www.dergipark.gov.tr
ISSN:2148-3736
El-Cezerî Fen ve Mühendislik Dergisi
Cilt: 6, No: 3, 2019 (558-570)

El-Cezerî Journal of Science and Engineering
Vol: 6, No: 3, 2019 (558-570)

DOI: 10.31202/ecjse.558383

ECJSE

Research Paper

An Efficient Solar-Hydrogen DC-DC Buck Converter System with Sliding Mode Control

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Received/Geliş: 26.04.2019 **Accepted/Kabul:** 17.07.2019

Abstract : This paper focuses on two different scenarios to benefit from solar energy more efficiently. One of them is photovoltaic houses and storing their energy as hydrogen, the other one is photovoltaic cars and storing their energy as hydrogen. The common point in these two photovoltaic sourced scenarios is convert and storage of the hydrogen energy more efficiently. The direct current (DC) photovoltaic energy is converted to the desired voltage level using the DC-DC buck converter for generating hydrogen with electrolysis process. The electrolysis load for hydrogen production needs low voltage and high currents especially. To supply these conditions the converter must be designed and controlled sensitively. For this aim, the sliding mode controller is proposed as a solution in this study. This controller is used the inductance current in the inner loop and supply a strong control for the converter under normal and abnormal conditions. The photovoltaic powered DC-DC buck converter for electrolysis load was simulated in MATLAB/ Simulink software more detailed using the sliding mode controller.

Index-Terms: Hydrogen energy, Hydrogen generation, Electrolysis, Photovoltaic sources, Buck converter, Sliding mode control

Kayan Kip Denetimli Verimli Bir Güneş-Hidrojen DA-DA Azaltan Çevirici Sistemi

Öz: Bu makale güneş enerjisinden daha verimli yararlanmak için iki farklı senaryo üzerine odaklanmaktadır. Bunlardan biri fotovoltaik evler ve enerjilerini hidrojen olarak depolamak, diğeri fotovoltaik otomobiller ve enerjilerini hidrojen olarak depolamaktır. Fotovoltaik kaynaklı bu iki senaryodaki ortak nokta, hidrojen enerjisinin daha verimli bir şekilde dönüştürülmesi ve depolanmasıdır. Doğru akım (DA) fotovoltaik enerjisi, elektroliz işlemiyle hidrojen üretmek için DA-DA dönüştürücü kullanılarak istenen voltaj seviyesine dönüştürülür. Hidrojen üretimi için elektroliz yükü, özellikle düşük voltaj ve yüksek akımlara ihtiyaç duyar. Bu şartları sağlamak için dönüştürücü hassas bir şekilde tasarlanmalı ve kontrol edilmelidir. Bu amaçla, kayan mod kontrolörü bu çalışmada bir çözüm olarak önerilmiştir. Bu kontrol cihazı iç döngüdeki endüktans akımını kullanır ve normal ve anormal koşullar altında dönüştürücü için güçlü bir kontrol sağlar. Elektroliz yükü için fotovoltaik kaynaklı DC-DC konvertör, MATLAB / Simulink yazılımında kayan kip modu kontrolörü kullanılarak daha ayrıntılı olarak simüle edilmiştir.

Anahtar kelimeler: Hidrojen enerjisi, Hidrojen üretimi, Elektroliz, Fotovoltaik kaynaklar, Azaltan çevirici, Kayan kip kontrolü

Bu makaleye atıf yapmak için
Sahin , M. E., "An Efficient Solar-Hydrogen DC-DC Buck Converter System with Sliding Mode Control" El-Cezerî Fen ve Mühendislik Dergisi, 2019, 6(3); 558-570.

How to cite this article
Sahin , M. E., "An Efficient Solar-Hydrogen DC-DC Buck Converter System with Sliding Mode Control" El-Cezerî Journal of Science and Engineering, 2019, 6(3); 558-570.

1. Introduction

Most of the fossil fuels used today are limited sources that have been started to be used in factories with the industrial revolution and are assumed to be run out within the next century. When fossil fuels are thought to have a life span between two and three hundred years, it is necessary to find new sources in order to sustain human life comfortable. Some of the sustainable energy sources are developed and implemented such as nuclear, geothermal, biomass and some renewable energy which have some detrimental effects on nature in the last century. On the other hand, the sun continues to heat our earth as an endless energy source. So why cannot we benefit from the sun more effectively? The main answer to this question is climate differences around the world, the difficulty of the storage of energy, and too high unit costs.

The main problem of renewable and other innovative energy sources is the storage of energy for sustainability. Although these sources are repeatable, these are not continuous. Storage of the energy in batteries is the common method, but expensive and restricted. Therefore, storage of the energy as hydrogen is proposed by the scientists for future generations as a new solution. Hydrogen energy is proposed by the scientists not only as a fuel but also a good energy transporter harmless on nature for the 21st century. However, the integration of hydrogen energy to the grid and the necessary technology investments complicated this transformation [1, 2].

On the other hand, the solar energy, which is our endless power source from the birth of the universe to today, is continuing to heat and illuminate our world. Solar collectors and solar cells are the main two parts of the absorption of solar energy [3]. With today's technology, this energy can absorb only 20-25% efficiently with different solar cells [4]. The solar radiation changes with time do not continue and are not stable every time [5]. These drawbacks make the use of storage systems compulsory. The conventional storage systems are inadequate and inefficient for the storage of so large energy [26, 31, 33]. This makes attractive the conversion of energy to hydrogen form with related conversion systems [2, 6, 27].

Depending on rapid technological developments in energy conversion, DC-DC converters are getting important for the application of power electronics. In recent years one of the suggested solutions is to obtain hydrogen gas from water electrolysis and storage of this gas by compression [7, 8]. The electrolysis of the water needs approximately 2 V DC voltage for hydrogen production [9]. However, the photovoltaic systems are designed for high voltages for common bus voltages 12 V or 24 V for battery charge especially [10]. Therefore, it is necessary to use a DC-DC buck converter to decrease the voltage and increase the current to desired values. Some different studies are proposed and tried in literature, but they are not tried for photovoltaic sources and electrolysis loads. Moreover, a robust and efficient controller for nonlinear electrolysis loads is not recommended in these studies [11-12].

The sliding mode controller is derived from the variable structure controllers, which are used to control the nonlinear switching power supplies. This control method has some advantages for high load changes and strong error control, effective dynamic response and easy application [13, 14]. The low voltage and high currents of DC-DC buck converter make necessary this controller to reduce the power losses and increase the stability of the dynamic system [15, 16].

This study focuses on two different scenarios. While one of them is photovoltaic houses and storage of their energy as hydrogen, the other one is photovoltaic cars and storage of their energy as hydrogen. For two photovoltaic sourced scenarios, photovoltaic energy is converted to the desired voltage level using the DC-DC buck converter for generating hydrogen with electrolysis process. The electrolysis load for hydrogen production needs low voltage and high currents especially and controlled sensitive. For this aim, the sliding mode controller is proposed as a solution in this study.

The photovoltaic powered DC-DC buck converter for electrolysis load was simulated in MATLAB/ Simulink software more detailed using the sliding mode controller for normal and short-open circuit condtions.

2. Two Main Scenarios And Proposed Converter System

Towards the hydrogen fuel and hydrogen economy in the future, some different scenarios are proposed by the scientists [2, 17-19, 28, 29, 34]. This paper focuses on two different scenarios to benefit from solar energy more efficiently. One of them is photovoltaic houses and storage of their energy as hydrogen. The other one is photovoltaic cars and storage of their energy as hydrogen. The common point in these two photovoltaic sourced scenarios is convert and storage of the hydrogen energy more efficiently. The composition of these two main scenarios is given in Figure 1.

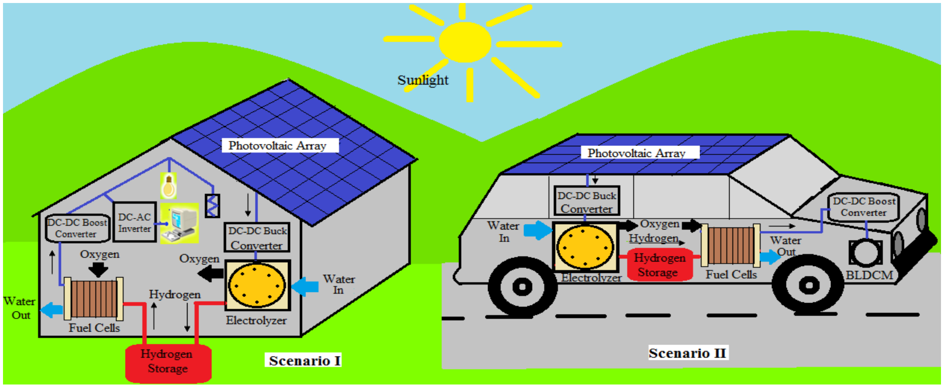


Figure 1. The composition of two main scenarios

For the first scenario at homes, we need a way to store solar energy for times when the sun is not shining. Hydrogen provides a safe, efficient, clean way to do this [20]. The solar energy is absorbed by photovoltaic arrays and converted to suitable voltages by the buck converter for the electrolysis process at homes. The electrolysis process needs only water and converts it to hydrogen and oxygen gases. The hydrogen gas is stored in hydrogen tanks especially in the underground for security and efficiency. This gas is burned directly or converted to electrical energy by fuel cells again.

The second scenario for vehicles is similar to the first scenario. The solar energy is absorbed by photovoltaic arrays and converted to suitable voltages by the buck converter for electrolyzes bus. The electrolysis process needs only water and converts it to hydrogen and oxygen gases. The hydrogen gas is stored in hydrogen tanks for cars appropriately. This gas is burned directly or converted to electrical energy by fuel cells again for cars similarly. The Toyota Corporation succeeded to produce such a car which is called ‘hydrogen car’, but it used batteries instead of photovoltaic for energy sources [21, 30]. Moreover, it is very expensive and does not work efficiently.

The common point in these two scenarios is how the energy will be converted more efficiently from solar energy to hydrogen energy. A buck type DC-DC converter is proposed as a solution for this problem in this paper. The DC-DC buck converter is designed for a 100 W commercial photovoltaic power input. These commercial photovoltaic panels generate 0-25 V output voltages for different loads and currents generally [22]. On the other hand, it is necessary to decrease the voltage level to the range of 1.23 V- 2.06 V which is needed for electrolysis [9]. For this reason, a buck type DC-DC converter is required.

The buck type DC-DC converter has to decrease the voltage level by about 2 V and increase the current level at the same ratio. The increasing current flow increased hydrogen production at the same time. For this reason, a robust controller is necessary under constant voltage and current with small fluctuations for nonlinear electrolysis load. The sliding mode controller is proposed in this study as a controller to control output electrolysis load voltage and buck converters inductance current. The sliding mode controller is applied to the measured current and voltage signals and generates a pulse width modulation (PWM) signal to switch metal oxide semi-conductor field effect transistor (MOSFET) devices. The general view of the proposed photovoltaic-electrolysis system with converter and controller is shown in Figure 2.

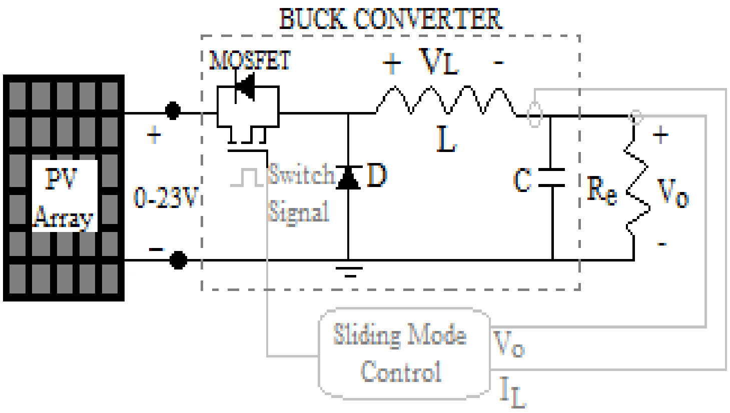


Figure 2. The proposed photovoltaic-electrolysis system general structure

3. The Proposed Photovoltaic-Electrolysis System Components

The proposed photovoltaic-electrolysis system and its model including main components are investigated in this chapter. These components are a photovoltaic array as a source, DC-DC buck converter, sliding mode controller and electrolysis load. These four components are defined, designed and investigated separately below.

3.1. Photovoltaic Array Model

The photovoltaic arrays cannot be thought as infinite or linear sources in the application. They act as finite and nonlinear sources as shown in their current-voltage (I-V) and power voltage (P-V) curves. For the proposed system, the 100 W power source is necessary and the necessary photovoltaic panel is selected from the manufacturer catalogs [22]. These photovoltaic panel characteristic values are given in Table 1.

Table 1. Electrical Characteristics of Photovoltaic Panels [22]

Specifications	Values
Maximum power (P_m)	100 W
Maximum power voltage (V_{pm})	18.6 V
Maximum power current (I_{pm})	5.38A
Short circuit current (I_{sc})	(I_{sc}) 5.76 A
Open circuit voltage (V_{oc})	22.8 V
PV Module efficiency	14.8%
Tolerance	±5%
Nominal voltage	12 V
Temperature coefficient of V_{oc}	-0.36%/K
Temperature coefficient of P_m	-0.46%/K
Temperature coefficient of I_{sc}	0.05%/K
Nom. opera. cell temperature	48 °C±2 °C
Maximum series fuse rating	12 A
Maximum system voltage	600 V

The photovoltaic array equation which is derived from the basic Shockley diode equation for all parameters is given in Equation 1 which was derived in previous studies. [4]. In addition, the solar cell current depends on cellular operating temperature (T) and the absorption of sunlight (G). The photovoltaic cells are connected in series and parallel to increase the voltage and current of the photovoltaic module. Using this equation photovoltaic module is designed in MATLAB/Simulink and adjusted for suitable parameter values as shown in Figure 3. The simulations are given in results.

$$V_{PV} = \frac{N_S.n.k.T}{q}\ln\left[\frac{(I_{SC}+K_I(T-T_{ref})).G+I_0-I_{PV}+N_P}{I_0.N_P}\right]-\frac{N_S}{N_P}R_s.I_{PV} \tag{1}$$

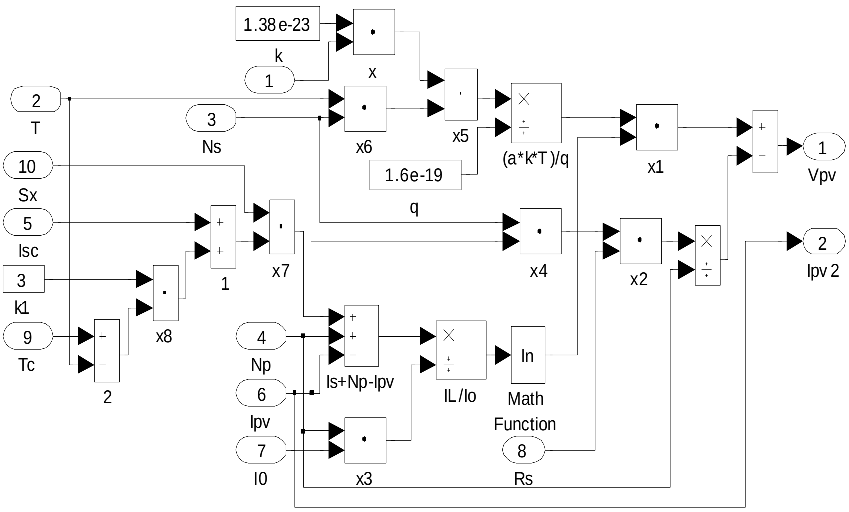


Figure 3. MATLAB/ Simulink functional model for photovoltaic panel

3.2. DC-DC Buck Converter

The main part of the proposed photovoltaic-electrolysis system is a DC-DC buck converter to reduce the generated voltage by a photovoltaic panel. This converter reduces the 18.6 V photovoltaic voltage to the range of 1.23 V- 2.06 V which is necessary for electrolysis. While the voltage value is decreased, the current value is increased in the same ratio depending on energy conservation law. These high currents naturally cause some loses on the components. Some solutions are proposed to reduce loses in different papers, therefore we will not focus on this matter in this paper [10, 12]. Only a selection of elements with low losses will be sufficient.

A 100 W DC-DC buck converter is designed to obtain a 2 V output voltage from 20 V DC input voltage. For the converter, circuit capacitor and inductor values were calculated for 100 kHz switching frequency and 5% ripple at output voltage as below Equations. The DC-DC buck converter is designed for electrolyzes load.

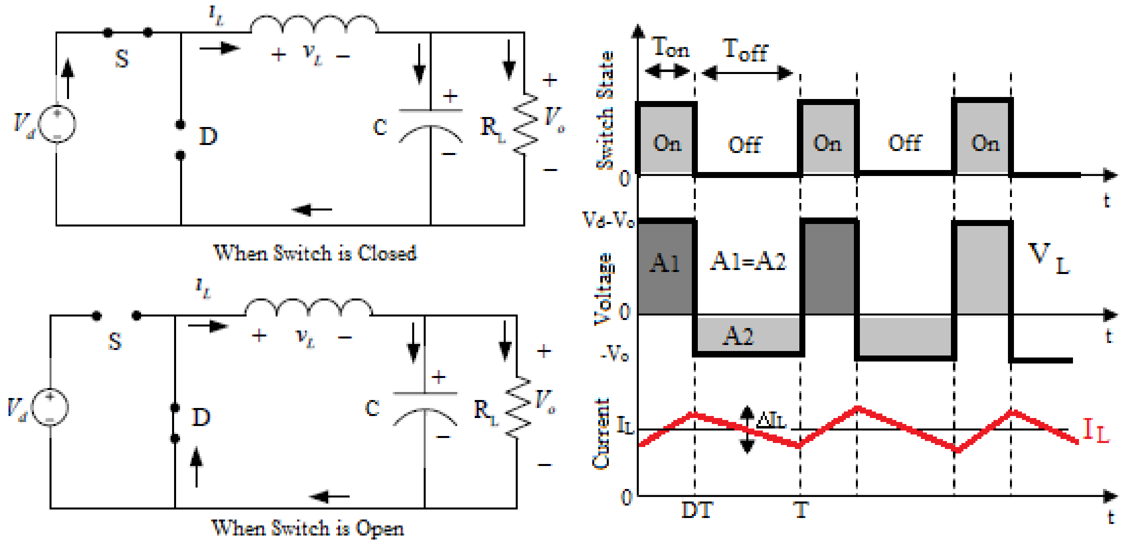
Inductance maximum ripple value and duty ratio are used to calculate inductance critical value as in Equation 2;

$$\Delta I_L = D(1-D)\frac{V_g}{f.L} \rightarrow L = D(1-D)\frac{V_g}{f.\Delta I_L} = 0.1(1-0.1)\frac{20}{100x10^3x10} \rightarrow L > 0.18\,\mu H \tag{2}$$

Output voltage ripple value and inductance ripple values are used to calculate capacitor critical value as in Equation 3;

$$\Delta V_C = \frac{\Delta I_L}{8.f.C} \rightarrow C = \frac{\Delta I_L}{8.f.\Delta V_C} = \frac{10}{8x100x10^3x0.1} \rightarrow C > 1250\ \mu F \quad (3)$$

The DC-DC buck converter works depending on two states of switching MOSFET. In the first state, the MOSFET switch is ON, depends on switching signal and the source voltage is applied to the output and current flows through the inductance, capacitor, and load. In the second state, the MOSFET switch is OFF, depends on switching signal and the inductance voltage is continued to be applied to the output as a source voltage, and current is continuously flowing through the inductance, capacitor, and load by the freewheeling diode. These states are repeated by the time and current flows continuously [23-25]. The DC-DC buck converter study states, voltage and current signals are given in Figure 4 (a, b).



(a) (b)

Figure 4. The buck converter study states (a), voltage, current and switching signals (b)

3.3. Sliding Mode Controller

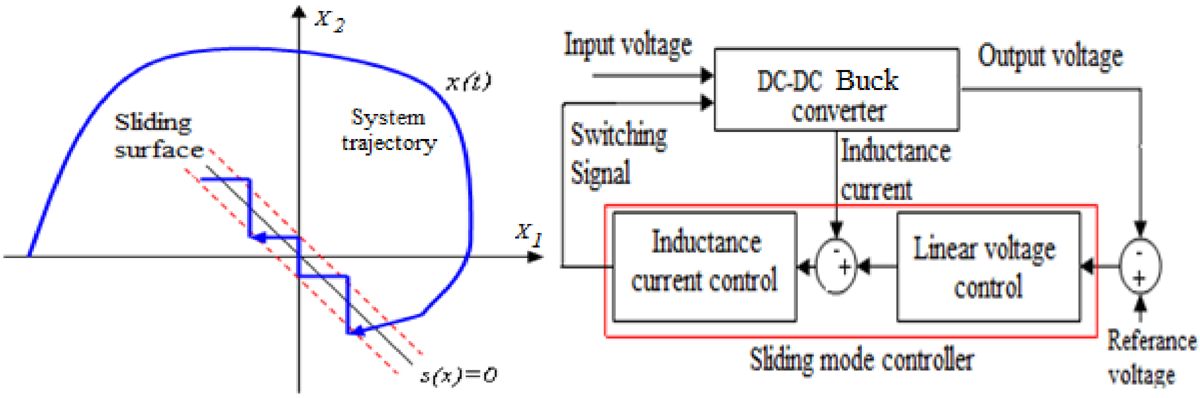
The DC-DC buck converter study states depend on the switching PWM signal which is generated by the error signal applied to Sliding Mode Controller (SMC). The error signal is generated for output voltage and inductance current variables. The sliding mode controller is used for the control of nonlinear switching power supplies. This control method has some advantages in the application such as high load changes, robust error control, effective dynamic response, and easy application [13, 14].

The SMC can be proposed as a good solution for variable structure systems. In practice, converter-switching devices are driven by a function of rapid values of state variables. The system trajectory stays in a zone on the state space as a result of this case. This region is called the sliding surface. The state equation for a nonlinear system is given in Equation 4. This equation defines the control rule of a nonlinear structure system at the same time.

$$\dot{x} = f(x) + g(x)u, \quad u = \{0,1\} \quad (4)$$

In the Equation 4, u is the numerical control input, on the sliding surface $s(x,t)=0$ is transient, $f(x)$ and $g(x)$ are continuous function vectors. State trajectories slide, into a balanced line asymptotically with a dynamic behavior for the SMC. There is s(x) used to define the controller rule and to determine the sliding surface is an important point. One other important point for the switching power supplies is that the system is being held on a switching surface. The Lyapunov approach was specially selected for these applications [13, 14]. This surface is shown in Figure 5(a).

The most important feature of SMC is the ability to achieve a response that is independent of the system parameters. For this reason, SMC is suitable for DC-DC converter applications. In practice, the velocity of the current change is faster than the velocity of output voltage change in the DC-DC converter applications. This control method is implemented by using inner current loop control and outer voltage loop control respectively for the SMC. A conventional linear controller is used for the voltage control, and a PWM or a hysteresis controller is used for the current control. The SMC is particularly used for the inductance current control [15, 16]. The common design of SMC for the DC-DC buck converters is shown in Figure 5(b).



(a) (b)

Figure 5. Sliding surface for SMC (a), the general structure of SMC for DC-DC buck converter (b)

3.4. Electrolysis Load Model

The electrolysis evident is necessary well understood before understanding the behavior of electrolysis load. When the suitable voltage is applied to the electrodes, which are placed in the water or liquid solution, a chemical reaction which is called electrolyze occurs. During the electrolysis process, hydrogen gas appears at the cathode, and oxygen gas appears at the anode. The voltage level of 2 V is enough for the decomposition of the water. While one-mole oxygen gas occurs at the anode, two-mole hydrogen gas occurs at the cathode during the reaction. The basic experimental set up for the alkaline electrolysis system is shown in Figure 6(a).

The electrolyzer, in reality, behaves like a nonlinear resistance during the chemical reaction. This nonlinearity depends on the chemical structure of the solution, the pressure of electrolyzes stack, temperature and the other parameters which exist during the chemical reaction [32]. The derived nonlinear mathematical model of the electrolyzer depend on these parameters is given in Equation 5 [10, 12].

$$R_e = R_{e0}\left[1+\alpha\left(\frac{I_e}{I_{e_{base}}}\right)^{\beta}\right] \quad (5)$$

In Equation 5, R_{eo} is initial resistance and its value is 0.08 Ω. The α and β are constant values that depend on nonlinear characteristics of electrolyzer model. These values are selected as a 0.35-0.65 for α, and 2-4 for β in typical applications. After these values have been written in Equation 5, the electrolysis load model is found as in Equation 6. The electrolysis resistance which depends on the electrolysis current as a nonlinear function is given in Equation 6. The electrolysis nonlinear load model is simulated in MATLAB/Simulink using this equation as in Figure 6(b).

$$R_e = 0.08\left[1+0.5\left(\frac{I_e}{50}\right)^{3}\right] \quad (6)$$

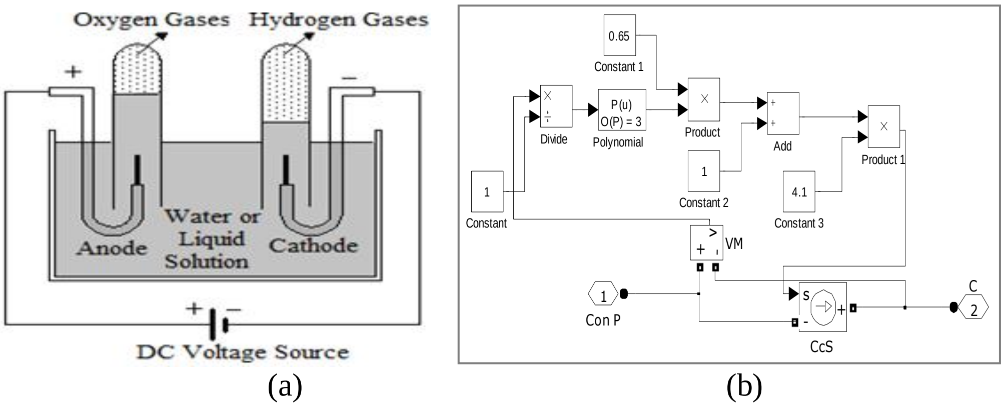


Figure 6. The basic experimental set up for alkaline electrolysis system (a), MATLAB/Simulink model of nonlinear electrolyzes model (b)

4. Design of MATLAB/Simulink General Model

The proposed photovoltaic sourced DC-DC buck converter for electrolyzes load with SMC controller was simulated in MATLAB/Simulink software. The simulation model of the proposed converter system is shown in Figure 7. The photovoltaic source model and electrolysis load model was used in this converter model instead of the linear source and load. The output voltage to compare the reference voltage and to obtain voltage error is applied to the Sliding Mode Control (SMC) block with the inductance current. The SMC control uses this signal and generates a PWM signal to drive the MOSFET switching.

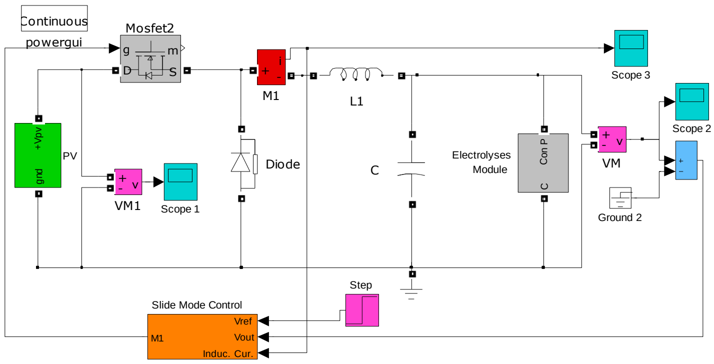


Figure 7. The simulation model of the proposed converter system in MATLAB/Simulink

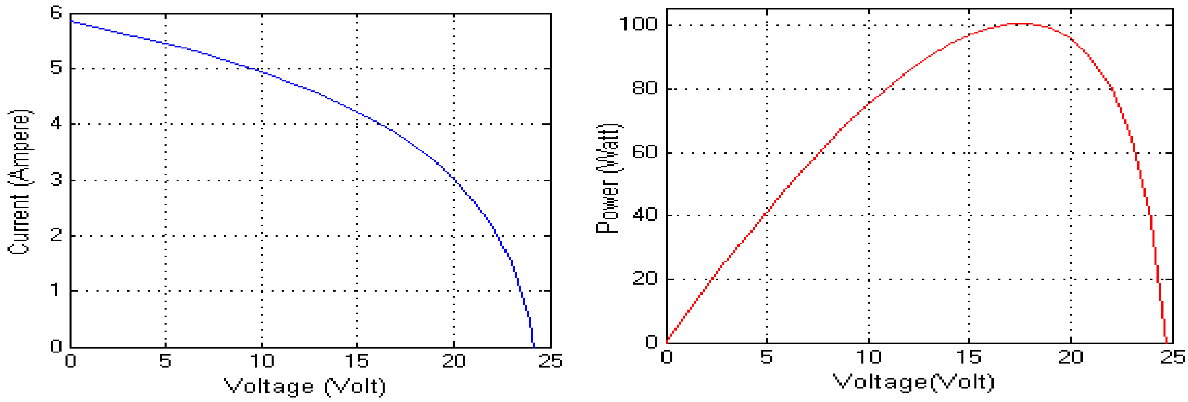
The simulation parameters of the proposed system model in Figure are given in Table 2. The simulation results are obtained using these parameters.

Table 2. Simulation parameters

Parameter type	Parameter value
DC input voltage	0-22 V
DC output voltage	2 V±5%
Nominal load current	40 A
Nominal power	100 W
Switching frequency	100 kHZ
Filter inductance	500 µH
Filter capacitance	2500 µF
Electrolysis initial resistance	0.08 Ω
SMC parameters (K_1, hysteresis band)	60, ±5
PV solar irradiation (G)	1000 W/m^2
PV operation temperature (T)	50 C^o

5. Simulation Results

Simulation results of the proposed photovoltaic sourced DC-DC buck converter with electrolysis load are given in this chapter. The simulation results were tried for different photovoltaic source and load conditions. The photovoltaic array is simulated for 100 W power photovoltaic panel characteristics which are given in Table 1. The simulation results are given in Figure 8. Figure 8(a) shows the current-voltage (I-V) characteristic of the photovoltaic source model. Figure 8(b) shows the power voltage (P-V) characteristic of the photovoltaic source model. The simulation results of this photovoltaic source model are suitable for the theory as expected.



(a) (b)

Figure 8. (a) I-V characteristic, (b) P-V characteristic of the photovoltaic source model

Simulation results for electrolysis load voltage, current and power are given in Figure 9. The electrolysis load voltage reaches 2 V in two seconds with small ripples. The electrolysis load current and power reaches 40 A and 80 W respectively in two seconds with small ripples similarly. The power losses on the output are originated from losses on the buck converter and the voltage and current shift from the maximum power point. Nevertheless, this output power is enough for the efficient electrolysis process. Different complex solutions can be proposed and studied to increase efficiency.

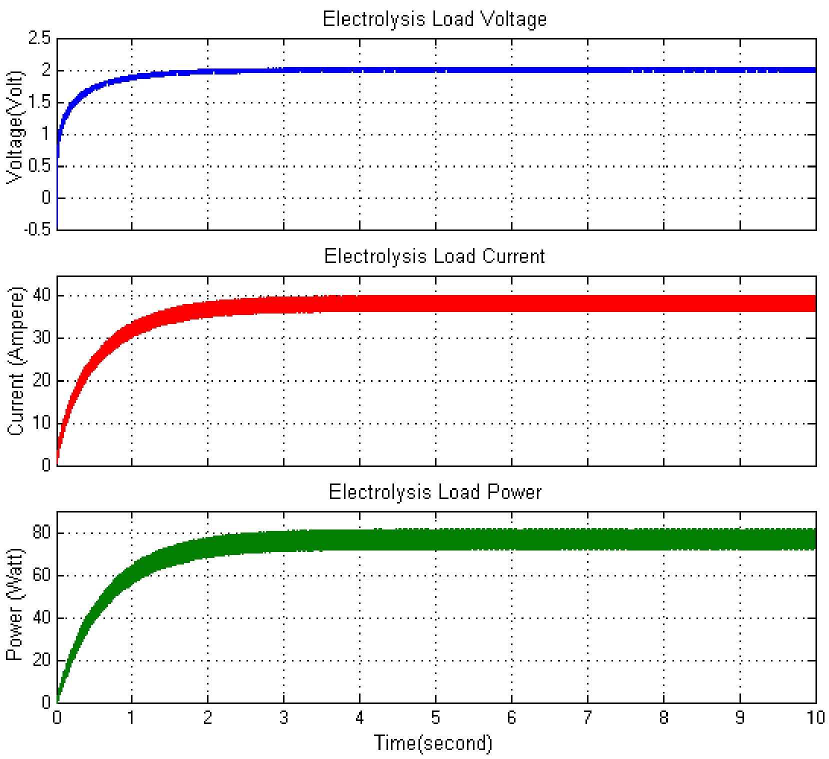


Figure 9. Simulation results for electrolysis load voltage, current, and power

The inductance current and voltage variation depending on switching PWM signal are given in Figure 10. When the MOSFET switch is ON depending on switching signal, the current increases and the inductance voltage is positive, when the MOSFET switch is OFF, the current decreases and the inductance voltage is negative. These results are suitable for the expected theoretical results and the converter studies in continuous mode.

The converter study conditions are tried for forced and unexpected conditions. Firstly, the electrolysis load is made a short circuit for one second. The output voltage, current and power variations are observed for this condition. These results are shown in Figure 11. The results are reaching the first expected values in a few seconds. Depending on energy storage components on the converter, the first response shows a little overshoot. Secondly, the electrolysis load is made an open circuit for one second. The output voltage, current and power variations are observed for this condition. These results are shown in Figure 12. The results are reaching the first expected values in a few seconds. Depending on energy storage components on the converter, the first response shows an overshoot similarly.

According to these results, it is possible to say the amount of the hydrogen gas produced from 100 W power PV module in one hour is 17.280 cm^3 or 17.28 liter theoretically through DC-DC buck converter and suitable electrolyzer devices. These results are calculated using the previous studies in references.

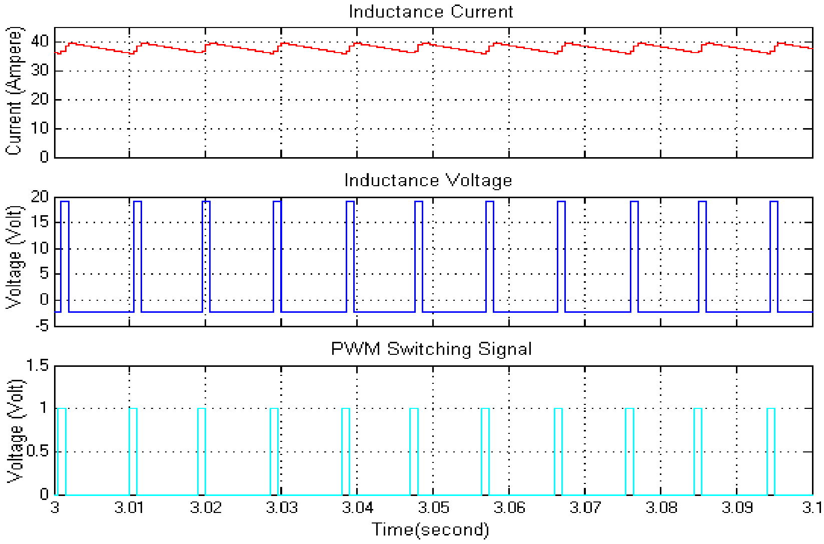


Figure 10. The inductance current and voltage variation depending on switching PWM signal

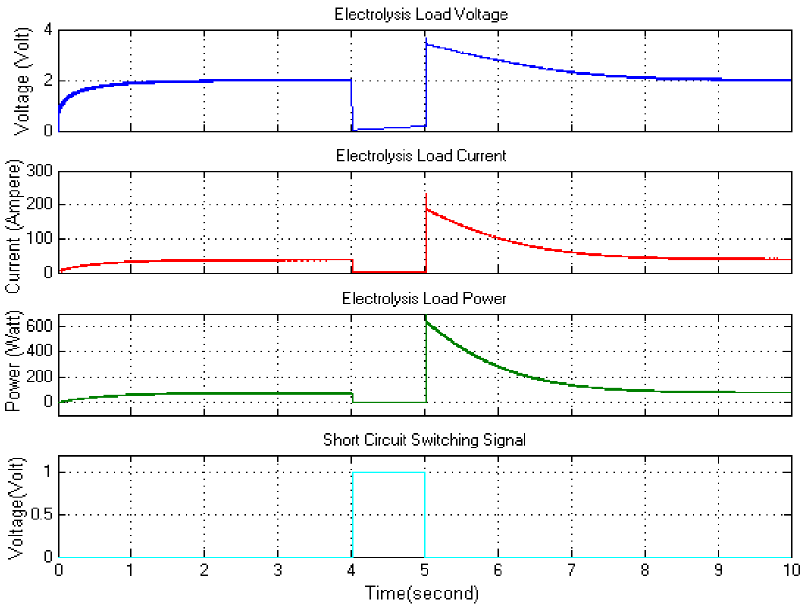


Figure 11. The output voltage, current and power variations for load short circuit

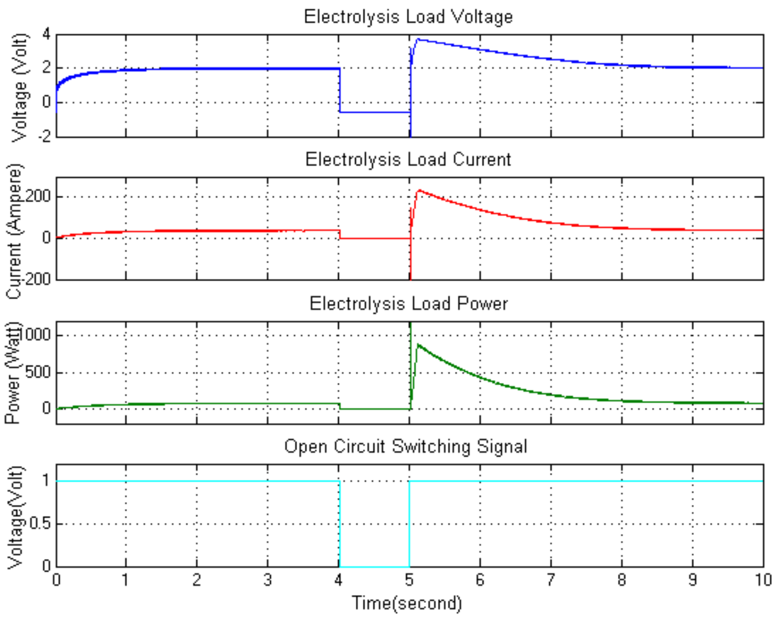


Figure 12. The output voltage, current and power variations for load open circuit

6. Conclusions

This paper focuses on two different scenarios to benefit from solar energy and storage of their energy as hydrogen. Photovoltaic energy was converted to the desired voltage level using the DC-DC buck converter for generating hydrogen with electrolysis process. The sliding mode controller is used in this study. The photovoltaic powered DC-DC buck converter for electrolysis load was simulated in MATLAB/ Simulink software more detailed using the sliding mode controller. The simulation results are investigated for output voltage, current, and power with photovoltaic sources. As well as, this result was repeated for inrush conditions such as short circuit load and open circuit load. These simulation results are suitable for theoretical results as expected. The simulation results can be tried for different controllers with MPPT systems using more efficient converters as a future study. In addition, this study can be realized experimentally spending more time by funds to improve the idea.

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