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A Microcontroller-Based Automatic Scheduling System for Residential Microgrids

B. Belvedere, M. Bianchi, A. Borghetti, M. Paolone

***Abstract*—The paper presents a microcontroller-based automatic scheduling system for the operation and control of the distributed energy resources connected to residential electric power installations, taking into account both the following operating conditions: 1) the grid connected operating mode, in which the household electric circuits are connected to the distribution network; and 2) the islanded operating mode, in which the household electric system is able to feed at least part of the load although being disconnected from the public distribution network. The considered residential electric power is assumed to include various distributed energy resources, also of innovative type, such as fuel cells and photovoltaic systems, and an energy storage device, such as a battery unit connected to the system through a voltage-source bi-directional power electronic converter, which allows the load balancing by means the battery charge and discharge in every operating condition. The operating behavior of the proposed automatic system is verified by using an experimental set-up equipped with commercial PEM fuel cell, a lead-acid battery storage system, a PV array emulator, and variable active and reactive loads of few kilowatts which are able to reproduce different load profiles.**

***Index Terms*—Microgrids, Fuel Cell, Microcontroller.**

NOMENCLATURE

P_{FC}	Power output of the Fuel Cell (FC)
P_{batt}	Power input or output of the battery storage system.
$P_{FC,max}$	Upper limit of the FC power output
$P_{batt,max}$	Upper limit of the power output of the battery converter
$P_{load,PV}$	Difference between load power consumption, without load shedding, and photovoltaic (PV) production.
SOC	State Of Charge of the battery
SOC^*	Optimal value of the SOC level
SOC_{min}	Minimum allowed SOC level
SOC_{max}	Maximum allowed SOC level
SOC^*_{min}	Lower SOC level of the FC regulator
SOC^*_{max}	Upper SOC level of the FC regulator

I. INTRODUCTION

DISTRIBUTED generation (DG) may result in enhanced continuity of service and in increased customer participation to the electricity market [1,2]. These opportunities could be fostered by allowing the operation also in islanded conditions [3-6].

In the literature, small distribution networks with several Distributed Energy Resources (DERs) and the capability to work also in islanded mode are called microgrids. In microgrid and household applications, the above mentioned capability to operate in islanded mode is permitted by the presence of energy storage devices and by the implementation of automatic scheduling systems (e.g. [7,8]). For the case of low voltage microgrids, the development of automatic scheduling systems for the coordinated operation of DERs is the object of intensive research activity in recent years (e.g. [5,9]). Research activities are also devoted to the development of automation systems able to improve household energy management (e.g. [10]).

However, additional research efforts appears to be needed to develop automatic systems suitable for residential applications that take into account the technical characteristics and constraints, with particular reference to the use of innovative type sources, such as Fuel Cell (FC), solar Photovoltaic (PV) or Thermo-Photovoltaic (TPV) systems, and reduced-size storage resources [12-19].

The paper describes an automatic system for the scheduling of available DERs in household applications. The automatic scheduling prototype is implemented in a microcontroller, which consists of a Digital Signal Processor (DSP) and a Field Programmable Gate Array (FPGA). Its performance is verified through its installation in an experimental test set-up equipped with a PEM FC, a battery storage system equipped with a specific power electronic converter, a PV array emulator and controllable active and reactive loads of few kilowatts [20, 21].

The structure of the paper is the following. Section II describes the functions of the developed automatic scheduling system. Section III briefly reviews the structure of the experimental set-up. Section IV presents and discusses the experimental results obtained by using the proposed automatic scheduling system. Section V concludes the paper.

II. FUNCTIONS OF THE AUTOMATIC SCHEDULING SYSTEM

We refer to a household microgrid composed by a FC, a battery storage system, a PV array and controllable loads. We assume that the maximum power provided by the PV array is lower than maximum power input that can be absorbed by the battery during the charging phase and that the FC may operate

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only when the system is disconnected from the external distribution system (islanded operating mode).

The microcontroller-based automatic scheduling system has been conceived in order to operate in the following modes:

1. Grid connected operating mode
   1.1. $SOC<SOC_{\max}$
   1.2. $SOC=SOC_{\max}$
2. Islanded operating mode
   2.1. FC in operation
      2.1.1. $P_{\text{load,PV}}<P_{\text{FC,max}}+P_{\text{batt,max}}$ and initially $SOC>SOC^{*}_{\max}$
      2.1.2. $P_{\text{load,PV}}<P_{\text{FC,max}}+P_{\text{batt,max}}$ and initially $SOC<SOC^{*}_{\min}$
      2.1.3. $P_{\text{load,PV}}>P_{\text{FC,max}}+P_{\text{batt,max}}$
      2.1.4. Intentional FC shut-down
   2.2. FC not operating
      2.2.1. $P_{\text{load,PV}}<P_{\text{batt,max}}$ and $SOC>SOC_{\min}$;
      2.2.2. $P_{\text{load,PV}}<P_{\text{batt,max}}$ and $SOC<SOC_{\min}$;
      2.2.3. $P_{\text{load,PV}}>P_{\text{batt,max}}$.
      2.2.4. Intentional FC start-up.

Table I summarizes the actions of the automatic scheduling system for each operation mode.

TABLE I
ACTIONS OF THE AUTOMATIC SCHEDULING SYSTEM FOR EACH OF THE OPERATION MODES

Operating mode	**Action**
Grid connected operating mode	
1.1	Battery charging so to reach the $SOC_{\max}$ value
1.2	No action
Islanded operating mode with the FC in operation	
2.1.1	Set of the FC output P_{FC} lower than $P_{\text{load,PV}}$ so to decreases the SOC to the SOC^* level
2.1.2	Set of the FC output P_{FC} greater than $P_{\text{load,PV}}$ so to increase the SOC to the SOC^* level
2.1.3	Load shedding until $P_{\text{load,PV}} = P_{\text{FC,max}}+P_{\text{batt,max}}$
2.1.4	Load shedding until $P_{\text{load,PV}}<P_{\text{batt,max}}$ and, before the FC shut-down, set $P_{\text{FC}}=P_{\text{FCmax}}$ until SOC becomes equal to SOC_{max}
Islanded operating mode with the FC not in operation	
2.2.1	No action until SOC becomes equal to SOC_{min}
2.2.2	FC connection and switch to an operating mode 2.1.1-2.1.4.
2.2.3	Load shedding until $P_{\text{load,PV}}<P_{\text{batt,max}}$.
2.2.4	After FC connection, permitted if $SOC<SOC^*$, set $P_{\text{FC}}=P_{\text{FCmax}}$ for a predefined interval.

The main distinction among the operation modes is provided by the availability of the external network and, as illustrated by Table I, a large part of the automatic scheduling actions requires the accurate estimation of SOC level of the battery and the control of the FC output P_{FC}.

When system is connected to the external network, the battery SOC is maximized.

In the islanded operating mode, the FC output is controlled in order to track the target SOC value, namely SOC^*, which is pre-determined as an average SOC level that allows to minimize the number of FC startup and shutdown operations. The values $SOC^*_{\min}$ and $SOC^*_{\max}$ define a relatively narrow band around the SOC^* target value.

The islanded operation is allowed also when the FC is not in operation, if the SOC value is greater than a minimum value $SOC_{\min}$, assumed to be sufficiently larger than the maximum discharge depth allowed by the battery manufacturer. Such a value is estimated by the microcontroller as a function of the discharge rate, battery type and environmental conditions (temperature).

The following two paragraphs are devoted to the SOC estimation and to the implemented FC-output control strategies.

A. SOC estimation

Several SOC models have been proposed in the literature [22], which can be grouped in the following categories: i) measurement of electrolyte specific gravity, ii) battery current time-integration, iii) battery impedance estimation, iv) measurement of the battery open circuit voltage, v) models that take into account the electrolyte temperature, discharge rate and other batteries parameters (e.g., the electrolyte solidification temperature).

The simplest SOC estimation is provided by the direct measurement of the battery terminal voltage under load conditions in comparison to the operating voltage limits of the battery, namely the maximum charging voltage and the minimum discharging voltage (this last related to the discharge rate). This comparison mainly allows the evaluation of the operating status of the battery package rather than its exact SOC.

The use of a more detailed SOC model that takes into account environmental conditions (temperature) and discharge rates, suitably tuned with the adopted battery type, may result in an improved operation of the system.

In general the SOC estimation may be provided by

$$SOC = \frac{C(t_0) - \alpha(I,\theta)\int_{t_0}^{t} i(t)dt}{C(I,\theta)} \tag{1}$$

where $C(I,\theta)$ is the battery capacity for a constant discharge rate I of the battery at electrolyte temperature θ, $C(t_0)$ is the battery capacity at time t_0, $i(t)$ is the instantaneous value of the battery current, and α is the efficiency coefficient associated to battery charge and discharge.

As an example, in [27] is proposed the following $C(I, \theta)$, conceived to predict the behavior of lead-acid batteries:

$$C(I,\theta) = \frac{Kc \cdot C_0^* \cdot (1+\dfrac{\theta}{\theta_f})^{\varepsilon}}{1+(Kc-1)\cdot(I/I^*)^{\delta}} \tag{2}$$

where θ_f is the electrolyte solidification temperature, and $K_c, C_0^*, \varepsilon, \delta, I^*$ are the model parameters to be identified by means of specific tests.

Such a model can be also suitably modified to be applied to different battery types, such as Ni-Zn [28].

B. FC output control strategy

In islanded conditions, the system is expected to operate mainly in mode 2.1.1 or mode 2.1.2.

These two operating modes are characterized by the adopted FC-output control strategy in order to follow system load request $P_{\mathrm{load,PV}}$, regulating also the battery SOC near to the SOC^* reference value.

Two simple control strategies have been implemented, namely a hysteresis regulator (regulator A) and a hysteresis proportional regulator (regulator B), illustrated in Fig. 1.

Both regulators set the FC output by tracking load request $P_{\mathrm{load,PV}}$ with an adjustment based on the error between the present SOC and the desired SOC^* value.

As illustrated in Fig. 1a), regulator A adds or subtracts a predefined step ΔP to the measured $P_{\mathrm{load,PV}}$ value if SOC is initially lower than SOC^*_{min} or larger than SOC^*_{max}, respectively.

As illustrated in Fig. 1b), regulator B adds, to the measured $P_{\mathrm{load,PV}}$ value, an adjustment proportional to the difference between SOC^* and SOC. The proportional coefficient is chosen so that the adjustment is equal to ΔP when SOC becomes lower than SOC^*_{min} or larger than SOC^*_{max}.

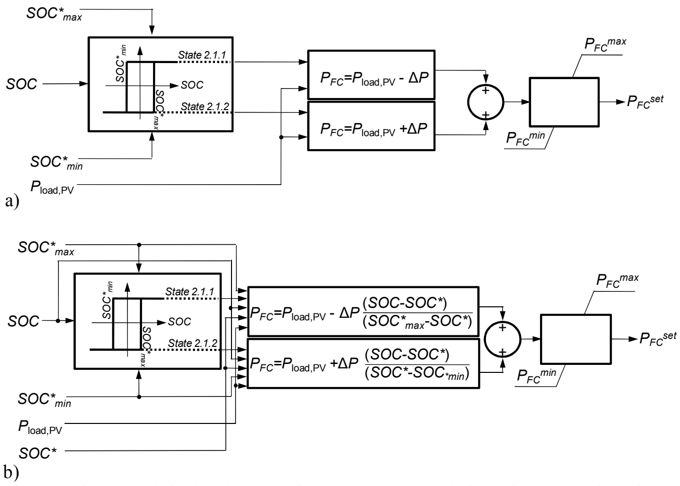


Fig. 1. Schemes of the implemented FC output controls in order to regulate the battery SOC in operation modes 2.1.1 and 2.1.2: a) with hysteresis regulator (regulator A), with hysteresis proportional regulator (regulator B).

With respect to the simple logic of regulator A, regulator B has been implemented in order both to guarantee the requested load following capability of the FC and to reduce the power exchange with the storage system.

III. Experimental set up

In order to verify the behavior of the proposed automatic scheduler system, a prototype has been implemented by using a modern Microcontroller, namely the DSP-FPGA National Instrument CompactRio.

The microcontroller-based system has been installed in an experimental set-up, whose structure is shown in Fig. 2. It consists of a 4.8 kW commercial PEM FC, a lead-acid battery storage system connected to the AC node by means of a 4.2 kW bidirectional voltage-source converter, a PV array emulator connected to the AC node by means of a 1.7 kW current-source converter, a 5 kW and 3 kvar variable electric active and reactive loads which reproduce programmable load profiles through on-load tap-changer (OLTC) transformers with 400 tap positions, and a controlled switch board with the main overcurrent relays. The experimental set-up and is completed with a measurement system equipped with several sensors and DAQ (data acquisition) boards.

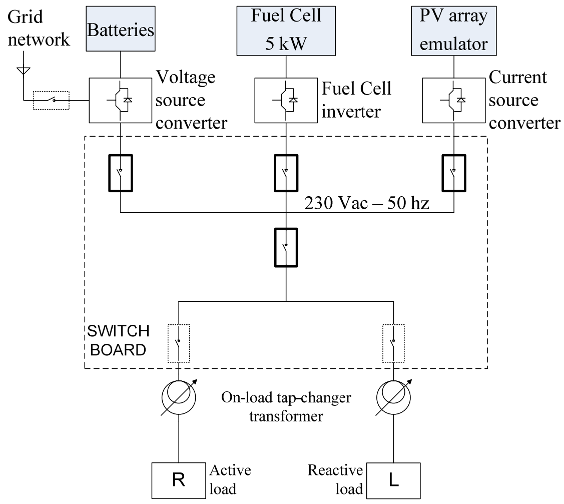


Fig. 2. Architecture of the experimental set up.

Fig. 3 illustrates the links between the microcontroller-based automatic scheduling system and the experimental set-up. The microcontroller collects the data required for the battery SOC estimation (battery DC voltage, current and temperature) and for the FC stack monitoring. The outputs provided by the microcontroller are the FC connection status, its output power set point P_{FC} and the load shedding signals. The microcontroller also provides the monitoring functions of the AC power flows between the loads and the sources.

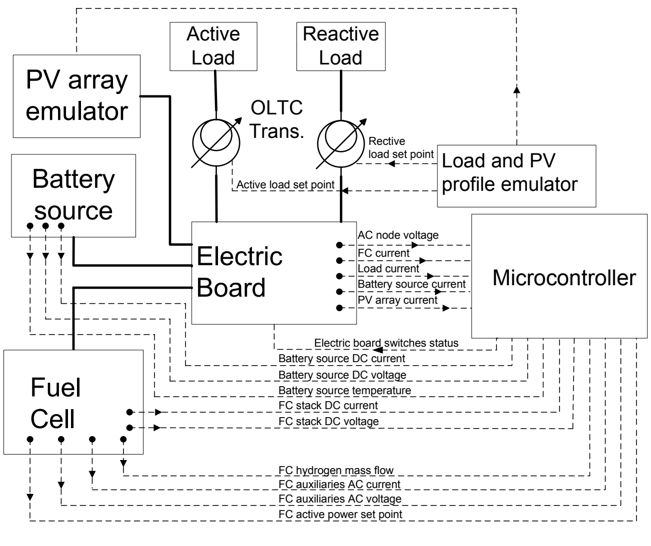


Fig. 3. Links between the microcontroller and the other components of the experimental set-up.

IV. Experimental results

This section shows the dynamic behavior of the system and the action of the automatic scheduling prototype during an 800 s long test characterized by the active power load profile $P_{load,PV}$ shown in Fig. 4.

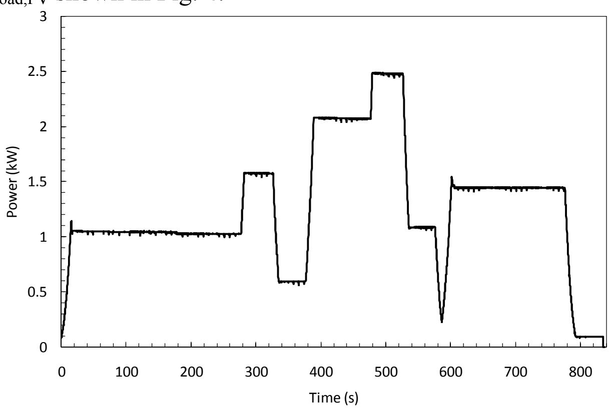


Fig. 4. Load profile adopted during the experimental tests.

During the test, the battery *SOC* is estimated by using the measurement of the battery on-load voltage. The SOC^* value is equal to 50 V, whilst SOC_{min} and SOC_{max} are set at 46,7 V and 52 V, respectively. The values SOC^*_{min} and SOC^*_{max} are 49 V and 51 V, respectively. These values have been chosen in order to verify all the possible operating modes during a short duration test.

The profiles of both the FC power output and of the power of the storage battery system at the AC terminals are shown in Fig. 5, for both cases of FC regulator A (Fig. 5a) and FC regulator B (Fig. 5a).

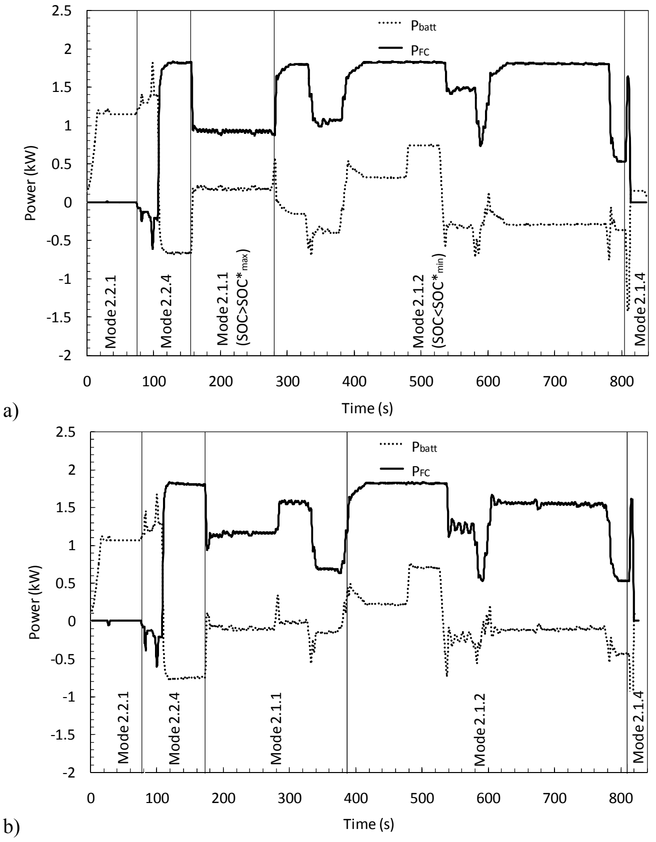
When the test starts, the FC is not in operation, $P_{load,PV}<P_{batt,max}$ and the battery voltage is lower than SOC^*_{min} (i.e., operating state 2.2.1). At 75 s, an intentional startup command is sent to the FC (i.e., operating state 2.2.4).

Soon after the FC connection, Fig. 5 shows that the FC power output has a negative value corresponding to the FC auxiliaries power consumption. The startup of the FC has a fixed duration of about 20 s, after which it starts to generate at the 1.8 kW. The system remains in this operation mode until SOC exceeds SOC^*_{max} and then the FC power level is set by the FC regulator (mode 2.1.1).

Fig. 6 shows that the battery voltage becomes greater than SOC^*_{max} around at 173 s. The system switches from operating mode 2.2.4 to operating model 2.1.1. Regulator A fixes P_{FC} equal to $P_{load,PV}$ minus a ΔP_{down} value, chosen equal to 200 W, whilst Regulator B sets P_{FC} equal to $P_{load,PV}$ minus an adjustment equal to the product between 200 and the difference between the battery voltage and SOC^*, being SOC^*_{max}-SOC^*=1.

For the case in which Regulator A is used, at 280 s the battery voltage becomes again lower than SOC^*_{min} and the system switches to operating mode 2.1.2 and remains in this mode following the load profile. On the other hand, for the case in which Regulator B is used, the switch to operation mode 2.1.2 is delayed until 390 s (dashed line in Fig. 6), due to the fact that regulator B tries to follow load request minimizing the power compensation by the storage system.

At 780 s $P_{load,PV}$ starts to reduce to 100 W and the P_{FC} output is limited to the minimum output value equal to 500 W, which contributes to increase the battery voltage. At 805 s an intentional FC shutdown command is scheduled and the battery is charged so that the voltage exceeds the SOC_{max} value.



a)

b)

Fig. 5. Profile of the FC power output and profile of the power of the storage battery system at the AC terminals: a) obtained by using the FC regulator A; b) obtained by using the FC regulator B.

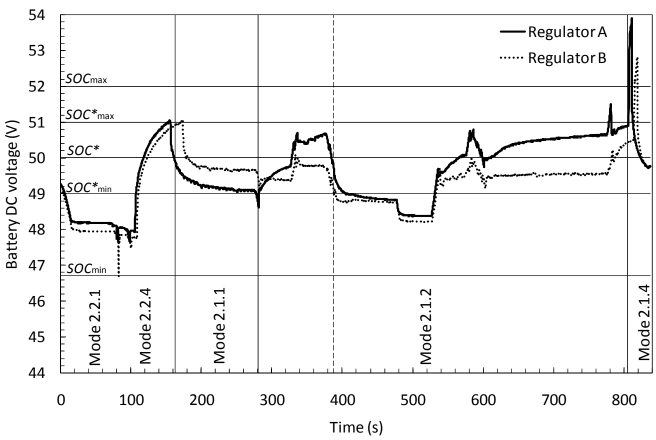


Fig. 6. Profile of the battery DC voltage used to infer its *SOC*: a) obtained by using FC regulator A; b) obtained by using FC regulator B.

As shown by Fig. 7, the measured H_2 total consumption during the test is equal to 411 nl (normal liter) or 392 nl when Regulator A or Regulator B is used, respectively. The difference is due to the difference action of the two control strategies and also justified by the fact that the use of Regulator A results into a larger battery SOC level during the test, as shown, in Fig. 6, by the comparison of the battery voltage profiles.

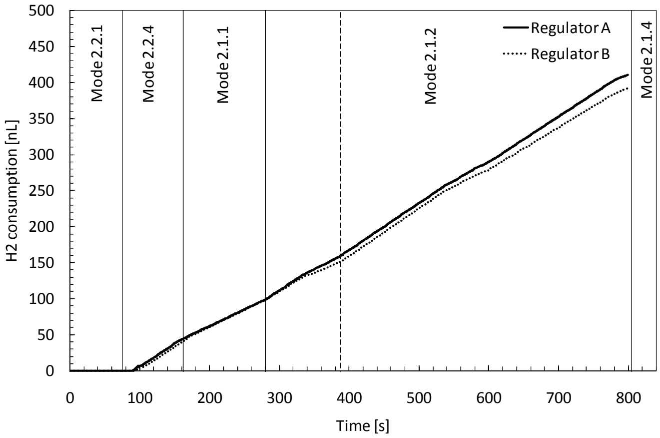


Fig. 7. Cumulative H2 consumption during the test: a) obtained by using FC regulator A; b) obtained by using FC regulator B.

V. Conclusions

The paper shows the main characteristics of an automatic system required for the scheduling of available DERs in household applications. The prototype of this system has been implemented into a microcontroller in order to verify its performances by means of an experimental test set-up equipped with a PEM FC, a battery storage system connected by a specific power electronic converter, a PV array emulator and controllable active and reactive loads.

The main operation variable is the battery state of charge. For its regulation two control strategies of the FC have been implemented in order to test different uses of the storage system. The obtained experimental results allow the comparison of the two control strategies in terms of H_2 consumption and storage system utilization.

Additional research activity will be focused on the implementation of more detailed *SOC* models and other FC control strategies. Long-run experimental tests are also planned to better evaluate the differences between FC control strategies.

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