) = a_3\hat{x}(k) + b_3u(k)$, where $a_3 = [0,0]^\intercal$ and $b_3 = [0, c_3, c_4, 0, 0]$. The excessive use of the battery can be minimized by penalizing $\sum y_3(k)^2$.
- $y_4(k) = P_2G(k) = c_4(P_{2g}(k) + G_{2p}(k))$, such that $y_4(k) = a_4\hat{x}(k) + b_4u(k)$, where $a_4 = [0,0]^\intercal$ and $b_4 = [0, 0, 0, c_4, c_4]$. The excessive use of the power-to-gas installation can be minimized by penalizing $\sum y_4(k)^2$.

The augmented state and output vectors are now defined as:

$$\begin{aligned}x(k) &= [\hat{x}(k), y_1(k), y_2(k), y_3(k), y_4(k)]^\intercal\\ y(k) &= [y_1(k), y_2(k), y_3(k), y_4(k)]^\intercal.\end{aligned} \quad (7)$$

The discrete state-space of the complete dynamic model is described as:

$$\begin{aligned}x(k+1) &= Ax(k) + Bu(k)\\ y(k) &= Cx(k),\end{aligned} \quad (8)$$

, where

$$A = \begin{bmatrix} I_{2\times2} & 0_{2\times4}\\ 0_{4\times2} & 0_{4\times4}\end{bmatrix},\; B = \begin{bmatrix} b_a, & b_b, & b_1, & b_2, & b_3, & b_4\end{bmatrix}^\intercal,$$
$$C = [0_{4\times2}, I_{4\times4}],$$
$$\text{with}\quad \begin{aligned} b_a &= {}^1/_{Q_1}\,[0, \eta_1, -1/\eta_1, 0, 0]\\ b_b &= {}^1/_{Q_2}\,[0, 0, 0, \eta_{2a}, -1/\eta_{2b}]\end{aligned} \quad (9)$$

, where $I_{n\times n}$ is the identity matrix of order n.

B. System Constraints

To optimally manage the power flow of the system as described in equation (9), the following inequalities have to be satisfied

- The power flows on the system depicted in Figure 1 have positive magnitudes subject to their maximum values

$$\begin{aligned} 0 \leqslant P_1(k) \leqslant P_1^{max}, &\quad 0 \leqslant P_g(k) \leqslant P_g^{max}\\ 0 \leqslant P_c(k) \leqslant P_c^{max}, &\quad 0 \leqslant P_d(k) \leqslant P_d^{max},\\ 0 \leqslant P_{2g}(k) \leqslant P_{2g}^{max}, &\quad 0 \leqslant G_{2p}(k) \leqslant G_{2p}^{max}.\end{aligned} \quad (10)$$

- The power generated by the *PV* panels (P_{pv}) is greater than or equal to the sum of the power consumed by the load (P_1), the power charging the battery (P_c) and the power transformed into hydrogen (P_{2g}),

$$P_{pv}(k) \geqslant P_1(k) + P_c(k) + P_{2g}(k). \quad (11)$$

- The demand (P_L) never exceeds the sum of the power from the solar panels (P_1), the power discharged from the battery (P_d), and the power transformed from the hydrogen (G_{2p}),

$$P_L(k) \geqslant P_1(k) + P_d(k) + G_{2p}(k) \quad (12)$$

- The state of charge of the *BESS* should always remain operating within the pre-defined lower and upper limits,

$$B_{min} \leqslant SoC(k) \leqslant B_{max}. \quad (13)$$

The primary objective is to develop a control framework which would ensure the consumption of the electrical power generated by the photovoltaic source by the local demand. The second objective is to minimize the consumption of electrical power supplied by the utility grid when there *BESS* is fully charged. The third objective is to store hydrogen from March to September and to utilize it from October on. The optimal control problem is thus formulated as follows.

$$\begin{aligned}\min\; J(k) = \textstyle\sum_k^{k+N_p} &\left[P_1^2(k) + (P_{pv}(k) - y_2(k))^2\right.\\ &\left. + y_3^2(k) + y_4^2(k)\right],\end{aligned} \quad (14)$$

subject to the constrains described in Section III-B. In the objective function (14), N_p represents the prediction horizon, which in this case corresponds to one day (24 hours) with a sampling period of 15 minutes for one year.

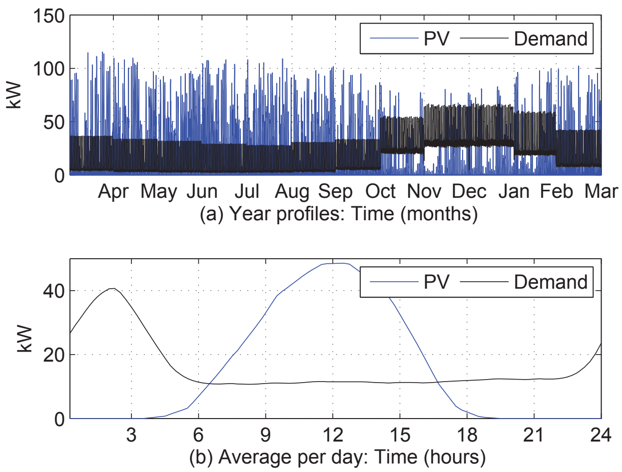

Fig. 2: PV and Demand profile during one year

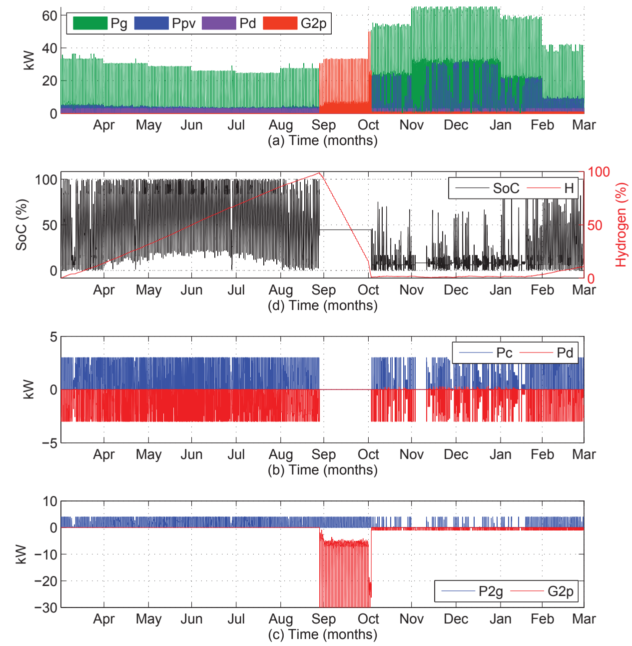

Fig. 3: (a) Contribution of each source to satisfy the system demand. (b) State of charge level (in black) of the BESS and hydrogen level (in red) of the power-to-gas installation. (c) BESS charge and discharge power. (d) Power-to-gas cycles.

C. Model Predictive Control

Model predictive control (MPC) is applied to the system described in equation (9) using the objective function (14) subject to the constraints described in Section III-B. Full details of MPC can be found in [10]. The first step in solving the MCP problem is to calculate the gains $F \in \mathbb{R}^{(N_p \cdot ny)\times n}$, $\Phi \in \mathbb{R}^{(N_p \cdot ny)\times(N_c \cdot nu)}$, $E \in \mathbb{R}^{(N_p \cdot ny)\times(N_c \cdot nu)}$ and $\mathbb{H} \in \mathbb{R}^{1\times(N_c \cdot nu)}$ as follows:

$$F = [CA \quad CA^2 \quad \dots \quad CA^{N_p}]^\intercal,$$

$$\Phi = \begin{bmatrix} CB & 0 & \cdots & 0 \\ CAB & CB & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ CA^{N_p-1}B & CA^{N_p-2}B & \cdots & CA^{N_p-N_c}B \end{bmatrix} \quad (15)$$

$E = \Phi^\intercal\Phi$ and $\mathbb{H} = (Fx(k) - R(k))^\intercal\,\Phi$, where N_c denotes the control horizon ($N_c \leqslant N_p$) and

$$R(k) \;=\; [P_L(k) \quad P_{pv}(k) \quad 0 \quad 0]^\intercal. \quad (16)$$

The next step is to compute the predictive output with respect to the input

$$Y(k) = Fx(k) + \Phi U(k). \quad (17)$$

Since the objective function (14) can be expressed as:

$$J(k) = (Y(k) - R(k))^\intercal(Y(k) - R(k)), \quad (18)$$

substituting (17) in (18) and neglecting the terms independent of $U(k)$, minimizing $J(k)$ can be expressed as

$$\min \; \{2(Fx(k) - R(k))^\intercal\Phi U(k) + U(k)^\intercal\Phi^\intercal\Phi U(k)\}\,. \quad (19)$$

The optimization problem described in the equation (19) can be solved using any available quadratic optimization routine. In this work, the optimization problem (19) was solved using the solver `quadprog.m` from the MATLAB optimization toolbox, as detailed in [11].

IV. Control Algorithm Validation

Figures 2 presents in the subplot (a) the PV and demand profiles for one year with a sampling ratio of 15 minutes created synthetically and in the subplot (b) the average demand and PV production per day. These profiles are assumed to represent the projection in the future of a Swiss region as expected in [2], where it is envisaged that PV potential in Switzerland will increase from the current contribution of less than 1% to an approximately 20% of the total generation. Note that measurements are not presented for one calendar year. Instead measurements start in April and end on March of the next year. The main idea behind this is to illustrate how the power-to-gas installation can use the PV excess from the sunniest months of the year to generate and store hydrogen and use the gas later to inject power back to the system when there is little or no PV. From Figure 2 (a), it can be noticed that PV (in blue) considerably surpasses the system demand (in black) during the first months. From October this trend changes inversely until March when PV is available again. Then it is possible to start the hydrogen storage process again.

In order to test the algorithm developed and described in Section III, the priorities of the optimizer and the logic behind the controller are summarized below:

- Only one source supplies power to the demand at a time while the others remain idle.
- Since self-consumption is encouraged in the algorithm, produced PV always flows first to the demand.
- PV excess after supplying the demand charges the *BESS*.
- PV available after supplying the demand and charging the *BESS* is transformed into hydrogen and stored.

- *BESS* discharge everyday from 8pm at a constant rate until the lowest level of the state of charge allowed by the manufacturer is reached, so that it is ready to charge again on the next sunny day.
- Power-to-gas installation stores as much hydrogen as possible during the sunniest months.
- From October, the stored hydrogen is used to produce power as long as possible to fully meet the demand.
- The utility grid is used only to feed the load when the other energy sources are empty.

A. Simulation Results

To demonstrate the effectiveness of the control algorithm described in Section III, the information depicted in Figure 2 was used as input in the system described in Figure 1 following the logic presented before. The results are shown in Figure 3 (a)-(d) and discussed next.

Figure 3 (a) presents the contribution of each element to meet the demand. The green trace corresponds to the power delivered by the grid, the blue trace is the power contributed by the PV panels (self-consumption), the purple trace is the power discharged from the *BESS* to the network, the and red trace is the power obtained from the hydrogen that was stored during the first months (power-to-gas installation). Figure 3 (b) presents the *BESS* state of charge $SoC(k)$ level in black and the hydrogen $H(k)$ stored in the tank in red at each instant of time, both magnitudes are given in percent. The success of the control algorithm is demonstrated in the results presented in this subplot. It can be noticed how the *BESS* is charging and discharging power from April to September on a daily basis. During this period of time, the intensity of the PV generation is enough to allow the generation and storage of hydrogen from the excess, as indicated by the rising red trace in Figure 3 (b). From October, when the PV production decreases, the stored hydrogen is used to produce power and fill the demand. It can be observed that for about 31 days the power-to-gas installation fulfills the total demand until it runs out of hydrogen and during this time neither the *BESS* nor the grid are used. From November after all hydrogen has been consumed, the PV production level is low and is impossible to completely charge the *BESS*, therefore the demand is mostly met using the active power from the grid.

Figure 3 (c) depicts the charge (in blue) and discharge (in red) powers from the *BESS*. The intense use of the battery can be seen during the first six months. Then the battery is not used while the power-to-gas installation spends the stored hydrogen to meet the demand. After one month, the battery is back to service with less intensive activity than before due to the low PV potential as a result of the weather conditions (lack of sunlight during the winter). Finally, Figure 3 (d) presents the similar case for the power-to-gas installation with the charge and discharge of the *BESS*. The blue trace represents the case when hydrogen is stored from the PV, and the red trace represents the power from the hydrogen injected back to the system. From the results presented in the subplot it can be clearly observed that this storage system is mainly used in October.

V. Conclusion

In this work an advanced algorithm to control the power flow on an energy system with renewable and two storage systems was presented. The control mechanism makes use of the model predictive control theory and enables the user to introduce several constraints to meet different optimization goals. An objective function that take into consideration all the user constrains is presented and transformed the problem into a minimization problem. An important contribution of this paper is the systematic analysis of the power-to-gas concept and its inclusion in the optimum operation of the power grid, which is of high interest in Switzerland. The results presented here demonstrated that it may be a viable and sound idea to use the power-to-gas and gas-to-power technology as a long-term storage for the purpose of power system applications.

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