Fuzzy Logic Based Management of a Stand-Alone Hybrid Generator

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Abstract-- **The paper deals with a fuzzy logic based strategy managing the power flows in an hybrid generation plant. Such a plant works in island mode and is composed of: a wind turbine, a photovoltaic generator and a fuel cell/electrolyzer energy storage system. The performances of the proposed strategy are evaluated by simulation in different operating conditions. To this purpose some performance indexes are considered, such as: the frequency deviation, the stability of the DC bus voltage and the AC voltage total harmonic distortion. Simulation results confirm the effectiveness of the proposed power management strategy, providing the ground for the practical realization of a fuzzy logic based control system. Moreover the efficiency of the developed fuzzy logic controller is compared to that of a more conventional controller taking into the fuel cell H_2 consumption, the amount of H_2 generated from the Electrolyzer and the final battery state of charge (SOC).**

Index terms-- **Fuel Cell/Electrolyzer Energy Storage System (FC/E-ESS), Fuzzy Logic (FL), Hybrid system, PhotoVoltaic Generator (PVG), Power flow management, Wind Energy Generator (WEG).**

I. INTRODUCTION

Strong concerns over global warming and shortage of conventional fuels have powered an increasing interest around the generation of electric power from green energies.

The solar irradiation is becoming one of the most important renewable energy resource, since it is pollution free, inexhaustible, and permits an on-site electric energy generation [1,2]. Wind, on the other hand, is a clean energy source that increasingly contributes to reduce the dependency from fossil fuels, taking full advantage from a progressive cost reduction of the wind generator technology in times in which the cost of traditional fuels instead increases [3]. The Fuel Cell (FC) technology is an attractive option to compensate the discontinuity of some renewable energy sources like solar irradiation and wind, thanks to a high efficiency, a fast load response, the modularity, and a large fuel flexibility [4].

An hybrid generation system composed of a WEG and a PVEG, in theory features a load supply continuity higher than simple PV or wind generators, due to the overlap of the availability of the two primary sources. However, a fully exploitation of all the available energy can hardly been accomplished without a suitable energy storage system. Among several possible solutions a FC/E-ESS can be considered coupled to an additional Lead Acid battery bank. The FC/E-EES is the main energy storage system while the Lead Acid batteries are used to compensate the low dynamic of the FC system. In the considered plant, the main task of the batteries is to hold the DC bus voltage within the rated range in case of sudden load variations. Therefore the capacity of the batteries is relatively small.

A stand alone hybrid power generator must be suitably controlled in order to obtain the maximum possible efficiency and the maximum possible continuity of load supply. Specifically, the power exchange among WG, PVG, FC/E-ESS and the loads must be tightly regulated in order to ensure that all the captured energy is delivered to the loads. To do this a system management unit computes the references for the control systems of the three main elements of the system on the basis of measurements of the power generated from WG, PVG and FC/E-ESS, the DC bus voltage, the amount of H_2 in the storage tank and the battery state of charge (SOC). The definition of an optimal management strategy for a quite complex system as the considered hybrid generator can hardly be accomplished with a traditional method, therefore, a FL approach is instead proposed in this paper.

II. SYSTEM CONFIGURATION

Fig.1 shows the schematic diagram of the considered standalone hybrid system. The three main elements: WEG, PVG and FC/E-ESS are supposed to be controlled by three independent control systems, also accounting for the Maximum Power Point Tracking (MPPT).

Suitable mathematical models of all the elements of the system have been previously modelled and a detailed description of the models is beyond the objective of this paper.

A dump load is also considered consisting in a power converter delivering the excess power to a resistor bank. When the power generated from sun and wind exceeds the load demand, the excess energy is delivered to the electrolyzer to be stored under the form of hydrogen in a suitable reservoir tank.

As the generation plant works in island mode, if the power generation is insufficient to sustain the loads, the stored hydrogen is exploited to supply a FC stack delivering the power balance to the load.

If the H_2 storage tank and battery are full, any excess power is transferred to dump load. System sizing is beyond the purpose of this paper.

Details about parameters of the four main subsystems of the considered plant are given in Tables I and II.

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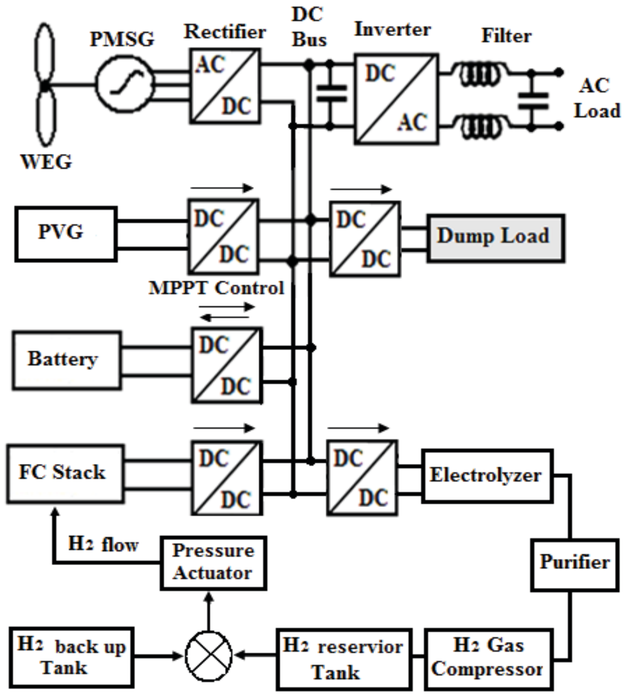

Fig. 1- Schematic of the hybrid generation system

TABLE I
PVG AND WEG MAIN DATA

PVG	
Module model	Solyndra® - SL001-157
Module unit	157Wp at STC
Module open circuit voltage	92.5 V
Module number	3 × 4 = 12
Power rating	1.88kWp
WEG	
Model	TN-1.5 Nozzi Nord
Rated power	1.5kW
Cut in/Cut out speed	4m/s & 20m/s
Generator type and ratings	1.5kW PMSG @ 50 Hz

TABLE II
FC STACK AND ELECTROLYZER MAIN DATA

FC Stack	
Model	Nexta™ (PEMFC)
Rated power	1.2 kW
Operating voltage	22-50V
Temperature range	3°C - 40°C
Electrolyzer	
Model	Von Hoerner
Rated power	2.25kW
Voltage range	30-100V
Battery (lead acid)	1kWh at 96 V

III. POWER MANAGEMENT STRATEGY

Fig.2 shows a flow diagram of the proposed power management strategy. It starts from the evaluation of P_{net} the difference between the whole generated power and the load power demand as:

$$P_{net} = P_{pv} + P_{w} - P_{load} \qquad (1)$$

where P_{pv} and P_{w} are respectively the power generated from PVG and WEG, P_{load} is the load power. The value of P_{net} determines the plant operational mode. If $P_{net} > 0$, there is an excess of generated power while if $P_{net} < 0$, the generated power is insufficient. The excess power is supplied to the electrolyzer if the battery is fully charged and if the H_2 reservoir tank is not full. However, if the excess power is greater than the electrolyzer rated power, part of the energy is transmitted to the dump load. If the reservoir tank is full then the excess power is totally delivered to the dump load. If a lack of power is detected and enough hydrogen is available in the reservoir tank, the fuel cell stack is turned on. The lack of power is classified into small, normal and high in order to determine the most suitable strategy to compensate the shortage.

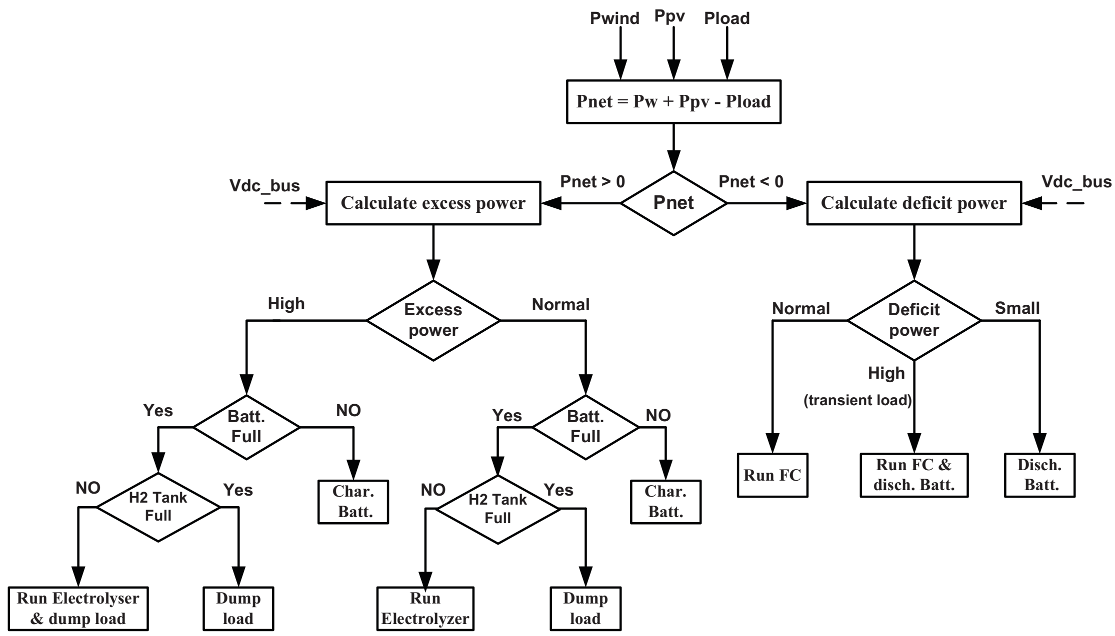

Fig.2- Power flows management

The FC/E-ESS is operated alone if the lack of power is lower than its rated power. However, if the lack of power is small enough only the battery is used. If the lack of power is high, the battery is tasked to support the FC/E-ESS, as in the case of a sudden load variation in order to compensate the low dynamic of the stack.

The management strategy shown in Fig. 2 has been implemented exploiting a FL approach.

The linguistic description of FL global behaviour controller avoids the need for a detailed model of the controlled system or of the control strategy. The performance of the FL controllers is better than conventional controllers and also is considered more robust in the case of uncertainty [6].

The FL graphical user interface (GUI) toolbox implemented by MATLAB/Simulink has been used as it is simple and effective. This FL toolbox supports Mamdani-type inference.

The main task of the control strategy is to determine the references for the control systems of the subsystems of the hybrid generation system as shown in Fig. 3. The FL strategy is built using a Mamdani inference with four input variables and two outputs. The input variables are the net power P_{net}, the normalized Hydrogen tank pressure, the DC bus voltage and the battery state of charge (SOC). For all these variables triangular membership functions are used, excepting for the normalized pressure, where a generalized bell function is used instead.

The output variables are the reference power for the control systems of the FC/E-ESS and the batteries. Triangular membership functions are used for these variables.

As shown in Fig. 4 the DC bus voltage is described through three linguistic terms, which are: low limit, normal, and high limit. The SOC of battery has three membership functions, namely: empty, medium and full.

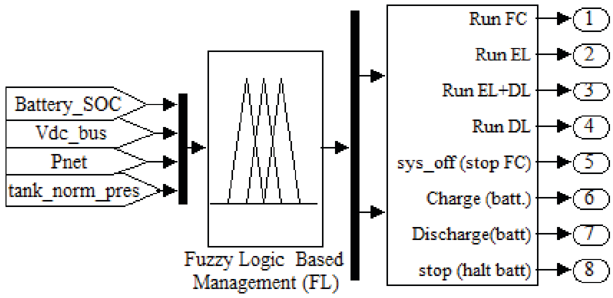

Fig. 3. FL based management strategy

P_{net} has five membership functions: high-excess, normal-excess, small deficit, normal deficit, and high deficit (transient load). The storage tank pressure has three membership functions; empty, medium and full. The battery power has three membership functions: charge, discharge, and stop (idle) mode, while the FC/E-ESS operating mode has five membership functions, that are: running fuel cell stack (FC), running electrolyzer (EL), running electrolyzer and dump load (EL+DL), running dump load (DL), and turning off the fuel cell system (Sys-Off).

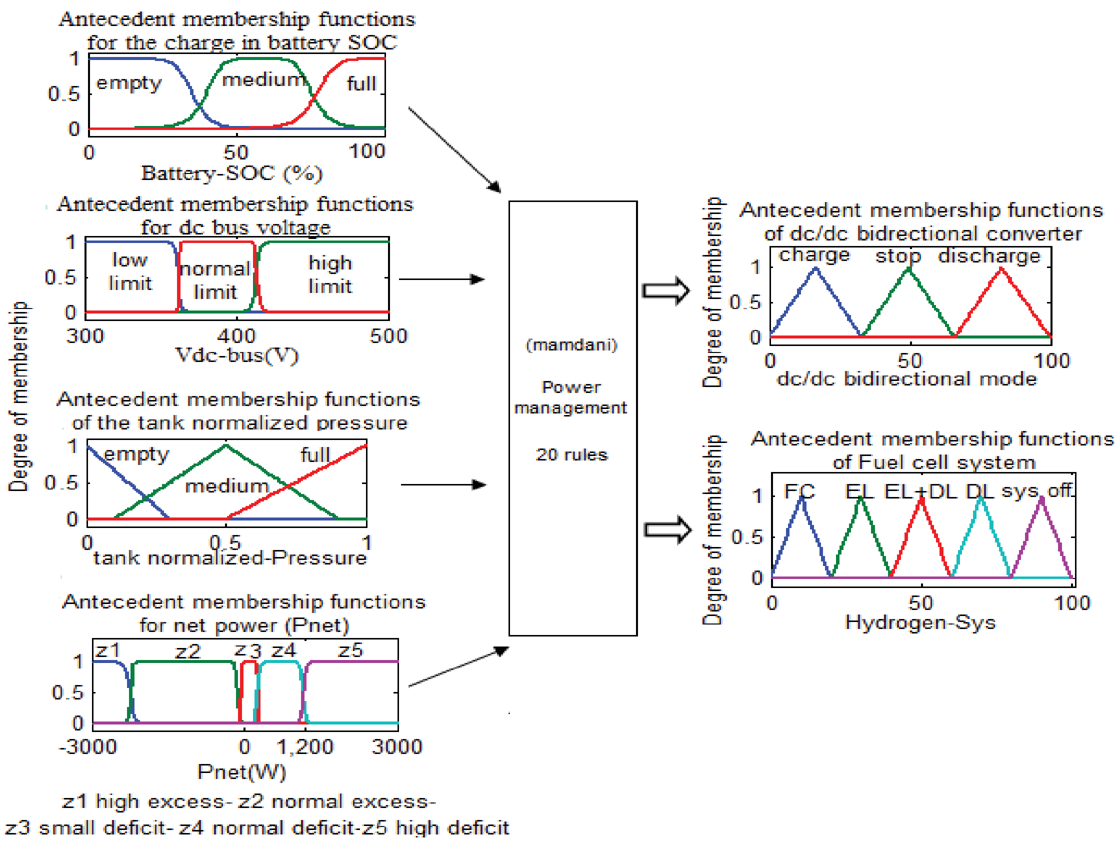

Fig. 4. Fuzzy inference system

IV. SIMULATION RESULTS

Two sets of simulated tests have been accomplished. The first is aimed to confirm the effectiveness of the FL based management using performance indexes (the frequency deviation, the stability of the DC bus voltage and the AC voltage total harmonic distortion). The other is aimed to compare the FL controller with a more conventional controller. Considered energy performance indexes are: the amount of H_2 consumption by fuel cell, The amount of H_2 generated from Electrolyzer, and the final battery state of charge (SOC).

A. Performance of FL based management

Three cases are considered, dealing with different weather data and load demand day profiles. The ambient temperature is assumed to be constant (25°C) throughout the simulations. The solar radiation is expressed in per unit, the base value being 1kW/m^2, the wind speed is expressed in the actual values, the power flow and load demand is also expressed in per unit system at base value 1kW, and the DC bus voltage is normalized at 400V. A well known network stability index is considered, the normalized frequency deviation, that is computed as:

$$\Delta f=(f-f_r)/f_r \qquad (2)$$

where: f_r is the grid rated frequency (50 Hz) and f is the actual frequency. The variation of the DC bus voltage level is considered as a further system stability index. In general, voltage variations are caused from sudden changes of the load or weather conditions. The DC bus voltage is controlled to remain within the 370 – 420V range. THD is an index to take into account when evaluating the quality of the output AC voltage.

<u>CASE 1:</u> This case deals with an excess of generated power. The battery is assumed full charged at the beginning. Results of time domain simulation are shown in Fig. 5. The simulation test can be divided into four intervals:

(0-20s): the average wind speed is about 8.5m/s and the average load is 0.45pu. The solar radiation is zero. WEG covers all the load demand and the net power is zero.

(20-60s): the average wind speed rises from 8.5 to 11m/s and load demand rises to 0.6pu. The solar radiation rises gradually to about 0.75pu. The excess power increases gradually to 2pu with the increase of the solar radiation and wind speed, as shown from the P_{net} diagram. According to the developed power management strategy, the excess power is delivered to the electrolyzer. Therefore, the storage tank normalized pressure increases as the hydrogen is pumped in.

(60-80s): The load demand decreases to 0.2pu, the solar radiation rises gradually to 0.95pu, while the wind speed is constant. The excess power in this interval is higher than the electrolyzer rated power. About 0.4pu is then delivered to the dump load, while about 2.2pu is delivered to the electrolyzer. The storage tank normalized pressure increases as the Hydrogen is still pumped in.

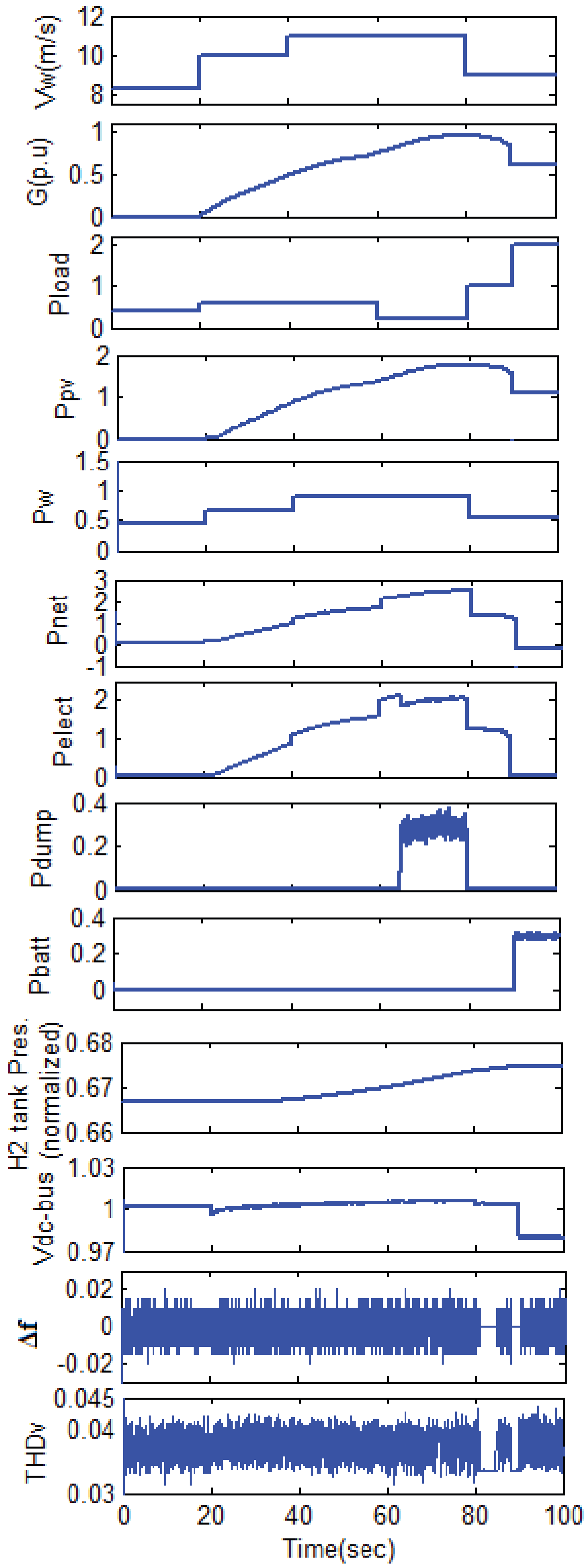

Fig. 5. Case 1 - Time domain simulation

(80-100s): The load demand abruptly rises from 0.2 to 1 to 2pu. The solar radiation and wind speed decreases to 0.6pu and 9m/s, respectively. Within this interval (at 90s) a small power lack occurs as the load rises to 2pu. The power lack is compensated by the batteries according to power management strategy.

The system is stable during all the considered intervals as it is possible to observe from the Δf diagram. In fact, the normalized frequency deviation is always less than 0.02, moreover, the DC bus voltage remains constant around 1pu. More precisely, after 90s, the DC bus voltage decreases to 0.98pu, which is still within the allowed range of variation.

CASE 2: Deals with an insufficient generated power. Results of the simulation test is shown in Fig. 6.

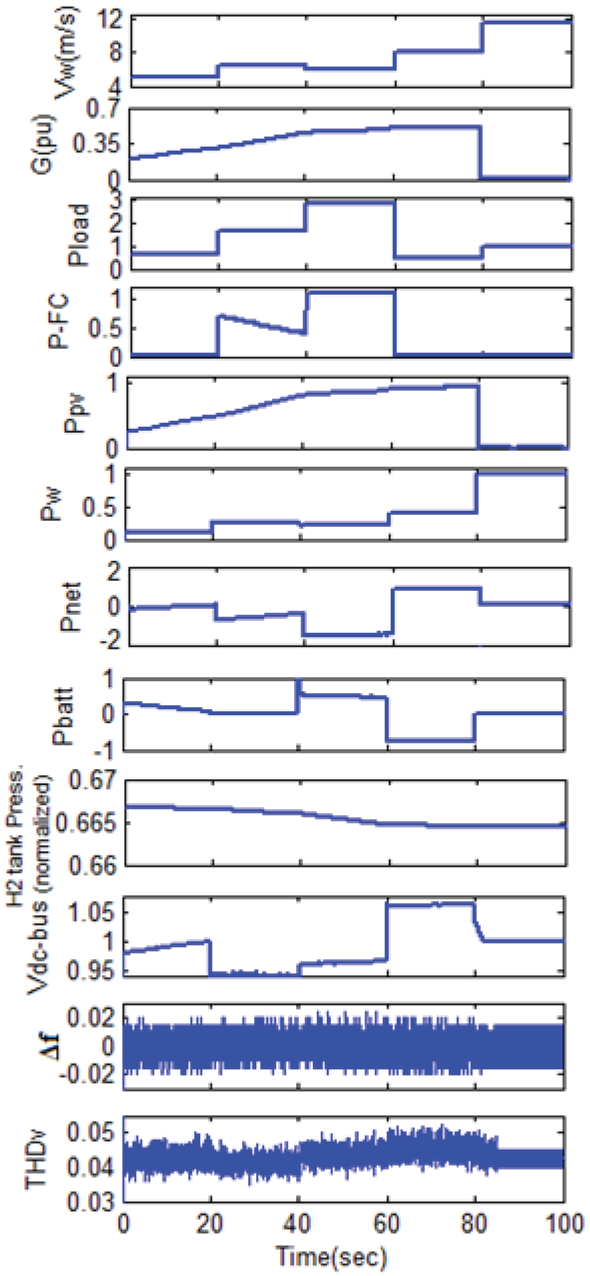

Fig. 6. Case 2 - Time domain simulation

The simulation can be divided into five intervals:

(0-20s): The average wind speed and the load demand are 5m/s and 0.6pu, respectively. The solar radiation rises gradually from 0.2 to 0.3pu. As the power lack is small (< 0.2pu), it is compensated only by the batteries.

(20-40): The load demand increases to 1.6pu, while the wind speed and the solar radiation increase to 6.4m/s and 0.45pu, respectively. The lack of generated power increases. FC/E-ESS covers the difference while the power drawn from batteries is null. The H_2 storage tank pressure decreases as the H_2 is pumped out.

(40-60): The load demand rises to 2.8pu, while the wind speed decreases to 6m/s and the solar irradiation increases to 0.5pu. The FC/E-ESS and the batteries cover the power difference working together. The storage tank pressure decreases as the H_2 is still pumped out.

(60-80): The load demand suddenly decreases to 0.5pu, while the wind speed increases to 8m/s. the solar irradiation is constant. The excess power is transferred to the batteries.

(80-100s): The load demand and the wind speed increase to 1pu and 11.5m/s, respectively, while a sudden PVG shutdown occurs. In this interval two simultaneous changes are taken into account. The WEG supports all the load demand.

The system is stable during all the five intervals, as it is confirmed by the Δf index which is always less than 0.02 . The DC bus voltage is sensitive to sudden changes in weather data and load, but it is still kept within the allowed range. Moreover, the AC voltage THD does not exceed 0.05.

CASE 3: This case deals with zero power generation from WEG and PVG systems which means $P_{net} < 0$ during all simulation test. Results of the time domain simulation is shown in Fig. 7. The simulation test can be divided into three intervals:

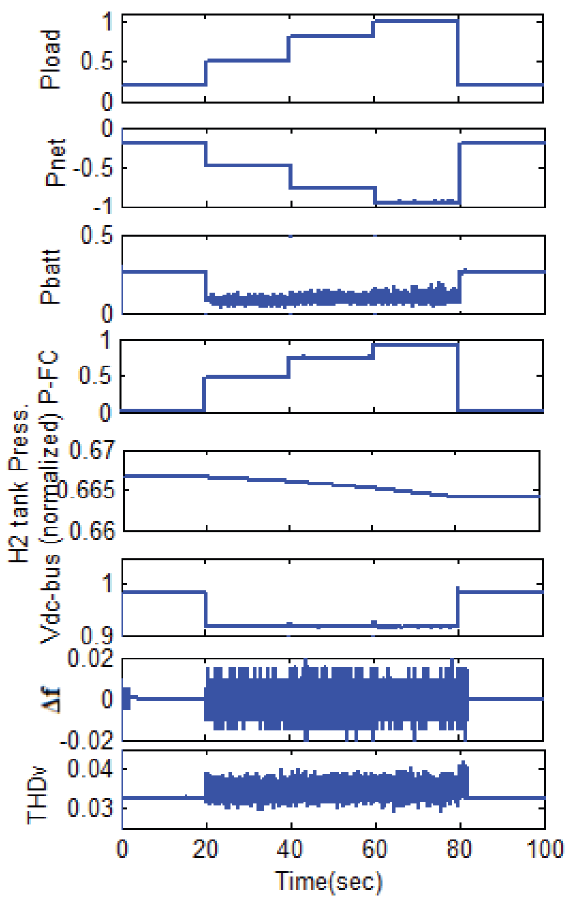

Fig. 7. Case 3 - Time domain simulation

(0-20s): The average load demand is about 0.2pu. As the power lack is small, it is compensated only by the batteries.
(20-80s): The load demand increases from 0.2pu to 1pu. According to power management strategy FC covers the lack power during those periods, while the power drawn from batteries is less than 0.1pu just to maintain the DC bus voltage in the designed range. The H_2 storage tank pressure decreases as the H_2 is pumped out.
(80-100s): The load demand decreases again to 0.2pu. As the power lack is small, it is compensated only by the batteries. The storage tank pressure keeps constant as no H_2 is pumped out or pumped in.

The system is stable during all the intervals, as it is confirmed by the Δf index which is always less than 0.02 . The DC bus voltage decreases suddenly as the FC stack covers the power lack, but it is still kept within the allowed range. Moreover, the AC voltage THD does not exceed 0.05, which is a standard requirement [5], all over the five intervals of the three cases.

B. Comparison between the FL based strategy and a conventional one based on a deterministic approach.

The performance of the developed fuzzy logic based management strategy has been compared to that obtained by an optimally tuned conventional one. The last being implemented through deterministic management rules. Besides the performance indexes used in the FL based management in section A, energy management indexes are used in this section which are : the H_2 consumption of the fuel cell stack, the amount of H_2 generated from Electrolyzer, and the battery state of charge (SOC).

The designed dynamic model is not able to deal with long time simulation that is important to show up the energy performance. In order to overcome this problem 1728 seconds is used to simulate 24 hours of hourly average load demand for two residential users in Italy as well as real weather data measured in CNR-ITAE/Messina, Italy for a typical winter day: hourly average wind speed, hourly average solar radiation and hourly average ambient temperature.

Fig. 8 shows the main benefits of the FL based management which are: a reduction of the fuel cell stack H_2 consumption, an higher amount of H_2 generated from Electrolyzer, and an higher final battery state of charge (SOC). According to Fig. 8 a great matching is obtained in THD, frequency deviation in both cases. The DC bus voltage in both cases is stable with dips and rises in some intervals but still within the accepted range.

It is worth to note that the conventional controller is optimally designed in order to perform a fair comparison with the FL controller. This is clear from the results obtained in the simulation test shown in Fig. 8, which shows great matching in power performance indexes like stability of DC bus voltage, frequency deviation, and THD.

The comparison shows the superiority of FL controller to the conventional controller in terms of H_2 consumption and generation as well as the final SOC of battery.

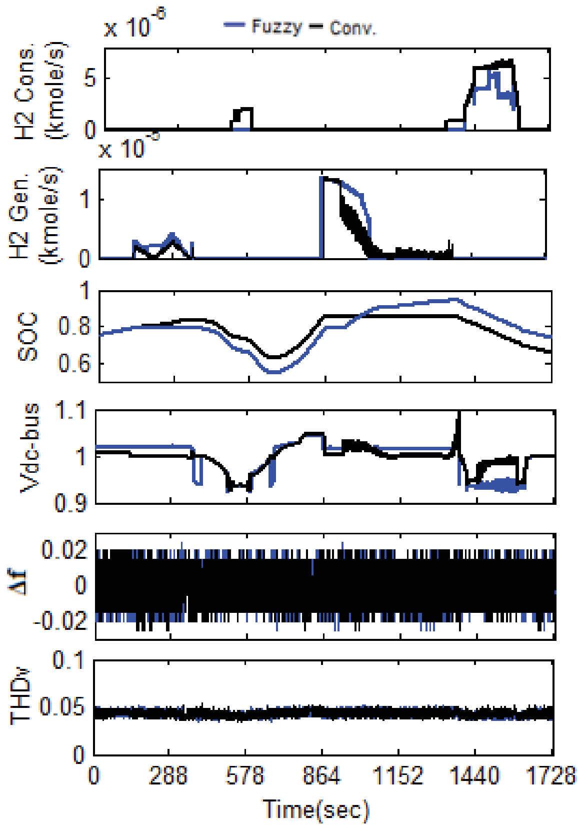

Fig. 8. Simulation results of comparison study between FL based management and conventional controller

V. CONCLUSION

This paper has proposed a FL approach to the design of a power management strategy for a standalone hybrid system encompassing a WEG, a PVG, and a FC/E-ESS.

The management approach based on fuzziness in values of excess/deficit power, DC bus voltage, battery SOC, and H_2 storage tank capacity offers more realistic and practical decisions compared with conventional management based on deterministic logical rules.

FL based management controller optimizes the energy generation and conversion in the single components (FC/E- ESS).

Time domain stability analysis has been implemented to check the consistence of the developed strategy in different operating conditions. Obtained results provide the basis for a practical realization.

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