Matlab/Simulink Simulation of Solar Energy Storage System

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Abstract**—**This paper investigates the energy storage technologies that can potentially enhance the use of solar energy. Water electrolysis systems are seen as the principal means of producing a large amount of hydrogen in the future. Starting from the analysis of the models of the system components, a complete simulation model was realized in the Matlab-Simulink environment. Results of the numerical simulations are provided. The operation of electrolysis and photovoltaic array combination is verified at various insulation levels. It is pointed out that solar cell arrays and electrolysers are producing the expected results with solar energy inputs that are continuously varying.

Keywords**—**Electrolyzer, Simulink, solar energy, storage system.

I. INTRODUCTION

THE sun as the originator of all living creatures needed many millions of years to create the fossil energy materials, but mankind has almost totally used up all this materials within a period of less than two hundred years. Now, the human intelligence has progressed to be capable of utilizing the sun energy directly. The reached sun energy to our global are exceed the world Energy consumption for approximately 6000 fold [2]. According to scientific studies the total of all oil resources of the world will be exhausted within 40 to 50 years [3]. Also the nuclear energy will not cover the world demand of the future in addition to the problems of its waste disposal hazards. The biggest energy source represents the sun which mainly emits its energy by electromagnetic waves onto the earth. Its solar constant amounts 1353W/m^2 [4], [5]. The solar constants indicate the performance which reaches a surface of one-square meter, situated externally of the earth atmosphere, which shows vertical to the emission direction. Every day the sun radiates, or sends out an enormous amount of energy. As matter of fact the sun radiates more energy in one second than all the human have used since the beginning of time [1]-[5]. To convert sun energy into electrical energy solar cells have proved to be excellent. Their factor of expenses has considerable decreased through the mass production. Most economical are those cells which possess an efficiency of approximately 25%. Conversion of solar energy to chemical free energy in the form of molecular hydrogen and oxygen is attractive because the products are stable, versatile, and nonpolluting. Hydrogen gas is so much lighter than air that it rises fast and is quickly ejected from the atmosphere. This is why hydrogen as a gas (H_2) is not found by itself on Earth. It is found only in compound form with other elements. Hydrogen combined with oxygen, is water (H_2O). Hydrogen combined with carbon forms different compounds, including methane (CH_4), coal, and petroleum. Hydrogen is also found in all growing things for example, biomass. It is also an abundant element in the Earth's crust. Hydrogen has the highest energy content of any common fuel by weight (about three times more than gasoline), but the lowest energy content by volume (about four times less than gasoline) [6]. It is one of the most promising alternative fuels for the future because it has the capability of storing energy of high quality and it is in accordance with a sustainable development. Hydrogen has therefore been visualized to become the cornerstone of future energy systems based on solar energy and other renewable energy sources [7]. The concept of using hydrogen as an energy carrier in storage and transport of energy, i.e., the so-called hydrogen economy, has therefore been studies by many scientists. It is also this author's belief strongly that particular attention should be paid to hydrogen energy based systems. Hydrogen can be produced chemically from hydrocarbons (e.g., renewable fuels such as methane, ethanol, or methanol), but this will not be considered in this paper. A more attractive option is to produce hydrogen from water via water electrolysis, simply because of the abundance of water on earth. The basic chemical reaction for splitting water in hydrogen and oxygen is

$$H_2 + energy \xrightarrow{yields} H_2 + \frac{1}{2}O_2 \tag{1}$$

For this reaction to occur, an amount of energy must be added, while the opposite reaction releases energy. The oxygen in water electrolysis in last equation is usually release to the atmosphere, but may be stored in an artificial structure as well. Thus, in theory, if hydrogen is produced from natural energy resources the hydrogen cycle is 100% environmentally benign energy cycle, because solar energy for all practical purposes can be regarded as an infinite source of energy, the hydrogen cycle is one of the best options for a sustainable future. Since water is one of the most abundant resources on earth, covering three fourths of the earth's surface. Hence water electrolysis systems are seen as the principal means of producing a large amount of hydrogen in the future.

II. SOLAR ENERGY STORAGE SYSTEM

Since electrical energy is capable of performing chemical work, it is possible to split the molecules of normal water into

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the two gases namely Hydrogen and Oxygen. Hydrogen can be produced from solar energy and water by water electrolysis. Although the photo electrochemical (PEC) methods for direct water splitting are being developed, the technically most viable path is by coupling a PV photovoltaic module or array to an electrolyze [8], [9]. Most of the industrial electrolyzes used today in capacities up to several thousand m^3/hr are used on alkaline [koh] electrolyte. Electrolyzes using a polymer, proton-conducting membrane (PEM) as the electrolyte, are being developed, particularly for small-scale hydrogen generation [9]. In PV powered hydrogen generation systems performance is limited by the efficiency of PV's conversion of solar energy to electrical energy, which in commercial devices is about 15%. Conversion efficiencies of newly developed multi-junction PV cells reached up to 42% [8]. One of the important issues in photovoltaic/electrolysis (PV/EL) hydrogen generation systems is maximum power transfer problem between two devices at different irradiance conditions. A typical PV system, maximum power points MPP change with irradiance and temperature. Usually, in directly connected systems, there is a mismatch between input PEM electrolysis I-V characteristic and output PV's MMP characteristic. To overcome this problem, PV/EL systems are usually supported with additional MPP tracker power electronic control device. To operate at the MPP, the MMP tracker device sets optimum impedance harmony between PV and EL system in response to irradiance variations. However, this causes additional cost and complexity of a number of smaller units-cells, which can be connected in series and/or in parallel. With appropriate sizing optimization approaches of both PV and EL it is possible to directly connect these two systems. In this paper, a more effective, optimum sizing strategy of both devices is proposed for MPP natural tracking at a wide irradiance interval in directly connected PV/EL hydrogen generation systems. By this way we achieve a stored solar energy which is even transportable Fig. 1 shows the proposed system. The main components of the system include a PV-generator, an electrolyzer, and a hydrogen storage (compressed gas).

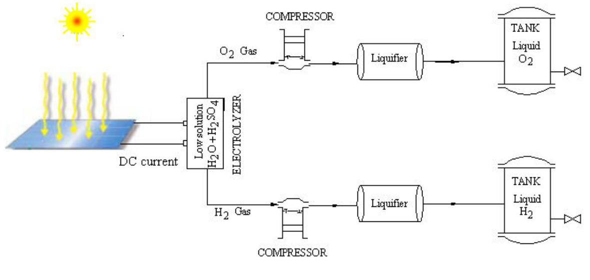

Fig. 1 Schematic of solar-energy storage system

This type of energy storage provides significant advantages when compared to conventional batteries in terms of energy density and long-term storage. By using an electrolyzer, hydrogen conversion allows both storage and transportation of large amounts of power at much higher energy densities. Thus, hydrogen generation can lead a pathway for solar-based energy generation to contribute directly to reducing the dependence on fossil fuel.

III. HYDROGEN ECONOMY

Hydrogen is ecologically beneficial. Its combustion doesn't release carbon dioxides and sulfur dioxides are also not created. The only by-product is simple vapor. As well there is no radioactivity produced. Hydrogen is absolutely nonpoisonous. One kilogram of hydrogen releases at its combustion 33kW/h electrical energy. This is the threefold of energy of benzene. In principle, then one can an envision an energy economy in which hydrogen is produced from water and electrical energy, is stored until it is needed, is transmitted to its point of use and there is burned as a fuel to produce electricity, heat or mechanical energy.

Hydrogen can be transmitted and distributed by pipeline in much the same way that natural gas is handled today. The movement of fuel by pipeline is one of the cheapest methods of energy transmission; hydrogen pipeline would be no exception. A gas-delivery system is usually located underground and is therefore inconspicuous. It also occupies less land area than an electric-power line. Hydrogen can also be stored in a huge quantities by the very same techniques used for natural gas today.

IV. SIMULINK MODELING SOLAR ENERGY STORAGE SYSTEM

Each physical component of the proposed system is modeled as a separate component subroutine and Simulink block for a modular system simulation program. All of the developed models are based on physical and chemical principles, as well as empirical parameters. The models have been designed to be as general as possible and all the blocks take both design parameters, (such as number of cells in series and/or parallel) and specific component characteristics obtained from manufacturers (such us current-voltage curve) into account. Simulink offers the advantage of buildings hierarchical models, namely to have the possibility to view the system at different levels. Thus each block can contain other blocks, other levels.

A. Modeling of PV Panel

The mathematical model of the photovoltaic (PV) generator is based on the one-diode equivalent circuit [9] as shown in Fig. 3.

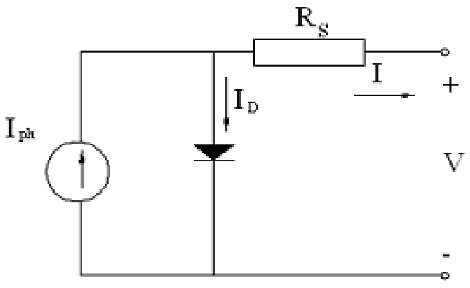

Fig. 2 Model for a single solar cell

The relationship between the current I and the voltage V of the equivalent circuit can be found by equating the light current I_{ph}, diode current I_D, to the operation current I as follows:

$$I = I_{ph} - I_D = I_{ph} - I_{sat}\left[e^{\frac{q(V+IR_S)}{nkT}} - 1\right] \quad (2)$$

where I_{ph} the light current [A], I_{sat} the diode reverse saturation current [A], R_s, the series resistance [Ω], V the operation voltage [V], and I the operation current [A].

q = charge of one electron$(1.602 \times 10^{-19} C)$,
n = Diode idealising factor, and
k = Boltzman's constant $(1.38 \times 10^{-23}\ J/K)$.
T = Junction temperature in Kelvin.

When the PV module operates at its maximum power point, the produced power is given by,

$$P_{max} = V_{max} \times I_{max} = \gamma \times V_{o.c} \times I_{s.c} \quad (3)$$

where V_{max} *and* I_{max} are terminal voltage and output current of PV module at maximum, power point (MPP), and γ is the cell fill factor which is a measure of cell quality.

The energy output in the form of current is directly proportional to the energy input in the form of solar irradiation. There is a small temperature coefficient, $\alpha_{I_{scT}}$ on the order of a few milliamps per degree Celsius to account for temperature differences recognized empirically.

$$I_{ph}(G,T) = I_{scs} \times \frac{G_a}{G_{as}} + \propto_{scT} (T - T_s) \quad (4)$$

where:
I_{scs} = Short circuit current at standard test condition,
G_a = Solar irradiance (W/m^3)
G_{as} = Solar irradiance at standard test condition (1000W/m^3),
$\propto_{scT}$ =Temperature coefficient of short-circuit current.
T = Cell temperature (^{o}C)
T_s = Cell temperature at standard test conditions (25 ^{o}C)

The open circuit voltage under given environmental conditions is calculated as follows:

$$V_{oc}(G,T) = V_{ocs} + \beta_{o.c.T}(T - T_s) + \frac{kT}{q} \ln\left(\frac{I_{mpp}}{I_{scs}}\right) \quad (5)$$

V_{ocs} = Open-circuit voltage at standard test condition.
$\beta_{o.c.T}$ = Temperature coefficient of open-circuit voltage,
I_{mpp} = Current at MPP

Under open circuit condition; $I_{ph}(G,T) = I_D(G,T)$

But $I_D(G,T) = I_{sat}(G,T) \times \left[e^{\frac{V_{o.c}}{V_t}} - 1\right]$, Therefore

$$I_{sat}(G,T) = \frac{I_{ph}(G,T)}{\left[e^{\left(\frac{V_{o.c}(T)}{V_t(T)}\right)} - 1\right]} \quad (6)$$

$$V_t(T) = \frac{AkT}{q} \quad \text{Thermal voltage} \quad (7)$$

The previous equations have been translated into the Simulink diagram shown in Fig. 3 and the masked model shown in Fig. 4

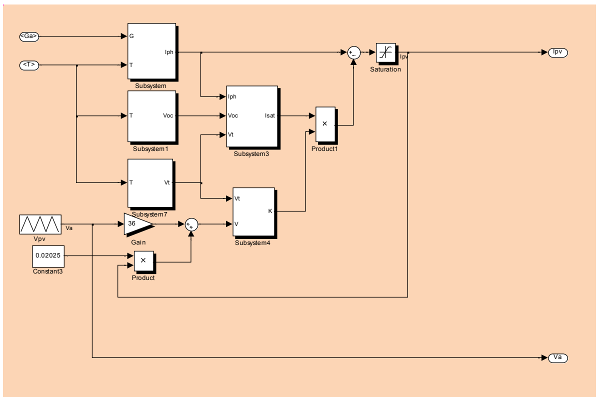

Fig. 3 Subsystem implementation of generalized PV model

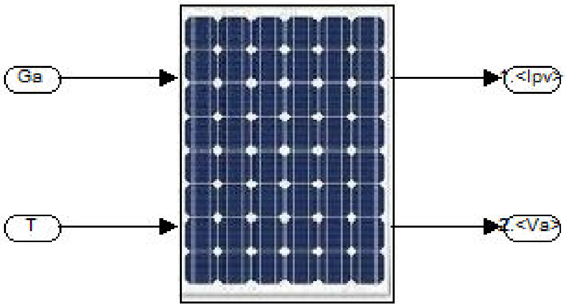

Fig. 4 Masked implementation of generalized PV model

The Simulink implementation of the PV module, illustrated in Fig. 2, is used to perform a simulation of the PV module for different values of irradiation and cell temperature.

B. Electrolyzer Model

An electrolyzer is a well known electrochemical device utilizing electrical current to decompose water into hydrogen and oxygen. It consists of several electrolyzer cells connected in series. The current in comparison to voltage feature of an electrolyzer depends on its working temperature [10] according to Faraday's law, the production rate of hydrogen in an electrolyzer cell is directly proportional to the transfer rate of electrons at the electrodes, which in turn is equivalent to the electrical current in the circuit expressed in the following equation,

$$n_{H_2} = \frac{\eta_F . n_n . i_e}{2F} \quad (8)$$

η_{H_2} = Hydrogen production rate, mol s^{-1},
η_F = Faraday's efficiency,
n_c = the number of electrolyzer cells in series
i_e = electrolyzer current [A]

F = Faraday constant [C kmol−1]

The ratio between the actual and the theoretical maximum amount of hydrogen produced in the electrolyzer is known as Faraday efficiency. Assuming that the working temperature of the electrolyzer is 40 °C, Faraday efficiency is expressed by:

$$\eta_F = 96.5 \times \left[e^{\frac{0.09}{i_e} - \frac{75.5}{i_e^2}} \right] \tag{9}$$

According to (8) and (9), a simple electrolyzer model is developed using Simulink, which is shown in Fig. 5.

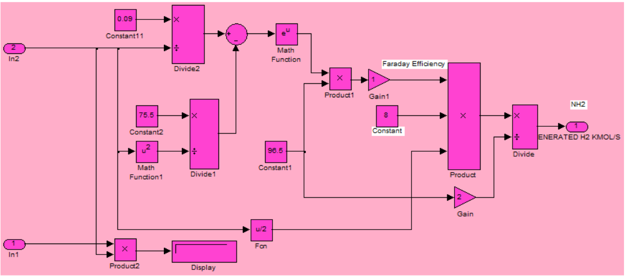

Fig. 5 The Simulink diagram of the electrolyzer model

C. *Hydrogen Storage Model*

One of the hydrogen storage techniques is physical hydrogen storage, which include using tanks to store either compressed hydrogen gas or liquid hydrogen. The produced hydrogen storage is stored in the tank whose system dynamics can be expressed as follows:

$$P_b - P_{bi} = z \times \frac{N_{H_2} R T_b}{M_{H_2} V_b} \tag{10}$$

P_b = Pressure of tank (pascal)
P_{bi} = Initial pressure of the storage tank(pascal)
R = universal (rydberg) gas constant(J/kmol K)
T_b = Operating temperature (K)
V_b = Volume of the tank (m^3)
Z = Compressibility factor as a function of the pressure,
$Z = \frac{PV_m}{RT}$, $P = pressure$, $V_m = molar\ volume,$
$T = temperature$

This model directly calculates the tank pressure using the ratio of hydrogen flow to the tank.

All auxiliary power requirements such as pumps, valves, fan and compression motor were ignored in the dynamic model, the simulink model of the hydrogen storage is depicted in Fig. 6.

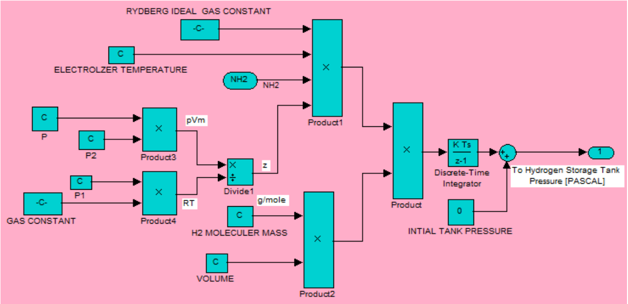

Fig. 6 The Simulink model of the hydrogen storage system

V. Simulation Results and Discussion

The previously described models were assembled to present the system depicted in Fig. 7.

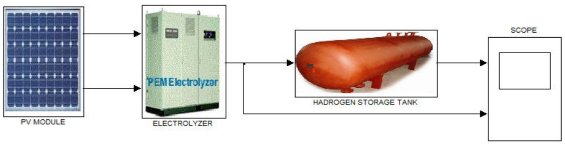

Fig. 7 Solar-Energy Storage System

Some of the key model inputs are listed in the Table I.

TABLE I
System Components Parameters

PV arry	
Power rating	1 kW
Short circuit current, I_{sc}	5.0 A
Open circuit voltage, V_{oc}	22.1 V
Coefficient of current, α_{scT}	(0.065±0.015)% mA/°C
Coefficient of voltage, β_{ocT}	(80±10) mV/°C
Temperature coefficient of power	(0.5±0.05)%/°C
Electrolyzer	
Rated power	500W
Maximum operating power level	500W
Minimum operating power level	125W
Hydrogen storage tank	
Volume	$3m^3$
Initial state of charge (soc)	50%
Minimum limit of soc (H_2 SOC $_{MAX}$)	30%
Maximum limit of soc (H_2 SOC $_{MAX}$)	95%

The models described in the previous section have been implemented in the Matlab-Simulink environment. These models have been verified, Figs. 8 and 9 show both the current-voltage curve and the power curve obtained from the simulation of PV module respectively

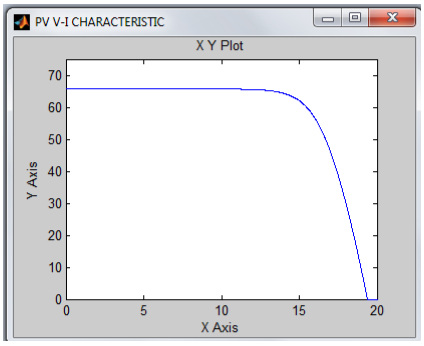

Fig. 8 Current voltage characteristic for PV

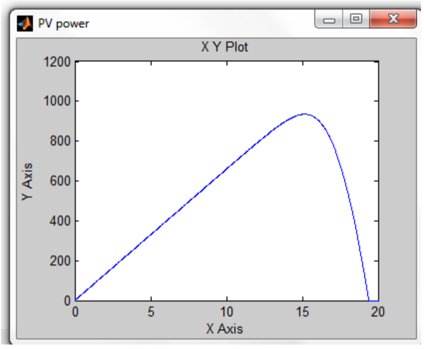

Fig. 9 Power characteristic for PV

Figs. 10 and 11 show the results of the simulation of solar-energy storage system.

Fig. 10 Hydrogen moles per second delivered to storage tank

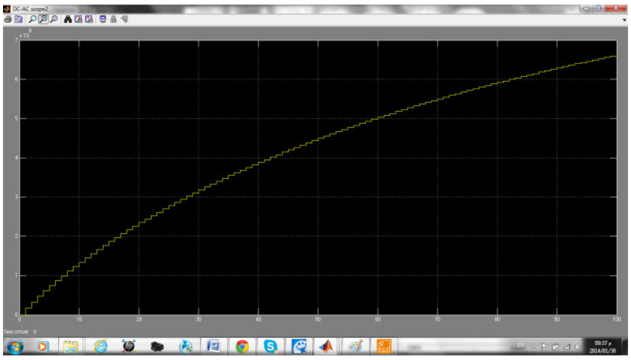

Fig. 11 Hydrogen storage tank pressure

The results from the simulation showed that all of the key component models were sufficiently accurate to perform short and long-term system simulation studies. The output of the hydrogen storage tank is constantly increasing due to the continuous supply of DC voltage to the electrolyzer.

VI. CONCLUSIONS

In this paper, the components of solar energy storage system modeled and tested using solar radiation and temperature as primary input and hydrogen as seasonal energy storage. The components were modeled in the Simpower Systems block of MATLAB Simulink. Renewable energy sources are highly dependent on environmental conditions such as season's weather. This storage energy system exhibits excellent performance under variable different radiant and temperature changes. We conclude that energy storage systems have the potential to improve the attractiveness of solar energy in Libya both technically and economically, especially in the future with greater development of solar power resources. Energy storage can help to mitigate technical issues associated with solar, wind and other intermittent generator integration with utility grids. More importantly, energy storage can mitigate the intermittent nature of renewable energy, its significant unpredictability, and its off-peak availability, making solar power better able to integrate with electricity markets and match typical electricity demand profiles.

REFERENCES

[1] The NEED Project P.O. Box 10101, Manassas, VA 20108 1.800.875.5029 www.NEED.org
[2] GCEP Solar Energy Technology Assessment - Summer 2006.
[3] K. Weissermel, H. J. Arpe, Industrial Organic Chemistry, fourth ed., Wiley, Germany, 2003.
[4] K. M. Hossain, D. N. Ghosh, K. Ghosh and A. K. Bhattacharya" Power Spectrum Analysis in Search for Periodicities in Solar Irradiance Time Series Data From Erbs"
[5] http://www.solarviews.com/eng/sun.htm
[6] Huashan Lia, Yongwang Liana, Xianlong Wang a, Weibin Maa, Liang Zhao" Solar Constant Values for Estimating Solar Radiation", Energy (2011), doi:10.1016/j.energy.2010.12.050
[7] Bryan K. Boggs, Gerardine G. Botte" On-Board Hydrogen Storage and Production: An Application of Ammonia Electrolysis" Journal of Power Sources 192 (2009) 573–581
[8] Cédric Philibert "The Present and Future Use of Solar Thermal Energy as a Primary Source of Energy" International Energy Agency, Paris, France, 2005.
[9] Mustafa. A. Al-refai "Matlab/Simulink Model for Simulation of Photovoltaic Module" First Conference and Exhibition on Renewable Energies and Water Desalination Technologies Tripoli Libya, March 11-13, 2008.
[10] Sagol BE, Seidel U,Szabo N, Schwaarzburg K, Hannappel T. Basic concepts and interfacial aspects of high-efficiency III-V multijunction solar cells. CHIMA Int J for Chemistry 2007;61:775-9.