Modeling, realization and test on field of a fuel cell - Na/$NiCl_2$ battery hybrid system as a base transceiver station power supply

D. Aloisio*, M. Ferraro, G Brunaccini, F. Sergi, N. Randazzo, G. Dispenza, V. Antonucci

CNR ITAE, Salita Santa Lucia Sopra Contesse, 5, 98126 Messina, Italy

aloisio@itae.cnr.it

ABSTRACT. *The telecommunications sector has grown exponentially in recent years due to mobile communications and internet diffusion. This trend seems to continue in near future driven by both further increase of mobile communications in less developed areas and likely diffusion of IoT (Internet of Things). Radio base stations (RBS) need a power grid that is stable and reliable. The approach of the project presented in this work is to replace the UPS and stabilizers with a hybrid fuel cell (SOFC) - Na/NiCl2 batteries capable of high quality energy performances. This kind of system can ensure power delivering where the electric grid is absent or weak or provide a wide range of power and energy services if installed where the grid is present. In particular, the system developed is able to supply both on-grid and off-grid RBS (1-10 kW) and medium sized data centers (+50 kW), integrated with RES (e.g. solar PV, wind), minimizing their unpredictability, and is consistent with future smart grids/smart cities infrastructures. The hybrid approach guarantees energy and power supply while the fuel cell works at a fixed power set point, so that the batteries follow rapid load variations. SOFC systems have too slow dynamics to follow the load power variations without compromising its own lifetime.*

The integration of this hybrid system in the RBS has been studied and designed by using customized power electronics converters. A modelling tool has been developed in MATLAB environment to help in evaluating size, performance, and operative algorithms of this type of hybridization. The real system has been assembled and tested at the CNR ITAE Laboratories. Then it has been moved to a real telecommunication site, in Palermo, to work directly coupled to an operating load.

RÉSUMÉ. *Le secteur des télécommunications a connu une croissance exponentielle ces dernières années en raison des communications mobiles et de la diffusion Internet. Cette tendance semble se poursuivre dans un avenir proche, sous l'effet à la fois d'une nouvelle augmentation des communications mobiles dans les régions moins développées et d'une diffusion probable de l'Internet des objets. Les stations de base radio (RBS) ont besoin d'un réseau électrique stable et fiable. L'approche du projet présenté dans ce travail consiste à remplacer l'UPS et ses stabilisateurs par une pile à combustible hybride (SOFC) - batteries Na / $NiCl_2$ capables de performances énergétiques de haute qualité. Ce type de système peut assurer la fourniture d'énergie lorsque le réseau électrique est absent ou faible, ou fournir* *une large gamme de services d'alimentation et d'énergie, s'il est installé là où le réseau est présent. En particulier, le système développé est capable de fournir des RBS (1-10 kW) connectés ou non au réseau, et des centres de données de taille moyenne (+50 kW), intégrés à RES (par exemple, les panneaux solaires photovoltaïques ou éoliens), ce qui réduit leur imprévisibilité et est compatible avec les futures infrastructures de réseaux intelligents / de villes intelligentes. L'approche hybride garantit l'approvisionnement en énergie et de puissance tandis que la pile à combustible fonctionne à un point de consigne de puissance fixe, de sorte que les batteries suivent les variations rapides de charge. La dynamique des systèmes SOFC est trop lente pour suivre les variations de la puissance de charge sans compromettre sa propre durée de vie.*

L'intégration de ce système hybride dans le RBS a été étudiée et conçue à l'aide de convertisseurs électroniques de puissance personnalisés. Un outil de modélisation a été développé dans l'environnement MATLAB pour aider à évaluer la taille, les performances et les algorithmes opérationnels de ce type d'hybridation. Le système réel a été assemblé et testé aux laboratoires CNR ITAE. Ensuite, il a été déplacé sur un véritable site de télécommunication, à Palerme, pour fonctionner directement couplé à une charge d'exploitation.

KEYWORDS: *SOFC, hybrid system, smart energy.*

MOTS-CLÉS: *SOFC, système hybride, energie intelligente.*

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1. Introduction

Companies which provide communication services, need to strengthen their communication networks to meet the growing number of expected users, cover new areas and improve the quality of their services. This necessarily leads to a growing energy request for supplying these types of infrastructures. Furthermore, it is necessary that energy used to sustain such communication systems is itself of high quality, ensuring the goodness of service and offering many new energy-intensive services (e.g. high speed and high-volume data communication). Hence, a great interest is growing in research of new types of energy systems, since they are efficient, independent, stable, reliable and sustainable, so that they can be used in areas where electric grid does not hold these features or is completely absent (remote and underdeveloped parts of the world). Also, demand for wireless solutions around the world is increasing, prompting service providers to seek and wisely use multiple energy sources.

All forecasting trends (i.e. Figure 1) on telecommunications show how this technology field will become more and more energivorous in next years (Oertzen, 2017; Andrusenko *et al.*, 2015; EY, 2018; ITU, 2015), so giving an important open question on how the energy will be efficiently delivered.

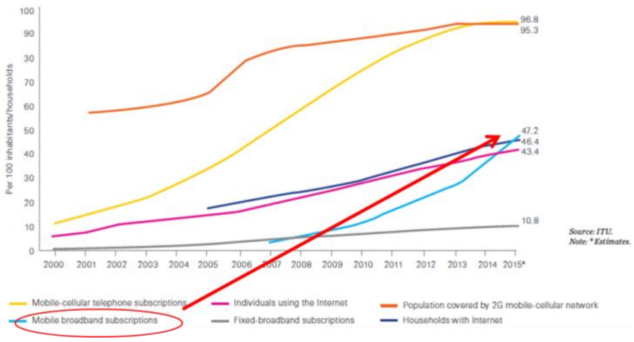

Figure 1. Recorded TLC subscriptions for various types of communication until year 2015 (ITU, 2015)

The approach described in this work try to answer this question by proposing a hybrid SOFC fuel cell- $Na/NiCl_2$ batteries system for TLC power delivering. The system can provide all the features discussed above, in terms of energy quality and power requests, and pursues some of the most important trends in the power supply market for the telecommunication industry. They are:

-replacement of traditional AC (Alternating Current) power backup systems with DC (Direct Current) technologies for power supply and energy storage, reducing efficiency losses due to multiple use of electric power converters;

-energy services provided by grid connected systems (electricity production and storage, heat supply) within surrounding smart grids. There are market opportunities in various service segments (Tier 1, Tier 2), power levels (0 to 5kVA, >5 to 40 kVA, above 40 kVA), and for various applications (base radio stations, data centers, industrial automation)

-standard voltages for telecommunication stations, such as 48V and 60V.

Hybrid energy technologies are emerging (Krishna and Kumar, 2015; Sawle *et al*., 2018; Ibrahim *et al*., 2015) as an answer to these questions. They can also satisfy the needs of the future energy requirements such a reduction of environmental impact and CO_2 footprint, consequent reduction of energy consumption (and OPEX), i.e. more efficient systems. It is important to highlight that there is no “one-size-fits-all” solutions (Upadhyay and Sharma, 2014; Olatomiwa and Mekhilef, 2014). Differences in climate, social environments, site objectives and usage expectations often differ one another in different sites/regions, so that a proper solution for a site can be inadequate in another. However, through computer simulations, developing tools, which test the behavior of these systems in different contexts, can be used to design satisfactory hybrid solutions for a wide range of real situations.

In particular, the modular approach used to develop the prototype in the “ONSITE” project is able to supply both on-grid and off-grid IT plants, for small

RBS (1-10 kW) and medium sized DC (+50 kW), integrated with RES (e.g. solar PV, wind) minimizing their unpredictability, so that it can be considered friendly with future smart grids/smart cities infrastructures.

2. The system

The developed system consists of a SOFC generator (electrically and thermally) integrated with two SNC ($NaNiCl_2$) batteries, interfaced with the electric grid by means of power electronic converters. The SOFC systems, the batteries and the electric grid provide energy to a telecommunications load (a small radio base station, RBS). Power converters perform the electric integration by interfacing different levels (and both DC and AC mode conversions) of voltages.

In particular, a low voltage DC bus (48V) is created by batteries and supply the TLC load. This guarantee the survival of the load even in case of faults, to restore the right operating conditions of the system.

This 48V bus is interfaced to a 400V DC bus by a bidirectional DC/DC converter. A second DC/DC converter coming from the SOFC generator insists on this 400V bus to regulate the output voltage of the fuel cell generator.

Finally, a bidirectional AC/DC converter is used to interface the system with the electric grid and AC loads (if necessary, i.e. a HVAC system). The overall system can work in both on- and off-grid conditions, maintaining the right AC parameter for the AC loads connected.

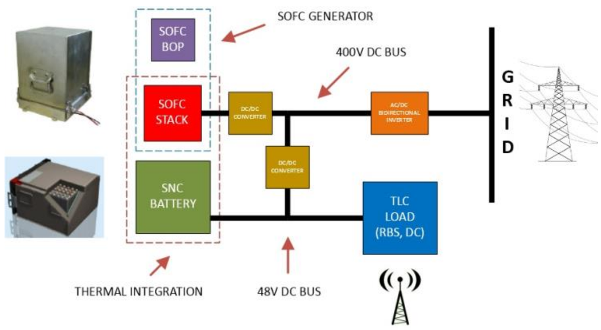

Figure 2. Hybrid system configuration

2.1. The SOFC and its model

The SOFC generator is a commercial model constituted by two 1250W stack working in parallel. The stacks are fed with Natural Gas at standard pressure and the working temperature is around 750 °C.

The generator is designed to operate at fixed working points with different power generation values. The dynamic allows to switch between states is 1A/min. The maximum net electric efficiency reachable at AC side is about 40%. However, including the thermal power recovery the total power efficiency can reach even 90% (mCHP, micro-Combined Heat and Power). To avoid destructive transient in case of grid or load failure, the generator is provided with a DC/DC booster, which steps up the voltage to 400 V DC, and a dump load, to avoid abrupt changes in power delivered when real loads show fast variations.

Figure 3. SOFC generator

Table 1. SOFC characteristics

Characteristics	Values
SOFC Stacks Operating Voltage range	52 to 75 Vdc
Feeding Gas	Natural Gas
Nominal Power	2.5 kW
SOFC Generator Operating Voltage (regulated)	400 Vdc
Operating Ambient Temperature	0 to +60°C
SOFC Stack Operating Temperature	750 – 780°C
Exhaust Temperature	<80°C
Heat Recovered Temperature Range	45 – 65°C

The model is obtained using the built-in stack model present in Simulink, whose parameters were customized through an experimental polarization test (IV-curve):

(1). OCV (open circuit voltage, i.e. Voltage @ 0A);

(2). Voltage @ 1 A;

(3). Voltage and current at nominal power point (according to manufacturer indication, 80% of the maximum power);

(4). Voltage and current at maximum allowed power point

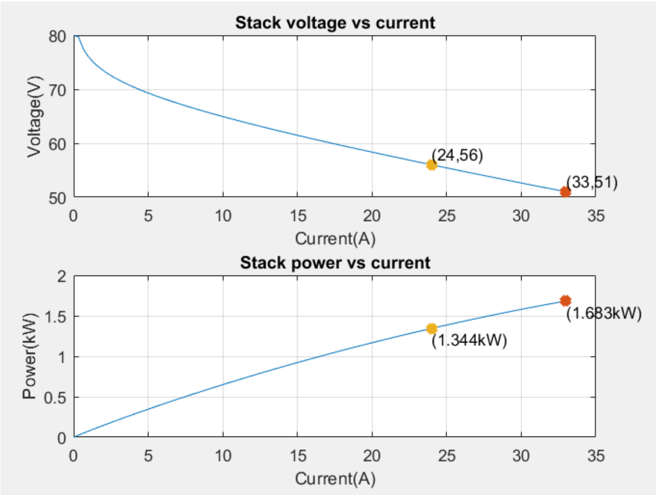

Figure 4. SOFC simulated curves

2.2. The battery and its model

The battery used is a commercial SNC. It is a 48V storage device designed for telecom applications. Main advantages of this technology are:

-constant performances in range -20° +70°,

-3000 cycles at 80% of DoD,

-70% lighter and 30% smaller with respect to conventional backup systems,

-very long storage life without maintenance,

-zero ambient emission,

-efficient material usage and 100% recyclable.

The operating temperature of the battery is around 270° C, reached after a startup procedure by using internal electrical heaters, self-maintained during operation, and maintained by consuming the battery charge during stand-by time. For this reason, the thermal integration with SOFC enhance the overall efficiency by using SOFC exhaust to limit the temperature drop while the battery is idle.

Figure 5. SNC battery

Table 2. SNC battery characteristics

Characteristics	Values
Nominal Voltage	48 Vdc
Operating Voltage Range	42 to 56 Vdc
Nominal Capacity	200 Ah
Maximum Discharge Current	50 A
Operating Temperature	270 °C
Operating Ambient Temperature	-20 to +60 °C

The model used for $Na/NiCl_2$ batteries has been obtained, simulated and validated in a previous work (Brunaccini *et al*., 2017). Without getting into details, the idea behind the model is the identification of two virtual batteries (with different reversible potentials) and the integration of them during charge and discharge processes: the reason is because two reactions have been considered as the main responsible for the battery behavior.

The first reaction, the main one, gives the name to this kind of batteries and involves Sodium/Nickel chloride and their metallic states.

$$\underset{\text{discharged cell}}{2NaCl + Ni} \leftrightarrows \underset{\text{charged cell}}{NiCl_2 + 2Na}$$

$$E = 2.58V$$

Figure 6. First reaction

The second one involves iron and happens at lower potential, when the system is deeply discharged.

$$\underset{\text{discharged cell}}{2NaCl + Fe} \leftrightarrows \underset{\text{charged cell}}{FeCl_2 + 2Na}$$

$$E = 2.35V$$

Figure 7. Second reaction

Starting from well-known literature battery models (usually describing lithium batteries) two main modifications have been performed:

Additional voltage drop at different current values has been added by using current controlled voltage sources (to model the internal resistance of the battery);

Variable resistors have been used to model the OCV variation at different SoC.

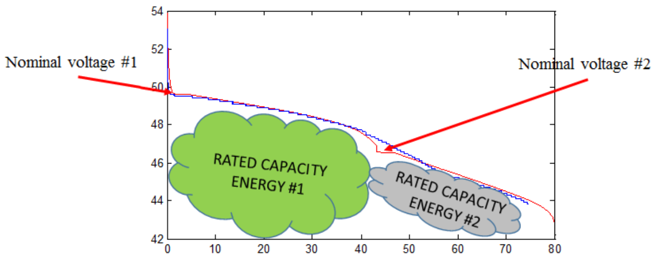

Figure 8. SNC battery behavior

Additional logic has been inserted to control charge and discharge processes of the two virtual batteries.

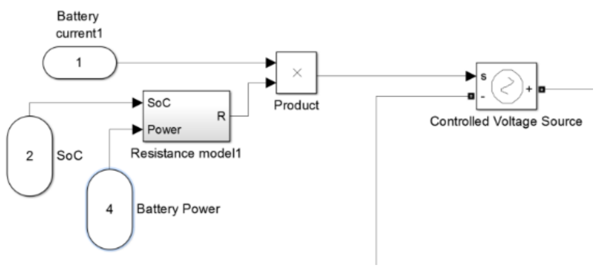

Figure 9. MATLAB modifications to lithium model

At first sodium-nickel reaction acts: when potential goes down second reaction reversible voltage, iron is involved to deeply discharge the battery. In case of charge, our simplified model considers complete reaching of 100% iron virtual battery SoC as the starting point to initialize the primary battery charging.

The strength of the model was validated in a previous work (Brunaccini *et al.*, 2017). The fitting algorithm was based on constant power discharge curves in a wide range of selected values (up to 6000W). Quite good results (fitting curves, in solid red) were achieved in a wide range of SoC.

2.3. Power electronics and models

Power electronics is an extreme important aspect to consider when a hybrid energy system has to be implemented. In fact, parameters such as overall efficiency, power output, flexibility, time response, can be dramatically influenced by the choice of power electronic components. To realize the real system, AC/DC and DC/DC converters have been chosen looking for companies which sell them as commercial products: this choice has been done to have systems which were as more reliable as possible. During test phase of the system, different architectures and products have been tested to find best compromise in terms of complexity, compatibility and management. The selected products are manufactured by an Italian commercial company, and are a high efficiency 6 IGBT bridge AC/DC and a buck boost DC/DC converter, with bidirectional power flow. From a modeling point of view, the simulation of these elements requires the knowledge of the electronic architecture used for power management and control. However, long time observation window simulation are not affected (at least at first glance) by those phenomena, that, on the contrary, are characterized by transient behavior (with short relaxation/extinction time, i.e. fast dynamics), so that they are not so crucial to know exactly how this electronics works. Hence, the chosen approach is to have some black boxes for converters, whose behavior, time response, efficiency, type of control are modeled by parameters coming from experimental measurements.

The idea behind the black box model is to use current/voltage-controlled generators for management of input and output power fluxes and submission of set point. Efficiency and time response are implemented by using additional blocks with values (efficiency, time response) taken from real converters.

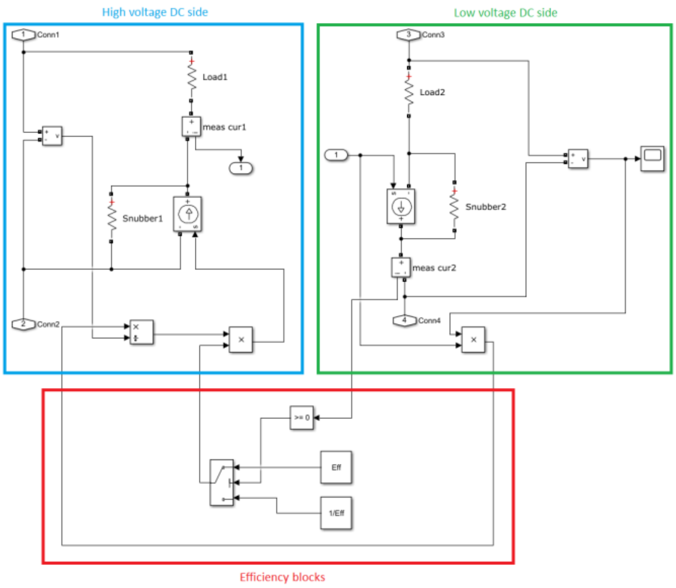

Figure 10. Bidirectional DC/DC model (current control)

DC/DC converter of the SOFC system is modeled as a unidirectional power converter, in which two current generators (SOFC side and 400 V DC bus side) set the SOFC working point and the scaled current injected to high voltage DC side, net of efficiency.

DC/DC converter of the battery system is modeled as a bidirectional power converter. The 48V DC load is inserted in parallel with batteries on the 48V DC bus side. In this case two possibilities are guaranteed: it can impose a current set point on the low voltage DC side or a voltage set point on the same side, as the real converter can. In first case the model use current generators for the low and high voltage sides. In the second case the current generator on the low voltage DC side is substituted by a voltage generator.

AC/DC converter is realized by using a fixed voltage generator to simulate the behavior of the real converter which impose DC voltage on the 400V bus. The AC current is imposed to the grid side by using power fluxes calculations, net to the efficiency. The instantaneous DC power is calculated by multiplying voltage and current on the DC side.

2.4. Load model

To create a simulation valid for the real application, we have used monthly consumption data retrieved from 2016 annual analysis of the real site, and modulated them to create a typical week load by using a literature work on the monitoring of a TLC Station (Spagnuolo *et al.*, 2015). The mean value of energy consumption during a month is used to shift the weekly load curve retrieved to have the same mean energy. In figures below are shown real data and the week profile.

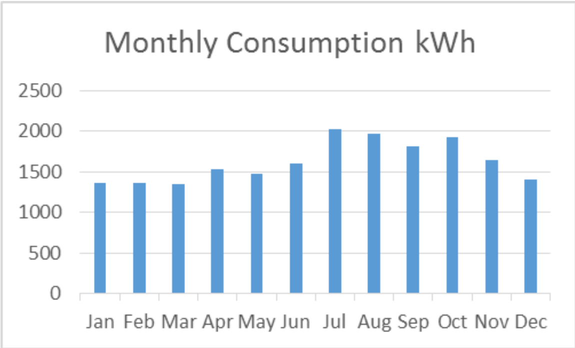

Figure 11. Monthly consumption of real load

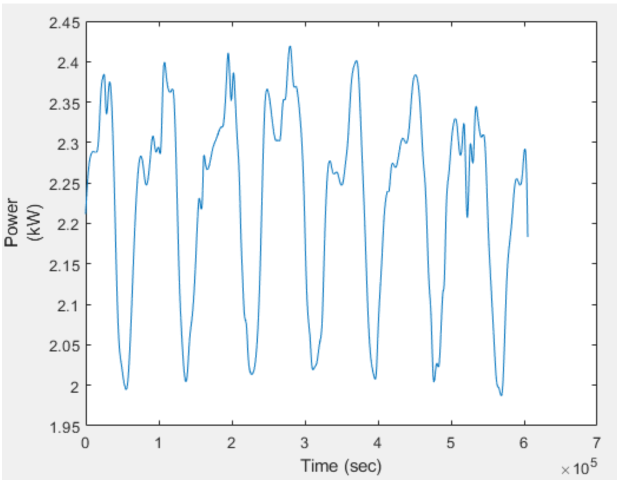

Figure 12. Load week profile (power)

2.5. Modes of operation and control logic

The whole system is monitored and managed by a supervisor realized using Field Point (FP) hardware from National Instrument. Several modules are installed on the FP chassis to dialogue with converters, battery, SOFC and automation cabinet for electrical connections.

Figure 13. Electric cabinet of the system

All data are collected and used to choose the right mode of operation minute by minute. Chosen converters ensure a great flexibility in terms of modes of operation: DC/DC converter can work by setting the high voltage bus value, or the DC low voltage bus one or the current set point on the DC low voltage side, leaving voltages floating and imposed by other elements (i.e. AC/DC converter); AC/DC can control the voltage on the DC bus or the current or voltage (island operation) on the AC side (CSI and VSI mode, in particular it can deliver also reactive power inside a proper capability curve). The supervisor can switch between these modes according to the state of the system: if connected to the grid the inverter can impose the voltage on the DC bus and DC/DC can apply a current or a voltage set point (galvanostatic or potentiation charge/discharge if considering the storage system); also, it can go to island operation mode with high DC voltage imposed by DC/DC and inverter turned to VSI mode.

To simulate the behavior of the system, the model provides both voltage and current control of the DC low voltage bus. These are the longest running modes of operation of the system during its own life, if connected to the grid.

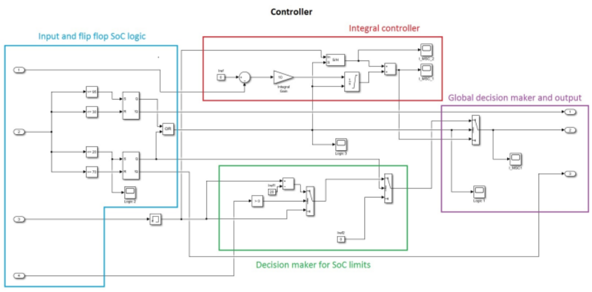

Figure 14. Control logic (DC current control mode)

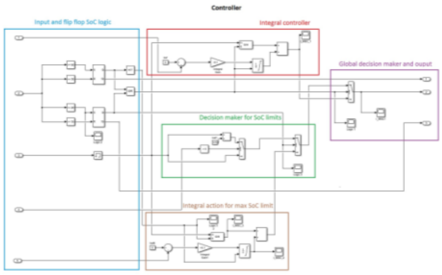

Figure 15. Control logic (DC voltage control mode)

The algorithm implemented imposes to work in a self-consumption mode if the batteries work within fixed limits of operations. Two external and two internal thresholds are used to manage the batteries when the limits are reached. The external thresholds are two chosen SoC limits of the battery package (i.e 20 - 90 %). When one of these conditions is reached the system exit from self-consumption and try to charge the battery if SoC is under lower limit or to discharge if the same is over upper limit. The internal limits of SoC are used by two flip-flops to decide when stop this charge or discharge of battery, started after an external limit was reached.

In voltage control mode, if battery reaches the maximum SoC set point, an integral action is used to voltage to set the current of the bidirectional DC/DC converter in the high DC side to zero, so leaving battery in discharge to the load.

The algorithm can be changed according to type of service the system would deliver. The model realized is used to evaluate the behavior of the real system under main working conditions.

3. Result and discussion

The system of this project has been designed, modeled, mounted, tested and installed during a four-year continuous work. The final goal was to have a real hybrid solution working on an experimental site to give answers concerning feasibility, durability, reliability of this type of system.

Figure 16. Pictures of system moving to the site

The model in particular is used to evaluate preliminary behavior under working conditions and can be used to design similar systems for other applications. The algorithm considers half of the system (one stack, one battery, and halved load) for calculations.

To show the response of the model two operation modes have been characterized: in the former case, the DC/DC uses current control mode to give current set point on the low DC bus; the SOFC woks at a fixed set point, and two different months are compared, March and July, in which monthly consumption is respectively the smallest and the greatest.

It is clear that with the energy source (SOFC) working at a fixed set point, the behavior of the hybrid system shows a charging or discharging trend of the battery if the output power of the SOFC is over or under the mean value of the load requested power.

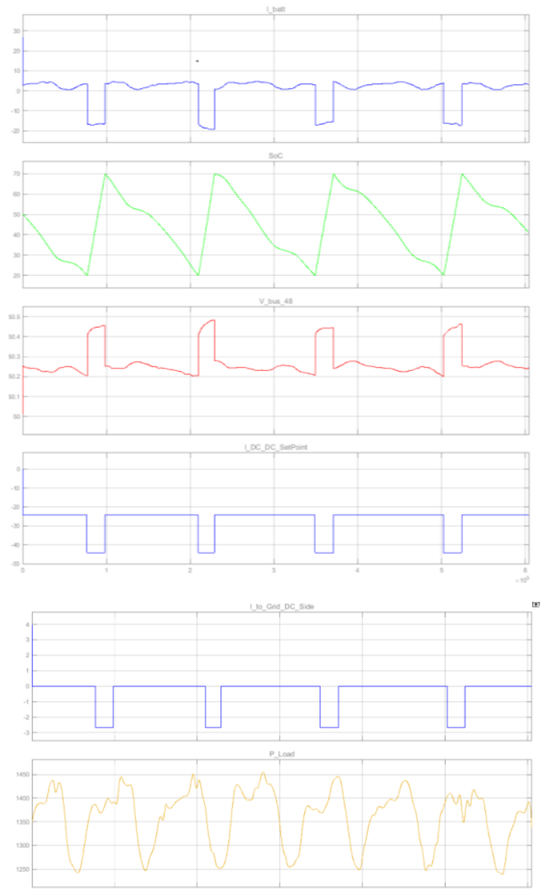

Figure 17. Behavior of the system, July, current control mode

In figures upon are shown the different behaviors of the system at a fixed stack power set point. The six graphs are in order (top to bottom, left to right):

-Battery current, (I_batt);

-SoC of the battery, (SoC);

-Low voltage (48V) DC bus, (V_bus_48);

-Current set point for bidirectional DC/DC converter (current control mode) or current of the DC/DC converter on the 400V DC side (voltage control mode), (I_DC_DC_SetPoint, I_DC_DC);

-Current going to the grid (negative if coming), on the DC side of AC/DC converter, (I_to_Grid_DC_Side);

-Power requested from the load, (P_Load);

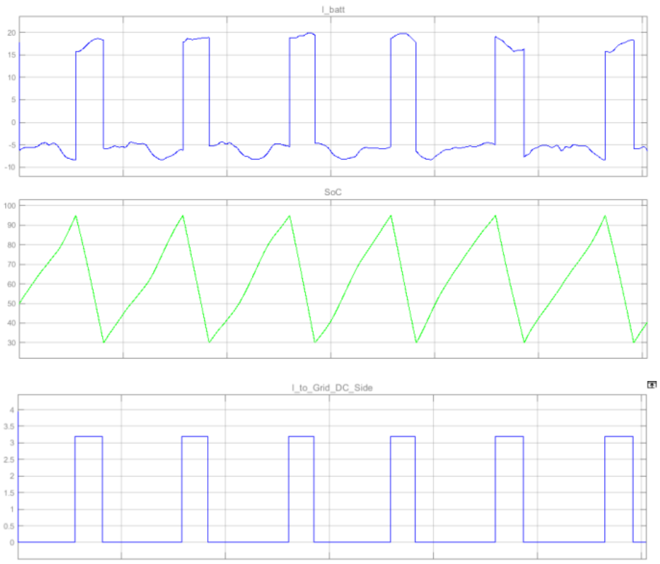

Figure 18. Behavior of the system (I_batt, SoC, I_to Grid_DC_side) March, current control mode

It can be noted that if battery goes over upper threshold the fuel cell power feeds directly the AC grid and battery supplies the load. If battery goes below the lower threshold the grid is also used to recharge it to an established value.

After this, voltage control mode of the DC bus is used. Figures below show how the system reacts in this working condition.

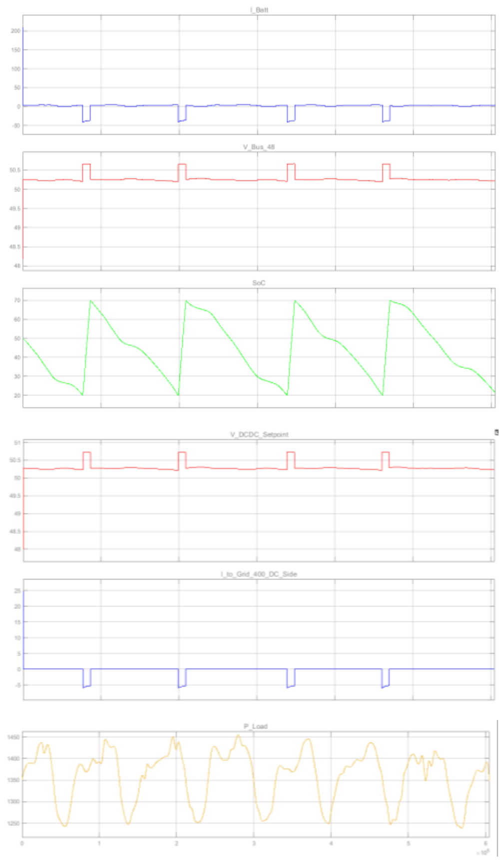

Figure 19. Behavior of the system, July, voltage control mode

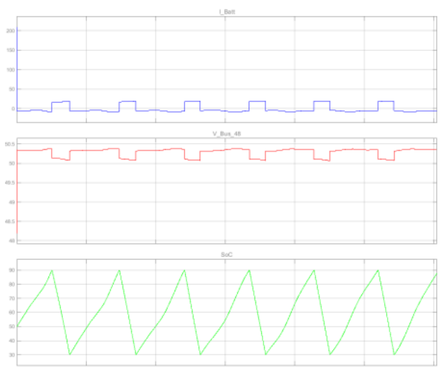

Figure 20. Behavior of the system (I_batt, V_bus_48, Soc), March, voltage control mode

The response of the system in both modes is quite similar. In voltage mode, when 90% of SoC is reached, only the battery supplies the load: this is achieved by using a feedback on current of the DC/DC (which has to be zero) to establish the voltage set point on the low voltage DC bus.

The last simulations are performed with DC current control mode at minimum and maximum SOFC power set point. For the sake of brevity, only maximum working point is reported in graphs below. It can be noted that due to efficiencies at least one recharge is required during the week for the most energivorous month (July).

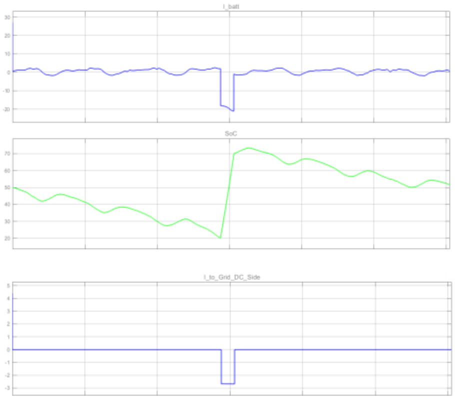

Figure 21. Behavior of the system (I-batt, SoC, I_to Grid_DC_side) July, current control mode, maximum SOFC set point

The model is useful to evaluate consumptions, efficiencies, stress of components. For example, it can evaluate number of equivalent charge/discharge cycles of the battery during a week and mean value during a year or evaluate a strategy for SOFC set point modulation. For example by using real data coming from the SOFC for production and efficiency the model can evaluate the whole efficiency of the week in different working condition.

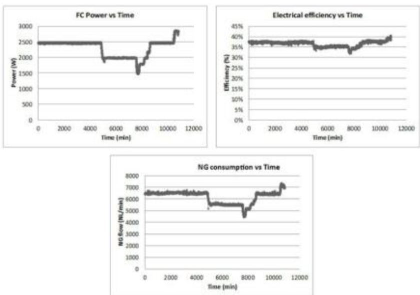

Figure 22. SOFC real curves with variable set point

To have a real parameter for efficiency, a value of efficiency of 0.45 is inserted to consider production and transmission losses for energy coming from the grid. The overall efficiency is evaluated by using the formula:

$$eff = \frac{En_{to\ load} + En_{to\ grid}}{En_{from\ SOFC} + En_{from\ grid}}$$

in which are considered energy contributions from real generator and utilizers. The battery charge and discharge processes and its round-trip efficiency are intrinsically considered in energy stored and released to load and grid in the day cycles. Obviously, to have a correct efficiency evaluation, the simulation starts from a specified SoC and finishes at the same SoC value (this is done to have a net zero energy stored and released contribution from battery). The next table and picture show efficiency values of the whole system at maximum and minimum SOFC power set point in July and trend of efficiency at different SOFC power set point in March. In particular, the figure shows that trend is determined by SOFC efficiency.

Table 3. System efficiencies

	Power (W)	Efficiency
Max SOFC Power	2800	0.365
Min SOFC Power	1500	0.346

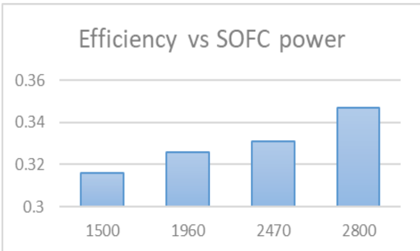

Figure 23. System efficiency variation with different SOFC set points

4. Conclusion

The present work describes a hybrid system supplying a telecommunication site as a real technical solution for this type of application in remote or difficult areas. The model realized has been used to implement control logic and simulate the response of the system. It is a valid tool to perform medium-long time simulations due to reduced complexity but very close to reality behavior. The system is now operating in a real site in Palermo.

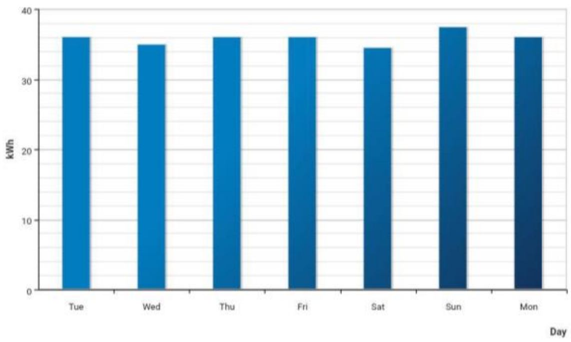

Figure 24. Real SOFC week production on the site of installation

Acknowledgments

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