Hybrid PV-FC Power System

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Abstract: - The purpose of the work is to design and optimise the operation of a system coupling a photovoltaic field, an electrolyser, a gas storage unit, a fuel cell and a power management unit using the cutting-edge technology materials. Such a hybrid system is intended to be an environmentally friendly solution, to maximise the use of the renewable energy production and in a near future to decrease the current level of investment and running costs. All components have been selected for an optimal, automatic, safe and reliable operation of the complete system. Fully instrumented, this test bench aims to furnish new data concerning each component and the complete system behaviour for variable real weather conditions and different load demands. The paper will present the complete description of the intended PV-FC system. It will point out the most important advantages and the competitive forecasted prices of that kind of systems.

Key-Words: - Photovoltaic, Electrolyser, Fuel Cell

1 Introduction

Hybrid systems based on the synergy between renewable energy sources and conventional energy systems (mostly photovoltaic/diesel systems) are known to be a reliable solution for the electricity supply of remote sites. Nevertheless, such a solution is not yet the ideal one, as the use of a conventional energy system induces emissions of both exhaust gases and noise that have to be drastically reduced when looking for environmentally friendly solutions.
The purpose of the work, through the PV-FC association, is to optimise the operation by implementing the following solution:

-Replacement of the conventional system by a Proton Exchange Membrane Fuel Cell (PEMFC), keeping the system reliability of supply at the same level while decreasing the environmental impact of the whole system.

-Introduction of an electrolyser, powered by the Photovoltaic (PV) generator, to produce the fuel for the PEMFC.

-Gas (Hydrogen and Oxygen) storage that can be sized for seasonal operation thus increasing the performance ratio of the renewable production.

-No battery for energy storage, avoiding the presence of a component, which still remains the weakest point of PV systems.

Such a hybrid system is intended to maximise the use of the renewable energy production and in a near future to decrease the current level of investment and running costs (a decrease by 10 to 100 is expected for PEM fuel cells within less than 10 years with forecasted costs down to 100 Euros/kW [1]).
Gas storage capacity, for both short and long term, is analysed in term of its influence on the optimal use of the solar energy. The use of the stored hydrogen ans oxygen is meant to increase the system efficiency when compared with system using oxygen from compressed air.
Such a system can be also used for cogeneration. The heat balances will be calculated and the heat production for domestic purposes will be evaluated.
A prototype unit will be built to act like a test bench that can be used to assist the development of all the tools dealing with modelling, simulation and energy management, necessary to allow an optimal design of pilot systems adapted to remote sites.
Due to the delay of the final step of the test bench realisation linked with the difficulty of part supply, experimental results cannot be presented yet. Nevertheless, this paper presents the precise description of the selected Hybrid PV-FC prototype, which can already illustrate numerous advantages of the coupling between a PV system and an electrolyser to store electricity in a gas form. Finally, the forecasted costs of those PV-FC systems will be estimated. To conclude, the different progresses that will help to develop those environmentally friendly systems will be stated.

2 System Description

The system is made up of a 4.8 kWp photovoltaic system (PV), a 5 kW Proton Exchange Membrane Fuel Cell (FC), a 12 kWh gas storage unit, a 5 kW alkaline electrolyser (EL), a small security lead-acid battery and a Power Management Unit (PMU). The Figure 1 shows the PV-FC system concept block diagram.

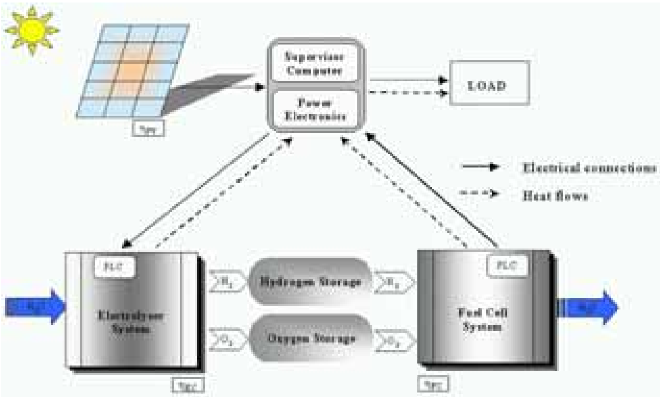

Fig. 1 - The PV-FC system concept diagram block

2.1 Normal Operation

The PV system supplies the load. The surplus of electricity is fed to the electrolyser producing hydrogen and oxygen at a pressure that should not exceed 10 bars. Gases are stored without compression for short or long term. In case of renewable energy deficiency to follow the load request, the fuel cell is switched on to meet the load. A small battery is added to safely stop the electrochemical components. If necessary, this battery can also help the system during transient steps when fast load variation occurs, but, it should never been used as an energy storage.

The Power Management Unit (PMU) is in charge of the conversion and the dispatching of the energy between each component. It should be connected to all other components of the system.

2.2 System Components

The PV field (PV) is constituted with 30 modules of 160 W. There are 5 sub arrays connected in parallel of 6 modules in series. The voltage and current of the system are 144 V and 24,5A respectively, at nominal conditions.

The electrolyser (EL) is an alkaline one constituted by 16 cells of 300 cm^2 in series. The nominal operating point is 177 A, 24 V at 80°C with an expected gas production efficiency of 85%. The control of the gas production is performed by a microprocessor unit, which is also used for the control of the fuel cell and the storage units. The produced gases are drained off the periphery by the way of electro valves. The electrolyte circulates naturally in the process.

The gas and water storage (ST) is directly connected to the two electrochemical components. Naturally evacuated out of the fuel cell periphery, the pure water is stored in a vessel and then provided to the electrolyser via a membrane pump. The storable capacity is 3 dm^3. The 12 kWh gas storage unit is comprise by 8 bottles (8*50 dm^3) for the hydrogen storage and by 4 bottles for the oxygen storage.

The fuel cell (FC) is a Proton Exchange Membrane Fuel Cell, that composed by a series of 25 elements with 900 cm^2. The nominal operating conditions are 210 A, 23.8 V with an expected efficiency of 50%. The FC needs as auxiliary 2 pumps: one circulates the water and the other allows the gas recirculation in the FC.

These three described components constitute the hydraulic part of the system, which is the storage subsystem comparable with the conventional battery based storage system, and it is entirely closed and controlled by the microprocessor unit. All the consumables produced by the electrolyser are stored and then consumed by the fuel cell, and vice versa. There should be no material losses and thus no water consumption under normal operation conditions, although a small water reservoir should be considered to maintain the total amount of water under different operating temperatures.

The small battery unit considered is only used to safely stop the system and may help the system to most quickly provide the variable load demand. The unit is composed by 2 batteries (12 V – 80 Ah) serial connected. The need of battery will be particularly studied with the test bench in order to assess the possibility to be replaced by a capacitor.

The Power Management Unit (PMU) is constituted by 4 DC/DC and 1 DC/AC converters relying on the same 300 V DC Bus. The energy management is performed accordingly with the programmable microprocessor unit stored software program developed.

The load (LD) is a variable resistive load of 5000 W (230VAC). This load can be regulated by the operator to simulate any load flow diagram with realistic loads.

The microprocessor based data acquisition unit allows the recording of all the data necessary to analyse the system performance and to develop simulation models for different load flow diagrams.

The proposed PV-FC system has been designed to operate automatically and safely. All components were considered to optimise the system performances. All components have been tested and show a perfect operation. The last stage to be performed is the connection of all components to the PMU.

After its final assemblage the studies should concentrate in some pre-working experiments, e.g. the water consumption of the system to accurately dimension the water reservoir, the intrinsic electrical consumption of the system which has to be evaluated and minimised, the necessary energy provided by the batteries for the actual system….

3 Philosophy of the Hybrid System

The proposed hybrid system has several characteristics that allow it to be a successful solution in stand alone units. Among others it should be pointed out its high energy conversion efficiency, the fact it is an environmentally friendly solution, that it is a completely autonomous system, and the will help to increase the usage of renewable energy.

The coupling of a PV system and an electrolyser allows converting at high efficiency renewable electricity into time-stable storage. There is no loss whatever the storage time and no need of consumption to avoid storage destruction.

Using a fuel cell to reconvert the gases back to electricity is a low efficiency process but allows building a silent energy generator without the need for external consumables.

The gas storage induces a complete autonomy during all the year and increases the use of the renewable production. If the system is sized to co-generate electricity and heat, those systems (load consumption /renewable production) could reach a high global efficiency even compared with classical PV-Battery systems.

3.1 Energy Conversion

The first advantage of the proposed system is to convert renewable electricity into a chemical form with an high conversion efficiency. The electrolysis efficiency is about 85%, based on the High Heating Value (HHV). The gas production efficiency, named Faraday efficiency, increases with the current density and hardly with the EL temperature [2]. Depending on the electrical connection between the PV field and the electrolyser, the adding loss is about 10%. The overall energy conversion is thus 75% from the renewable production through the gas storage.

Nevertheless, there are no losses due to a compressor since the electrolyser is able to produce pressurized pure gases. At present, the commercial electrolyser pressure is only between 10-25 bars, but, in the near future, it is expected that this pressure should increase up to 100 bars. Also when the energy is in a gas storage, there are no losses in time, in normal operating conditions.

The PV-EL coupling allows a conversion of renewable electricity at high efficiency in a time-stable energy form. The oxygen may also be stored as hydrogen is, and by storing the 2 pure produced gases it should allow the increase the fuel cell performances as well as limit the water losses in the system.

3.2 Environmental Friendly Solution

The electrolyser consumes pure water, largely present on the earth.

In case of fuel cell electricity regeneration, the exhaust product is pure water, which can supply the electrolyser. If oxygen, hydrogen and pure water are stored, the hydraulic system is closed, but it should always be taken into consideration the existence of few small hydraulic leaks.

Although electrochemical reactions are not 100% efficient, losses are only electrical or thermal. There is no significant consumables loss in normal operating conditions. Therefore, the PV-FC system should consume only exceptionally nitrogen in case of emergency stop of the 2 electrochemical devices for purging purposes.

In terms of noise, although the hydraulic subsystem requires electric motors for the electro valves, the level of the noise expected is very low when compared with a diesel generator, and can be easily compensated by inserting them into acoustic capsules.

3.3 Autonomy

In classical hybrid systems, the renewable obtained energy is stored in batteries. The batteries capacity corresponds to less than one-week of system autonomy (usually, 3-5 days), due to the dimensions and the weight of batteries but also to the adverse use of the batteries in case of too large storage capacity. The extension of autonomy is realized with a diesel generator, consuming fossil fuel.

In a hybrid PV-FC system, gas storage can be sized for the complete system autonomy. There are no technical constraints. The energy can be stored at anytime without losses and without deterioration whatever the consumption of stored gases is. For the proposed system, the large storage configuration can not be implemented due to the low electrolyser pressure considered. In any case, the higher the electrolyser pressure is, the smaller is the necessary storage capability, in a proportional way. In terms of autonomy, water and nitrogen consumption of those systems has to be as low as possible, i.e. null for normal operating conditions. In case of no water consumption achievement, PV-FC systems are really stand-alone energy generators.

3.4 Renewable Energy Usage

Since the hybrid energy production system is design

to be autonomous it should be sized using the local annual average value of the solar production as well as the load consumption.
To size the PV field, the equation (1) is usually used:

$$A_{PV} = \frac{E_{avg}}{\eta_{PV} P_R E_{solar}} \qquad (1)$$

In (1), A_{PV} represents the PV unit surface (m^2), E_{avg} the average load consumption (kWh/day), η_{PV} the PV efficiency (10-15%), P_R the performance ratio (System efficiency), and the E_{solar} the average solar radiation used to size the system (kWh/m2.day)
For the PV-Batteries classical system sizing, E_{solar} is the average solar radiation of the worst month during the year due to the short autonomy capacity.
The performance ratio depends on the components efficiency and on the time overlaps between the solar production and the load demand. In real applications in operation around the world, the system efficiency (P_R) varies between 20% and 70%. Figure 2 shows that the major domestic Stand Alone System (SAS) made up of PV and Batteries has a P_R between 30% and 40% [3].

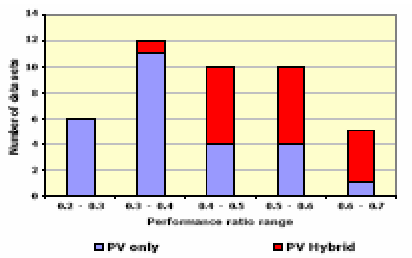

Figure 2 - Range of yearly performance ratio for typical domestic SAS [3]

For the PV-FC system, the possible annual autonomy allows a dimensioning based on the yearly average value of the solar production and of the load.
A simulation model based on the test bench components efficiency has shown that P_R is between 30% and 50% varying only with the match between the solar production and the load demand. 30% is obtained when the load demand occurs during the night (no over laps). 50% corresponds to the best match between the load and the sun. This ratio is limited to 50% due to the storage efficiency and to the fact that in case of annual autonomy, an important part of the solar production is effectively stored since it is produced during the favourable seasons for the adverse seasons.
All of these elements considered, the hybrid PV-FC system, when compared with the PV-Batteries systems, could allow a better use of the renewable energy and thus a reduction of the needed PV surface.
All solar production in the proposed system is in fact used by the end users or lost electrically or thermally in the system. The global efficiency of the proposed system can be improved if cogeneration is considered.

4 Forecasted System Cost

The actual investment for a hybrid PV-FC system is at present date a very important. This is due to the high actual cost of all its components. Since the system components are experiencing a huge development, the investment could become competitive when compared to the other classical SAS's in a short term period.
Table I describes the forecasted cost of the different components constituting the PV stand alone systems. The cost of the PV, the batteries and the converters is prevision for 2005 [1]. The forecasted price of the electrolyser corresponds to the actual industrial electrolyser cost (power range 30-300 kW). At present, there is no commercial electrolyser available in the range of 1 to 5 kW.

Table 1 - Forecasted prices for the system components

Component	Forecasted price	
PV	2 500	€/kW
EL	3 000	€/kW
FC	100	€/kW
Batteries	65-100	€/kWh
Gas Storage	50	€/Nm^3
Converters	300	€/kW

The FC cost presented in table 1 is the aim set by the automotive industry for the FC to be competitive against the thermal engine when replaced by an electrical one regardless of the EV topology and control strategy [4 – 5]. This very low price will be certainly respected due to the important market share that this industry has.
Concerning the gas storage, the actual cost is very high. Since the gas suppliers usually rent the storage installations, the price presented is set hypothetically considering the components simplicity.
All together table 1 shows that the forecasted cost of the hybrid PV-FC system components should become comparable to the PV-Batteries in a near future. Considering these values, the hybrid PV-FC system forecasted cost could reach 4 €/W that can be compared to the forecasted cost of 5 €/W in 2005 for the classical PV-Batteries [1]. Moreover, the electrolyser lifetime is between 10 to 15 years. On the other hand, the fuel cell operational guarantee is presently never superior to 4000 operating hours at

nominal conditions. At present date is impossible to precise the price of the produced kWh due to the data lack on the lifetime and running costs of the FC.
In any case it is visible that presently the hybrid PV-FC system is very expensive but due to the large increase in the investment around the world in the proposed technology it should become competitive when compared with the classical SAS depending on the forecasted cost reduction of its components.

5 Hybrid PV-FC Roadmap

In the present it is important to establish the roadmap for the development of the new hybrid system proposed in the present paper. The main topics we are presently concerned about are: the storage pressure level; the PMU development; the FC improvements; the cogeneration possibility; the components forecasted price; and the security issues.
Increasing the electrolysis pressure could largely decrease the necessary storage size. The actual complete autonomy is not conceivable due to the storage dimensions and also its price. The price of the storage has to be largely decreased to be competitive. The pressure increase will induce extra security measures in the system.
The progress in electronics has been huge in recent years so, currently the development of adapted PMU using the required technology allows high conversion efficiency and high performing energy management. The prototype unit in our test bench will be evaluated to confirm this efficiency.
Generically, the fuel cell has to be improved in many points, e.g. its expected efficiency is only 50%. That low efficiency has an important effect on the global system efficiency (30% to 50%). The issue of the FC lifetime should also be looked into thus allowing the current system to become commercially viable.
The development of electrochemical devices already designed for the cogeneration is important to increase the global efficiency of the systems. For stand-alone applications, special components should be developed for cogeneration.
All components should become less expensive in the near future, since the year of 2010 is the target for the market availability for these hybrid systems as competitive ones for stand-alone applications.
Also an important issue for the proposed roadmap and even survival of the hybrid PV-FC systems is safety. Presently the development has problems relating to the hydrogen and oxygen storage. This issue has to be particularly looked upon to avoid any human hazards that might risk the proposed system implementation regardless of being an environmental friendly solution.

6 Conclusions

New energy generators for stand-alone applications are expected to increase the comfort of people by providing them with clean energy in remote locations. The currently available solutions are either limited by a low autonomy that imposes a reduction of the energy consumption during worst seasons or by the usage of noisy and fossil based energy systems.
The proposed system allows a total autonomy, and aims to the absence of consumables. Although similar systems are not new the recent technology progresses in the fields of FC and electronics promise sustainable good performances and system reliability.
The hybrid system proposed is based on the analysis of a developing test bench. The installation of the PV-FC system has been designed to operate autonomously and with safety concerns. The components selection has been optimised to meet the best possible system performances.
The coupling of a PV unit with an electrolyser allows a high efficiency conversion from renewable energy into time-stable storage one. Using a fuel cell to get back to electricity allows building a noiseless energy generator without the need for consumables. The gas storage unit usage allows a complete autonomy for years and should increase the use of the renewable energy in SAS energy production.
The hybrid PV-FC system is currently very expensive but in the future, the current technology investments should allow it becomes competitive when compared with other stand-alone systems.
Although the presented system does not display high efficiency and still has a high price, technology progresses are expected in the short term, and it is possible to assume that the proposed solution will contribute to the batteries replacement in SAS.

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