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Simulation of a stand-alone power system using renewable energy sources and hydrogen storage

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An integrated system that comprises of a photovoltaic array and wind generators for the production of electrical power and storage of the produced energy in the form of hydrogen via water electrolysis for long term use in a PEM Fuel Cell, is currently being installed at Sunlight Systems SA. The design and analysis of the aforementioned integrated system, including the power electronics, require a detailed dynamic simulation model of the various subsystems. Multiple scenarios, which take into account the state-of-charge of the accumulator and the variable weather conditions regarding the renewable energy sources are used for the study and optimization of the system operation. Initially, each subsystem is modeled individually before integrating all the components in the simulation model. In this study, the simulated results for the energy production during a 24-h period of the renewable energy section of the unit are presented and analysed. When shortage of power occurred, the lead-acid accumulator provided the necessary power to the system. On the contrary, when surplus of energy was available, especially during midday, the lead acid accumulator was charged and potential operation of the electrolyzer was possible.

1. Introduction

Hybrid systems offer an off-grid energy supply for various applications such as electrification of remote rural areas that are not connected to the main grid, telecommunication stations and many other facilities. These hybrids systems are usually a combination of Photovoltaic Systems (PV-Systems), Wind Generators (WG's) and storage devices. The advantages of using PV-systems and wind turbines to generate electricity include the avoidance of pollutants emissions, long lifetime and low maintenance requirements [1]. Moreover, solar and wind energy is abundant, free, clean and inexhaustible. Despite the advantages, solar and wind energy are intermittent sources and for this reason it is essential to store the produced energy in another form in order to use it later. Traditionally, deep-cycle lead acid batteries have been used as the means of energy storage but recently fuel cells in combination with an electrolyser for hydrogen generation and hydrogen storage tanks have been considered for energy storage [1].

Hybrid wind/photovoltaic power generation systems have been studied extensively during the past few years. Previous studies regarding the modeling of stand alone power systems dealt with each subsystem individually. Øustein Ulleberg (1998), introduced and evaluated various models for each subsystem, except the wind generator. The results were very close to the experimental data from the implementation [2]. Kohle et al. (2003), presented a model for a PV-Array coupled with a wind generator which takes into account meteorological data and gives a daily profile of the produced energy [3]. Morever, other studies presented the experience gained through the operation of similar integrated systems and the experimental data were used in order to evaluate different automatic control strategies for their system [4,5].

In this study, the results from the simulation of a 5 kW_p PV-System coupled with three Wind Generators with maximum output power 1 kW_p each are presented. The produced energy in a period of time of 24-hours was the basis for the evaluation and estimation of the operation of the Electrolyzer, the Fuel Cell and mainly for the charge and discharge of the Lead-Acid Accumulator. The capacity extracted or added gave important information about the state-of-charge of the accumulator and the size of the storage unit due to the production of hydrogen through water electrolysis. The design and operation control of such a system is a non-linear one, due to the component characteristics and the complexity of the problem.

2. Model Description

The renewable energy system (RES) at Sunlight facilities consists of a PV array with an installed capacity of 5 kW_p and three wind generators rated at 3kW_p total. Part of the produced electrical energy is used to supply a 1kW load unit while the surplus energy is provided to a proton exchange membrane (PEM) electrolyzer which operates at 4.2 kW_p for the production of hydrogen. Hydrogen can be stored in cylinders under high pressure or metal hydrides for future use as an efficient energy source. In case there is a lack of energy due to weather conditions, a Proton Exchange Membrane Fuel Cell (PEMFC) rated at 4 kW_p is available to meet the required energy demand. Also, in order to account for short-term needs, a lead-acid accumulator with a total capacity of 3000Ah, 48V can be used. The accumulator can be charged by the renewable energy sources or the fuel cell depending on the availability of the RES. Furthermore, power electronic converters are employed for electrical power management and for the integration of the various subsystems. Figure 1 shows a schematic of the overall energy system.

3. Mathematical Model and Results

In this paper the operation of the Renewable Energy Section unit in order to calculate the produced power is analysed and discussed. The simulation was performed using Matlab Simulink® where a block diagram that comprised of the PV-System, Wind Generators and Lead Acid Accumulator was developed and studied.

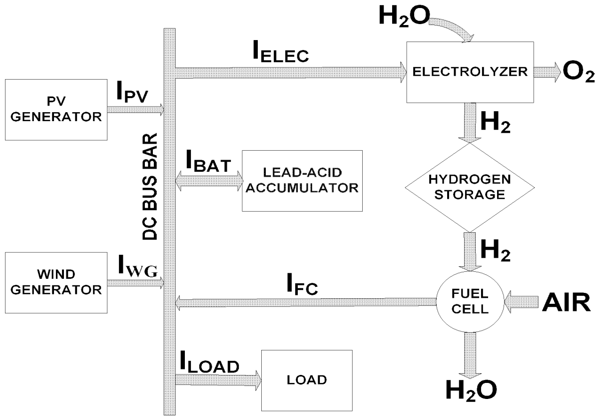

Figure 1: Block diagram of the proposed stand alone power system

The I-V characteristics in a PV-System was based on an equivalent electrical circuit that depicts the electrical phenomena during the solar absorption from the module. [3]:

$$I=I_L-I_D-I_{SH}=I_L-I_O\{\exp(\frac{U+I\cdot Rs}{a})-1\} \tag{1}$$

Where I_L, I_D, I_{SH} denote the light current, diode current and shunt current respectively in A, I_O the diode reverse saturation current in A, R_s the series resistance in Ω, α the curve fitting parameter, and V, I the operation voltage and current in V and A, respectively. The above parameters depend on the solar radiation and the cell temperature and can be easily calculated from manufacturer’s data which are provided for the PV-modules. The power from the PV-Array is described as known from (2):

$$P=V\cdot I\cdot\eta_{conv}: \tag{2}$$

Where η_{conv} is the efficiency of the DC/DC converter (~90-95%).
Respectively the equation that describes the output power for a specific value of the wind speed is given from [6]:

$$P_m=c_p(\lambda,\beta)\cdot\frac{\rho\cdot A}{2}v_{wind}^3\cdot\eta_{conv} \tag{3}$$

where P_m denotes the mechanical output of the turbine in W, c_p the performance coefficient of the turbine, ρ the air density in kg/m^3, A the turbine swept area in m^2, v_{wind} the wind speed in m/s, λ the tip speed ratio, and β the blade pitch angle in (deg), η_{conv} is the efficiency of the AC/DC converter (~90-95%).
The performance coefficient can be also estimated from manufacturer’s data about the rotor speed in relation with the wind speed [6]. The solar radiation profile and the wind

speed profile during a day are required to calculate the produced power from the RES unit. Such values for a typical day are presented in figures 2 and 3.

As it can been seen, the power production from the PV-system started during the sunrise with a peak at noon followed by a decrease until the sunset, while the power from the Wind Generators showed a wide fluctuation during the day.

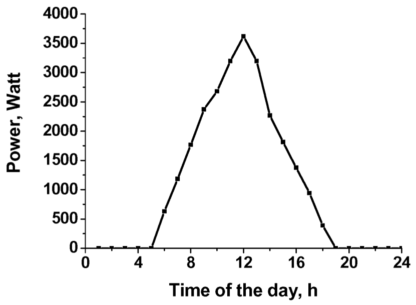

***Figure 2**: Output power from the Photovoltaic System*

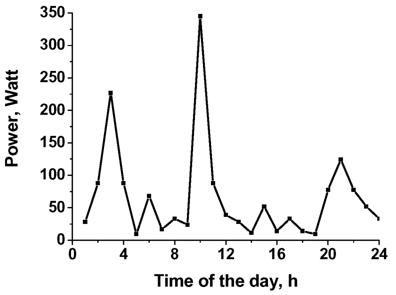

***Figure 3**: Output power from the Wind Generators*

The power gained from the RES is to be supplied to the load unit of 1kW. Figure 4 represents the current that has been calculated from the diferrence between the power from the RES and the power demand from the load. The negative values indicate that current from the accumulator has to be drawn in order to cover the need while positive values imply the excess power that can be stored to the accumulator or supplied to the electrolyzer. A very important parameter that needs to be studied in detail is the state-of charge (SOC) of the battery as it influences the operation of the accumulator. The upper SOC limit sets the upper bound that charging needs to stop and the lower SOC limit sets the lower bound that charging needs to begin. The state of charge of the battery is given by (4):

$$SOC(t)=SOC(t-1) + I_{bat}\cdot\eta_{bat}\cdot(\Delta t) \qquad (4)$$

Where η_{bat} is the efficiency factor, ~95%, I_{bat} is the charge/discharge current in A, and t is the time in hr.

Knowledge of the SOC is critical in order to optimize energy management and increase battery life. The development of acid stratification in the battery is caused due to operation at low SOC and leads among others to lower energy capacity available from the battery and high corrosion which may lead to reduced expected life [7]. Lead-acid batteries also require careful charging, because overcharging leads to water consumption, and eventually thermal destruction due to heat generation [7].

Figure 5 describes the state of charge of the accumulator based on the values of figure 4 and equation (4) for different initial values of SOC. As can be observed, an initial value of SOC=100% leads to an excess power after ten hours that cannot be supplied to the accumulator and has to be provided elsewhere. However, for an initial SOC equal to 80% or 90% such a situation can not occur during the day.

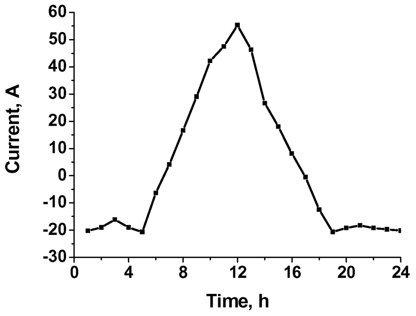

***Figure 4**: Net current after the supply of the load demand*

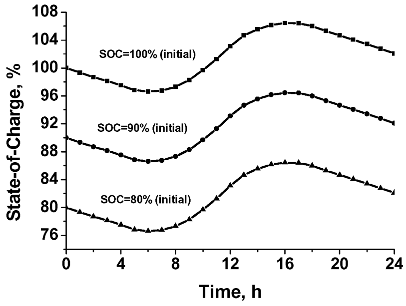

***Figure 5**: State of Charge of the accumulator during the day*

4. Results and Discussion

A dynamic simulation of the operation of a Renewable Energy System that consists of a PV array and three Wind Generators total has been developed. Part of the produced electrical energy was used to satisfy the needs of the load unit with the contribution from the accumulator when needed, while the surplus energy was used to charge the Lead-Acid Accumulator. The results revealed that a lower value of SOC around 85-87% should be taken into consideration in order to protect the accumulator from very deep discharge cycles. Further, an upper value around 92-94% is considered satisfactory because at that point the hydrogen production via electrolysis can be supported from the excess energy from the RES unit. As it can been seen in figure 4, the maximum current (or power) was detected between the hours 10.00-13.00 where there was increased solar radiation level. This deduction is very valuable because it can be used for the study and the estimation of the time period that electrolysis will take place.

By assuming that the accumulator SOC has reached the lower bound of 86%, there are approximately 210Ah that are needed for the accumulator to reach the upper bound of 93%. If it is assumed that only the fuel cell provides this power (worst case senario), then equation (5) estimates the required amount of hydrogen.

$$n_{H_2} = \frac{n_c \cdot I}{n \cdot F} \tag{5}$$

where n_{H2} denotes the hydrogen flow rate in mol s^{-1}, n_c the number of cells, n the number of moles of electron per moles of water (n = 2), and F the Faraday constant, 96485 As mol^{-1}.

For a typical fuel cell at 4kW the total amount of consumed hydrogen is given in table 1. Respectively for the 4.2kW electrolyzer, the hydrogen produced is also given from equation 5. The Faraday's efficiency was also taken into consideration at both procedures. As it can been seen in table 1, if the fuel cell alone would work to bring the SOC of the accumulator from the minimum to the maximum limit, then the hydrogen consumption would be greater than the produced amount from electrolysis, which would have taken place until SOC would reach the lower bound. Therefore a careful design of the storage unit should be taken into account to ensure the autonomy that the Fuel Cell requires.

Table 1: *Hydrogen production and consuption at the hydrogen unit*

	Total time of operation, h	**Hydrogen (lt)**
Electrolyzer	1.8	1550
Fuel Cell	2.1	3468

5. Conclusions & Future Work

A simulation model for an energy system based on RES with intermediate hydrogen storage has been developed. A number of dynamic scenarios have been investigated for typical wind and solar radiation profiles. Decision on the hydrogen production depends on the SOC of the battery. The model will form the basis for the design of the control system for the integrated system.

6. Acknowledgements

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