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Flexible and Scalable Energy Management of Islanded Renewable Energy Sources Storage Systems

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Power management in islanded off-grid hybrid power-to-power (P2P) systems is challenging due to multiple decisions that need to be taken at each time instance within a perpetually changing environment. In this work, an energy management strategy (EMS) is proposed as a supervisory control framework that relies on a finite state machine (FSM) approach. The FSM offers a systematic way to develop a flexible decision-making algorithm that is combined with propositional-based logic in order to describe the transitions between the different operating states of the integrated system's components. Easy extension of the EMS to larger and more complex systems without compromising the operational objectives is the major contribution of the developed algorithm. The proposed approach is implemented in an off-grid demonstration site located in Ginostra, Italy. At this site, the only source of power is a photovoltaic (PV) installation array that supports the specified residential loads. An operation analysis is conducted accompanied by an assessment of the site's environmental footprint. The results indicate that power is supplied without interruption to the load, and CO_2 emissions are decreased by 95.6 % in comparison with the former energy solution applied (diesel generators – DSG).

1. Introduction

Isolated micro-grids or off-grid remote areas are systems where energy storage from a variety of renewable energy sources (RES) is becoming a viable, cost-effective, and reliable alternative compared to on-site electricity generation using diesel engines (Hirsch et al. 2018). Hybrid hydrogen-based power-to-power systems integrated with fuel cells (FC), electrolyzers (EL) and batteries (BAT) can provide medium to long term storage capabilities (from several days up to months) by utilizing the available RES (Tschiggerl et al., 2018). To explore the behavior of an off-grid system with RES and hydrogen, the EU funded project called REMOTE (Remote Project, 2019) focuses on the application of such systems in four remote locations across Europe. The control strategy of the first demonstration site to be applied by Enel Green Power in the island of Ginostra employing technology from ENGIE EPS is presented here. A study addressing the energy management of hybrid energy storage systems (HESS) employing photovoltaics, batteries and hydrogen storage with a rule-based control approach has been reported in the literature (Nasri et al., 2016). The decision-making algorithm of the referred study is based on a heuristic if-then-else approach. Another study, employing a rule-based control strategy on a similar system integrated with wind-turbines, is reported (Cozzolino et al., 2016). The energy management of the previous study is also based on a decision-making algorithm that utilizes if-then-else rules. The heuristic approach followed in the referred studies is often limiting in terms of complexity when a larger set of rules is needed for the control of the system or the system under investigation integrates a greater number of components. To counter this limitation, this work describes the formulation of a generic energy management strategy which was developed in conjunction with the formulation of a decision-making algorithm. This algorithm, namely finite state machine, incorporates a propositional-based logic that aims to evaluate the state of each

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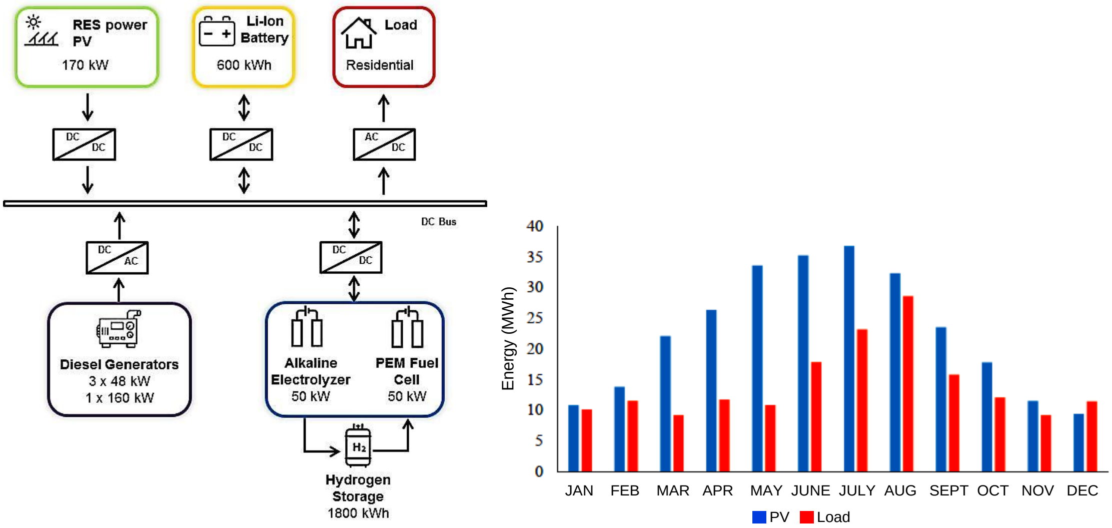
subsystem of the plant and result in the transition to a new state according to the operation principles of the integrated system (Ziogou et al., 2013). This methodology offers a more flexible and easily expandable systematic approach in the energy management of HESS than the commonly used if-then-else approach. The goal of this study is to generate some preliminary results that will indicate how the proposed hybrid P2P system can improve the local energy solution with the implementation of the aforementioned methodology. The results produced from the case study are used to demonstrate the power distribution among the individual subsystems of the site, the ability of the integrated system to exploit the available RES power and also its storage capabilities.

2. Application and system description

Ginostra is a small village located on an island in Southern Italy. It is regarded as off-grid since it is not connected to the Italian distribution and transmission grid. Currently, the load of the site is satisfied by using three 48 kW diesel generators and one 160 kW diesel generator. The energy system demonstrated by the REMOTE project in Ginostra will comprise of a 170 kW PV power plant, a 600 kWh li-ion battery bank, a hydrogen-processing unit with a 50 kW proton-exchange membrane (PEM) fuel cell and a 50 kW alkaline electrolyzer combined with 1,800 kWh of storage, plus the already employed diesel generators to provide back-up power (Figure 1a). The yearly PV production is 273 MWh and is shown in Figure 1b accompanied by the load demand. The integrated P2P system’s goal is the minimization or even the curtailment of fossil fuel consumption. A large amount of available power coming from PV (yearly surplus = 190 MWh, yearly deficit = 89 MWh) contributes towards this goal.



(a) (b)

Figure 1: (a) General configuration of the hybrid stand-alone RES H_2 system, (b) Monthly distribution of PV production and load

3. Energy management strategy and finite state machine

Energy management strategies are needed to supervise the operation of the integrated system, to evaluate the RES storage efficiency and coordinate the subsystems’ operation. The development of a suitable EMS is necessary to assess the performance and operation of the integrated system. The purpose of the EMS is twofold, to supervise the status of each subsystem and to be able to adjust to system operational modes. The derived set of rules can be used for the control of the operation of the subsystems, namely the electrolyzer, the fuel cell, the battery bank, the diesel generator and the hydrogen storage tank (HT). The EMS consists of a series of switching actions in order to drive the system from its initial state to an operating mode suitable to satisfy the load demand by taking into consideration each subsystem’s or/and device’s specifications and constraints. In this work, an FSM is used to describe the realization of the strategy for the operation of a hybrid P2P energy storage system. An FSM is a dynamic approach that describes the evolution in time of a set of discrete and continuous state variables. The solar hydrogen system exhibits two kinds of dynamics completely different in nature, namely discrete (e.g. start/stop of the FC) and continuous (e.g., the battery state of charge – SOC). The interaction between discrete and continuous operating states motivates the use of the hybrid approach, and thus the FSM appears as a powerful analysis tool for the realization of a generic EMS while the system requirements are translated into propositional-based logic representing a set of operating rules. An FSM is defined by a tuple $(Q, q_0, \delta, \lambda, X, Y)$ in which Q is a finite set of states, $q_0 \in Q$ is the initial state, δ is the state transfer function, λ is the output function, X is the finite input alphabet and Y the finite output alphabet. The alphabet (X, Y) represents the rules of operation. If FSM algorithm receives input x while in state q it produces output $y = \lambda(q, x)$ and moves to state $q' = \delta(q, x)$. This defines a transition $(q, q', x/y)$. The transitions between the states are described using formal propositional-based logic. The output function can enable or disable the operation of a subsystem (EL, FC, BAT, DSG and HT) based on the status of the accumulator and the hydrogen storage. The state of charge of the accumulator and the level of the hydrogen storage tank are the main parameters that drive the operating decisions of the EL and the FC. The level of energy stored in each device defines a set of Boolean variables (β) which are related to the operation of the subsystems. The value of each Boolean variable can be true or false and based on that, the respective subsystem is allowed to operate or not. In this propositional-based approach, a hysteresis band is used in the boundary limits of the accumulator to avoid irregular operation (reduction of frequent start-ups and shut-downs). For example, the operation of the FC depends on the level of H_2 in the tank. A Boolean variable β_{HT} represents the level of H_2 in the tank (Table 1).

Table 1: Hydrogen tank status variable

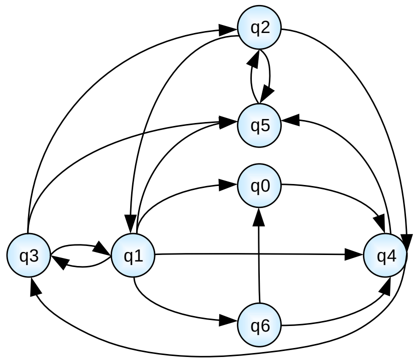
Variable status	Description
$[\beta_{HT} = 1] \leftrightarrow [HT \geq HT_{high}]$	Variable β_{HT} is true (=1) if and only if the pressure of H_2 in the HT is greater/equal to HT_{high} (4 bar)
$[\beta_{HT} = 0] \leftrightarrow [HT \leq HT_{low}]$	Variable β_{HT} is false (=0) if the pressure drops below HT_{low} (3 bar)

Similarly, a set of Boolean variables are defined for the FC operation (β_{FC}), the EL operation (β_{EL}), the DSG operation (β_{DSG}) and the SOC of the accumulator $(\beta_{min}, \beta_{FCoff}, \beta_{ELon}, \beta_{ELoff}, \beta_{max})$. In order to define the transitions of the FSM these variables are combined into propositional rules to provide the reasoning behind the subsystems' operation. In Table 2 a subset of the FSM's input alphabet is presented that corresponds to the transitions for the hydrogen production and consumption.

Table 2: Propositional rules and input alphabet

Propositional rule	Description
$x_1: [P > 0] \wedge [\beta_{ELoff} \wedge \beta_{HT}]$	There is a surplus of RES power (P) and the accumulator is charged to the point where the electrolyzer is allowed to operate while the H_2 tank pressure is lower than its maximum level (28 bar)
$x_2: [P < 0] \wedge !\beta_{min} \wedge !\beta_{HT}$	There is a deficit of RES power (P), the H_2 tank pressure is lower than its minimum level (3 bar) and the SOC of the accumulator is below the minimum (SOC <20 %)

Each rule constitutes a letter of the input alphabet. These set of rules are derived by the operation of the unit's subsystems. The FSM that describes the operation of our system is shown in Figure 2.



q0: System standby (System curtails excess RES)
q1: Charge BAT by RES
q2: Preserve BAT by FC or DSG
q3: FC covers load
q4: BAT covers load
q5: DSG covers load
q6: EL produces H_2

Figure 2: Finite state machine for the operation of the hybrid system

The use of the FSM that realizes the energy management strategy enables the study of the behavior of integrated systems in a flexibly due to its flexibility and adaptability. Overall the proposed EMS can incorporate engineering and computational knowledge and techniques for the application on the actual system and it can incorporate various operating modes. Additionally, it offers a theoretical context for the analysis and design of complicated energy systems involving multiple energy sources and loads.

4. Overview of the control strategy

A systematic methodology that decides about the power distribution actions among the subsystems considering the individual subsystems of the hybrid station is implemented. For this purpose, the EMS that was described in Section 2 was used in order to achieve this objective. A system level modeling approach was adopted for this study. The overall objectives of the hybrid P2P energy storage system are the preservation of battery life (main controlled variable: SOC_{BAT}), the safe operation of the other subsystems (operation within the limits of FC and EL) and optimal exploitation of the energy produced by the RES regarding load fulfillment and energy storage. According to the needs of the site, the appropriate strategy configuration was applied. Overall the simulations for the strategy were based on a yearly analysis as well as on a monthly analysis and the time interval of the simulation was 1 h. In this particular framework, the energy sources are the FC, the BAT, the DSG and the available RES for this specific demonstration site. The load demand defines whether the RES is sufficient to cover it or there is a need for power from another source. In other words, the energy surplus or deficit determines the operation of the individual subsystems. In case there is a surplus of RES power, this amount of energy can be stored in the form of electricity by the battery or in the form of H_2 in the pressurized tank (through water electrolysis, EL). Which of the two takes place, depends on the battery SOC. If the battery SOC has reached its maximum level, then and only then, the EL will operate to produce H_2. Instead, when the SOC is below its max, the battery is charged up to its maximum point. In case there is a deficit of RES power, then the battery covers the occurring shortage of power. If the SOC drops below its minimum point then the FC starts in order to cover the load. The DSG acts like a back-up energy source when the battery is discharged and the hydrogen tank is empty. In the extreme case where a long-lasting power deficit occurs, if the SOC of the battery is below 20 % then the FC (and DSG when the H_2 in storage is consumed) has the role of charging the battery up to the point that it can operate to satisfy the load (>40 %). In any other case, the battery is only charged by the RES surplus. The operational zones of every subsystem are shown in Figure 3. The arrows indicate whether the battery is being charged or discharged. The operational zone of the battery is set from 20 % to 80 %, only surpassing its maximum point when the EL has filled up the HT and there is still a surplus in the RES production. Then, the battery stores energy until it reaches 90 %, which is the point where RES curtailment occurs. This control strategy aims to preserve, under nominal operation, the battery life as well as to avoid frequent start-ups and shut-downs of the EL and FC. The battery SOC, which is the main controlled variable, fluctuates within its specified limits. The addition of the hysteresis bands in the control strategy secures the continuous operation of the EL and FC.

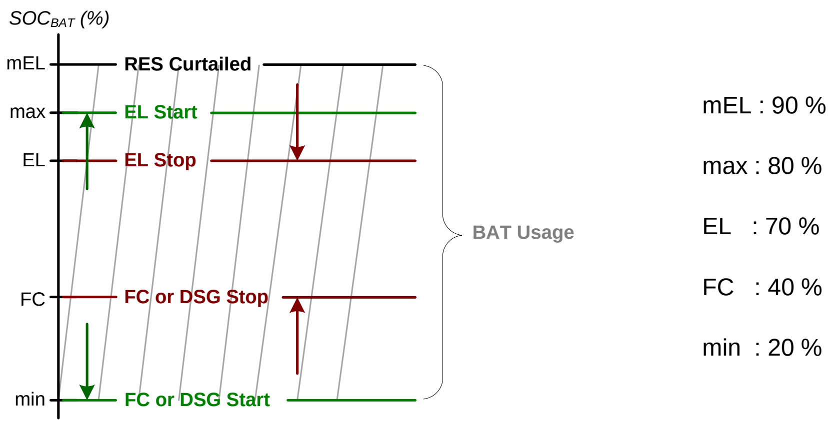


Figure 3: Finite state machine operational zones

5. Operation analysis results

The operation of the hybrid system is presented through the results of three days during a typical winter month (January).

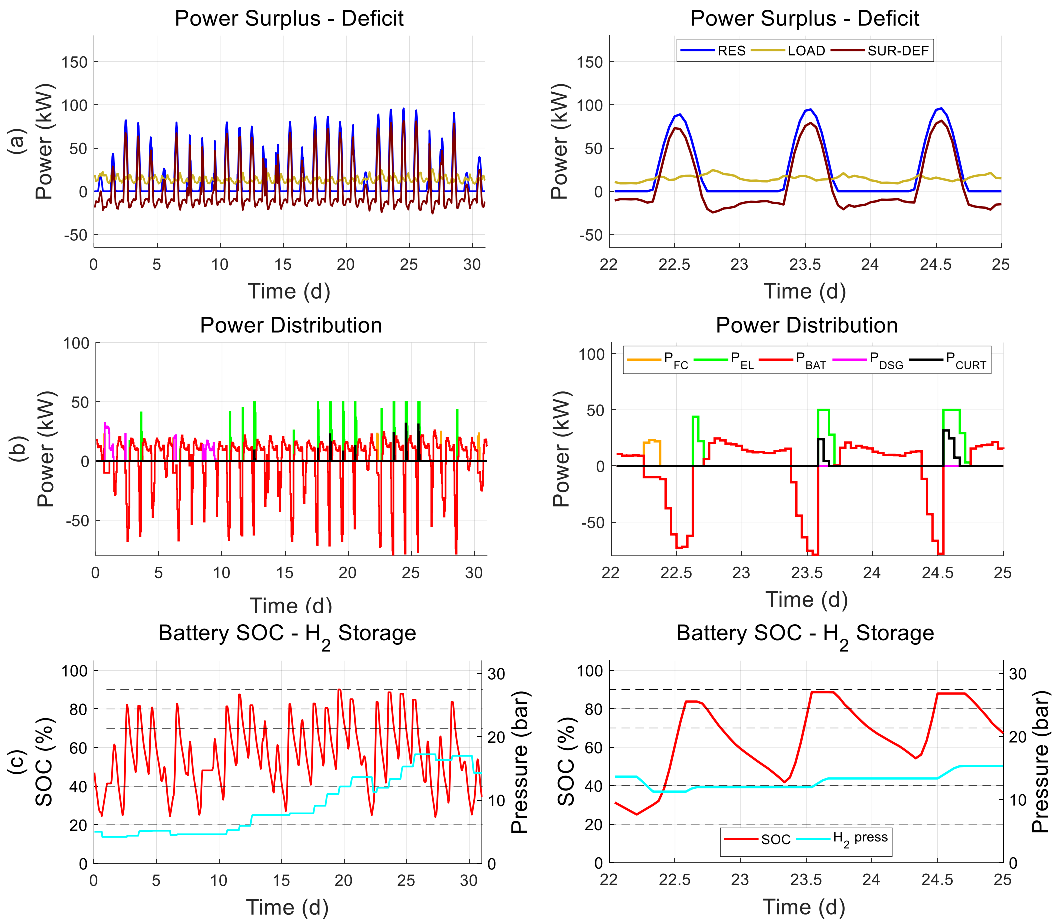


Figure 4: (a) Available RES, load and surplus-deficit, (b) Power distribution, (c) Battery SOC and hydrogen storage level. (Left) Whole January and (right) 3 d in January

The hourly distribution of power among the subsystems is displayed in Figure 4b. On the negative side of y-axis, when there is a surplus of RES power, the battery is being charged. When the SOC of the battery enters the hysteresis zone (20 – 40 %) and continues to drop below 20 % and there is a load demand greater than the RES available, then the FC takes on the load but also is responsible to charge the battery up to a point where it can operate safely within the zone of 40 – 70 %. If there was a shortage of hydrogen in the HT then instead of the FC, the DSG would operate in its place covering the load and charging the battery. As displayed in Figure 4c, the battery is the main module that meets the load duty, sitting idle only when it is charged above 80 % and allowing the EL to produce H_2 by exploiting the RES surplus. The power being curtailed in Figure 4b is a result of the RES surplus being greater than the maximum modulation range limit of the EL (50 kW). The available annual energy coming from RES is roughly 273 MWh, whereas the annual load demand is around 171 MWh, as it is calculated from the available data (Figure 1b). The satisfaction of the load demand is mainly met by the RES (47.8 %) and the battery (43.2 %). When there is not enough electricity stored then the FC takes on the satisfaction of the load (4.6 %). Through the months December and January, the lack of RES production plus the lack of stored energy (H_2) is resulting in need of the intervention of the DSG (4.4 %). Excess energy coming from RES is either stored or curtailed. In the Ginostra site, 38.5 % of the RES surplus is stored in the battery and only 9 % of it is stored in the form of H_2. The utilization of the battery is favored against H_2 usage, thus the big difference in the converted surplus percentage. However, the number that draws attention is the 50 % of the available surplus that is being curtailed by the system. This is a result of the small hydrogen tank in comparison to the excess energy that is available through spring and summer (Figure 1b) but also because of the maximum modulation range of the EL resulting in curtailing power over 50 kW (Figure 4b). The minimization of the need or even the exclusion of the back-up DSG can be achieved with the installation of a larger hydrogen tank. Figure 5 illustrates the percentage of the overall operational time that is derived for each subsystem. Again it is clear that the battery pathway is favored while the EL and FC are operating at a small fraction of the overall time (6 % and 1 %).

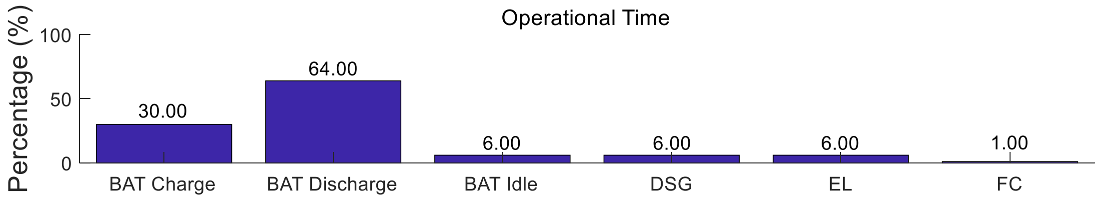


Figure 5: Operational time percentage for each subsystem

To decrease greenhouse gas emissions, a hybrid P2P system is to be installed to replace the current diesel generator set. The aforementioned replacement, as seen in the operation results above, minimizes the usage of the DSG to 4.4 % of the total load demand. This means that there is a reduction of 95.6 % in diesel consumption in comparison with the current solution. The quantification of the environmental footprint in terms of CO_2 emissions is shown in Table 3.

Table 3: Comparison of CO_2 emissions

	DSG	Hybrid P2P + DSG
Total load percentage covered by DSG	100 %	4.4 %
Total load covered by DSG	171 MWh	7.524 MWh
Diesel fuel consumed (30 % efficiency of DSG)	22,211.8 L	977.3 L
Kilograms of CO_2 produced (2.672 $kgCO_2$/L)	59,350 kg	2,611.4 kg

6. Conclusions

This work focuses on the results of a supervisory control framework based on the formulation of a generic energy management strategy exploiting a decision-making algorithm (FSM) which incorporates a propositional-based logic. The operation analysis study of the case of integrated hybrid P2P system (Ginostra) was performed assessing the goal to achieve optimal exploitation of the energy produced by the PVs regarding load fulfillment, energy storage and aiming the minimization of the DSG operation and energy curtailment. The study resulted in the uninterrupted satisfaction of the load demand alongside with minimum utilization of the DSG and a 95.6 % decrease in CO_2 emissions in comparison with the current DSG solution. Thus the implementation of this more flexible and systematic approach ensures the overall objectives of the operation of a hybrid P2P energy storage system which are the preservation of battery life and the safe operation of all electrochemical subsystems (FC and EL) in conjunction with the optimal exploitation of the energy produced by the RES. The proposed framework has the potential for future incorporation with multiple energy sources and a greater number of subsystems as a result of its flexibility and scalability. The optimization of the hysteresis zones' limits in order to achieve optimal operation and power distribution regarding the efficiency of the subsystems is also a subject to be addressed in future works.

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