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Evsel güç sistemleri için akıllı bir güç yönetim sisteminin tasarımı

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A Smart Energy Management System Design for Residential Power Plants

Araştırma Makalesi / Research Article

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ABSTRACT

In this study, a solar-hydrogen hybrid power generation system is modeled by developing a smart energy management system (EMS) to sustain a continuous power flow for a local load in a constituted residential hybrid power plant. The developed EMS checks the total energy demand of the hybrid power plant and operates the solar power plant or the hydrogen energy based power plant to provide a sustainable power for the local load. A new control card is developed and a real-time EMS is performed in Labview for controlling and monitoring the hybrid system. The implemented electronic control card manages the active power flow of the hybrid system to provide a sustainable power demand of the local load. The current energy demand of the residential power plants can be viable in the lack of the sun or hydrogen, thanks to the developed EMS. The proposed EMS is modeled in Matlab/Simulink, and verified by the experimental study. The experimental results show that the proposed EMS provides a sustainable energy infrastructure for the residential hybrid power plants, and it is also easy implemented and suitable for residential real system applications.

Keywords: Energy management, residential power plants, hydrogen energy, solar energy.

Evsel Güç Sistemleri için Akıllı Bir Güç Yönetim Sisteminin Tasarımı

ÖZ

Bu çalışmada, evsel hibrit bir güç sistemi içindeki lokal bir yüke, sürekli güç akışının sağlanması amaçlanmıştır. Bu amaçla akıllı bir enerji yönetim sistemi geliştirilerek bir solar-hidrojen hibrit güç sistemi modellenmiştir. Geliştirilen bu enerji yönetim sistemi, hibrit güç sisteminin toplam enerji talebini kontrol etmektedir. Bu sistem, lokal yüklere sürdürülebilir bir güç sağlamak için ya solar güç sistemi ya da hidrojen enerjisine dayalı güç sistemi olarak çalışmaktadır. Hibrit sistemin kontrol edilmesi ve gözlenmesi için yeni bir kontrol kartı geliştirilmiştir. Ayrıca Labview ortamında gerçek zamanlı bir enerji yönetim sistemi geliştirilmiştir. Lokal yükün sürdürülebilir bir güç talebi sağlaması için hibrit sistemin aktif güç akışını, geliştirilen bu elektronik kontrol kart yönetmektedir. Geliştirilen bu elektronik kart sayesinde evsel güç sisteminin güncel enerji talebi, güneş veya hidrojenin olmaması durumu için uygulanabilir. Önerilen bu elektronik kart Matlab/Simulink ortamında modellenmiş ve deneysel çalışma ile de doğruluğu sağlanmıştır. Deneysel sonuçlar göstermiştir ki önerilen bu elektronik yönetim sistemi evsel hibrit güç sistemlerine sürdürülebilir bir enerji altyapısı sağlamaktadır. Ayrıca, bu sistem gerçek evsel sistem uygulamalarına uygun olma ve kolay gerçekleştirilebilme özelliklerine de sahiptir.

Anahtar Kelimeler: Enerji yönetimi, evsel güç sistemleri, hidrojen enerjisi, solar enerji.

1. INTRODUCTION

The environmental conditions limit the solar power generation, thus the hybrid power systems are required to provide a sustainable power for desired electrical load demand. Besides, solar-hydrogen energy-based hybrid power plants have been coming into prominence due to becoming the residential applications widespread.

The hybrid renewable energy sources (HRES) are the combination of the wind, hydrogen, solar and other renewable energy sources operating at the same time [1]. The phrase of the HRES is also used to provide the required electrical and thermal energy demand of the consumers by combining all of the different energy technologies [2].

A solar-hydrogen energy based hybrid power energy system is an alternative and sustainable energy solution for the residential plants which fills the deficiency of the sole PV power generation system [3]. There are several methods to produce hydrogen from the solar energy. Today the most common method is to generate hydrogen to electrolyze the water at low temperatures [4].

A solar-hydrogen energy-based power generation system was proposed in [5]. In the study, an electrolyzer, a hydrogen storage tank and the batteries were designed to constitute the hybrid system. The daily generated and consumed power was monitored, and a new model was

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proposed to improve the performance of the fuel cell (FC) system in this study. A similar study was performed in [6]. Labview monitored the obtained experimental results from the hybrid PV-FC hybrid system. The grid connected, and standalone operational performance of the hybrid system was also researched in another study [7], and the properties of a polymer electrolyte membrane (PEM) electrolyzer were examined in the study. PV-battery, PV-FC stack and PV-FC-battery off-grid hybrid systems were designed in [8] to optimize and to specify the different storage technologies in this study. Most of these studies focus on modeling the hybrid system and consist of simulation studies.

Another standalone hybrid system consisting of a wind turbine, a PV array and a PEMFC stack was proposed in [9]. Providing the maximum output power of the system, decreasing the voltage fluctuation and the increasing the energy quality of the hybrid system is the main design and simulation issues researched in this study. A Matlab-Simulink model connected 1,2 kW PEMFC stack was presented in another study [10]. In this study, the analysis of the FC system is investigated, and the FC system is the sole source of the system. The simulation of a grid connected PV-FC system with Matlab, Simulink was also studied in [11]. A Matlab simulation model and the analysis of a hybrid power generation system consisting of a PV array and a PEMFC stack was also operated in [12].

This study focuses on developing a solar-hydrogen hybrid power generation system model with Matlab/Simulink. A sustainable power flow is researched for residential solar-hydrogen hybrid power plants. The general schematic of the proposed hybrid power generation system for residential plants is shown in Figure 1. A solar-hydrogen hybrid power generation system is designed to realize a sustainable power flow for the local load. The implemented electronic control card manages the active power flow of the hybrid system. Thus, the proposed management system provides a sustainable energy infrastructure for the residential hybrid power plants. Besides, the current energy demand of the residential power plants can be viable in the lack of the sun or hydrogen, thanks to the developed hybrid power plant and the management system.

2. MOELING OF THE HYBRID POWER GENERATION SYSTEM

The proposed hybrid power generation system designed for residential plants is modeled in Matlab/Simulink. The proposed model consists of a 100 Wp PEMFC stack, and a 160 Wp PV module. The proposed control system are developed to compare the both simulation and experimental results. A detailed model of the proposed system is introduced in this section.

2.1. PEM Fuel Cell Model

The mathematical models are used to obtain the characteristics of a PEMFC stack, and the polarization curve is obtained by evaluating the developed mathematical model in Matlab/Simulink. The operation of a PEMFC in a stack is nonlinear. This characteristic also depends on many factors, just like current density, cell temperature, membrane humidity and the partial pressure of the reacted gases.

The PEMFC stack consists of an anode, a cathode, electrolyte layer and the gas flow channels. The inputs of the PEMFC stack are hydrogen, oxygen, steam pressure and the current density of the PEMFC. The cell voltage equals to the multiplication of the number of PEMFC. The stack voltage is obtained from this multiplication. The developed model of the PV module is shown in Figure 2 (a), and the PEMFC stack is indicated in Figure 2 (b).

The cell voltage (Vcell) can be determined in any conditions by using equation (1). When a cell operates with a load, no load voltage (E) decreases with the increment of the voltages defined as (Vact). It is the activation voltage. (Vohm) is the ohmic voltage, and (Vconc) is the concentrate voltage.

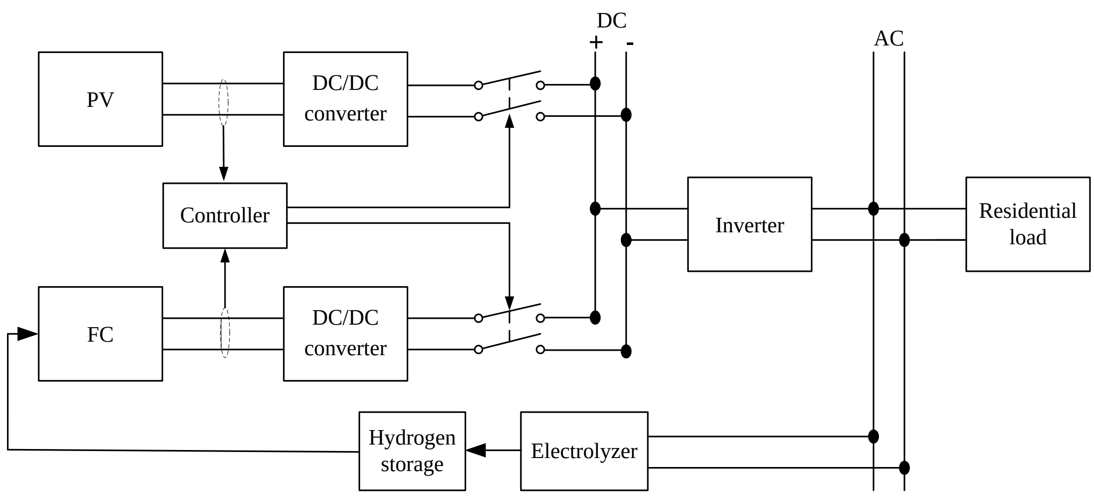
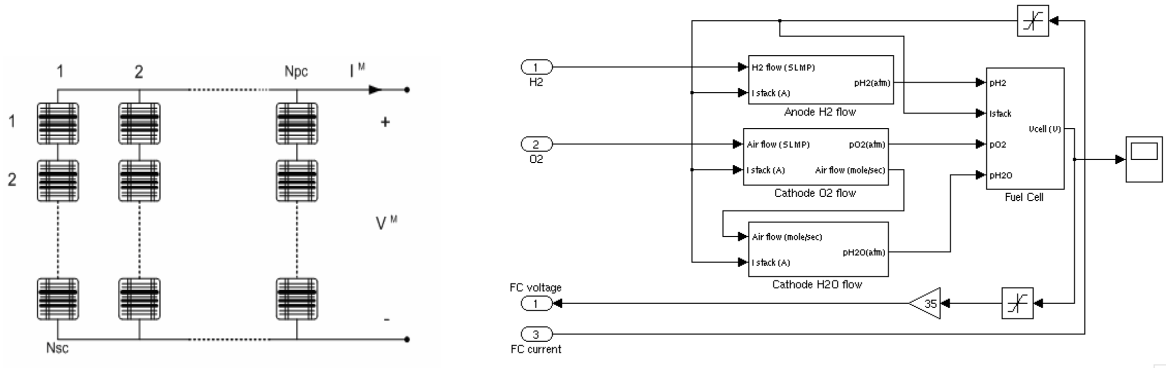


Figure 1. The general schematic of the proposed hybrid power generation system for residential plants



(a) **(b)**

Figure 2. (a) The PV module model, **(b)** PEMFC stack model

The cell voltage (Vcell) can be determined in any conditions by using equation (1). When a cell operates with a load, no load voltage (E) decreases with the increment of the voltages defined as (Vact). It is the activation voltage. (Vohm) is the ohmic voltage, and (Vconc) is the concentrate voltage.

$$V_{cell} = E - V_{act} - V_{ohm} - V_{conc} \quad (1)$$

The Nerst equation (2) gives the open circuit cell voltage (E). It is the function of the cell temperature (T) and the reactant partial pressures to obtain the characteristic curve of the PEMFC.

$$E = E_0 - 0{,}85.10^{-3}\,(T - 298{,}15) + \frac{R.T}{2.F}\ln\left(\frac{P_{H2}.P_{O2}^{\ 0.5}}{P_{H2O}.P^{0.5}}\right) \quad (2)$$

E_0 is the reference voltage, R is the universal gas constant, and F is the Faraday constant. P_{H_2}, P_{O_2} and P_{H_2O} are the hydrogen, oxygen and steam pressures, respectively. The total pressure in the stack is represented by P. The activation decrease can be analyzed by the Tafel equation [13].

$$E_{act} = -0{,}9514 + 0{,}00312T - 0{,}000187.T.[\ln(I)] + 7{,}4.10^{-5}.T.[\ln(C_{O_2})] \quad (3)$$

The current density in equation (3) is defined as "I". C_{O_2} is also oxygen concentration and it is determined as a function of the stack temperature in equation (4).

$$C_{O2} = \frac{P_{O2}}{5{,}08.10^{6}\exp(-498/T)}\ \text{mol.cm}^{-3} \quad (4)$$

The over activation voltage is indicated in equation (1) as a voltage drop, and Eact is negative in all of the arrays in equation (3). The equation (5) is used to avoid the adverse effect of this term [13].

$$V_{act} = -E_{act}\quad V \quad (5)$$

2.2. Photovoltaic Module Model

The PV modules consist of solar cells, which are connected in series and parallel to each other. Each branch of the PV modules consists of many Npc cells in parallel and number of Nsc cells in series in the proposed simulation model. The number of series and parallel cells also appears in the catalogs of the commercial PV modules.

The total voltage of the series connected PV cells is determined by summing the each PV cell voltage that has the same current. Similarly, the total current of the parallel-connected PV cells is determined by summing of each parallel cell branches. In Equations (6) and (7); the module voltage is V_M , and the module current is I_M .

$$V_M = N_{sc}.V_{new} \quad (6)$$

$$I_M = N_{pc}.I_{new} \quad (7)$$

The output power of the module is a function of the solar irradiance and the ambient temperature. I_D is an internal current flow from the p-n junction that constitutes the semiconductor material of a PV cell. It depends on the absolute temperature of the diode and the function of the current flowing through the load and the voltage. The saturation current (I_0) is defined in (8) as a function of the temperature;

$$I_0 = I_{0ref}\left(\frac{Tc}{T_{cref}}\right)^3.\exp\left[\left(\frac{qE_g}{nk_b}\right)\left(\frac{1}{T_{cref}} - \frac{1}{T_c}\right)\right] \quad (8)$$

In equation (8); I_{0ref}= Reference current, E_g= Bandwidth of the PV cell material. The photon current of the PV cell depending to the solar irradiance is explained in (9):

$$I_{ph} = [I_{sc} + \alpha(T_c - 25)]\frac{G}{G_{ref}} \quad (9)$$

In equation (9); G: Solar irradiance (W/m^2), G_{ref} : Reference solar irradiance (W/m^2), *Tc*: Effective PV module temperature (K), T_{cref} : Reference PV module temperature (K), A: Short current temperature coefficient of PV module (mA/K).

There are several mathematical determination methods in the literature to obtain I-V characteristics of the PV module. Equations (6)-(10) define one of these methods. Vref and Iref are the reference values of the I-V characteristic curve. The open circuit voltage, the short circuit current, the voltage temperature coefficient (α) and the current temperature coefficient (β) are the fixed values obtained from the catalog of a PV module. The new current is determined current in the algorithm. The new current is determined by the equation (10) [14, 15].

$$I_{new} = I_{ref} + \left[\alpha\left(\frac{G}{G_{ref}}\right)(T_c - T_{cref}) + \left(\frac{G}{G_{ref}} - 1\right) I_{sc}\right] \quad (10)$$

3. SIMULATION RESULTS

In this section, the proposed model is simulated under different load conditions, to compare with the experimental results. Table 1 shows the operating conditions of the proposed hybrid system in the simulation. Insufficient energy source (lack of hydrogen or solar irradiation is marked as (-) and sufficient energy source (enough hydrogen or solar irradiation) is marked as (+) in Table 1.

Table 1. The operating conditions of the hybrid system

State	Load	Solar Irrad. (W/m^2)	Hydrogen (lt/s)	FC Stack Operation	PV Array Operation
Q1	25 W	-	+	Yes	No
Q2	40 W	+	-	No	Yes
Q3	75 W	+	+	1st source	2nd source
Q4	125 W	-	-	No	No

3.1. The FC Stack Operation

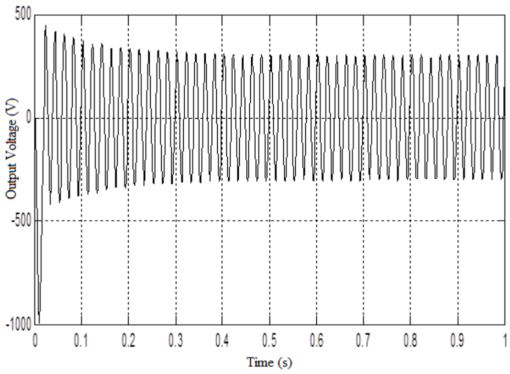
The developed model is simulated under different load conditions. The FC stack is operated with a resistive load. Figure 3 shows the FC simulation results obtained from the proposed model when the load is resistive (25 W). The output voltage of the FC stack is indicated in Figure 3 (a), and the load current in Figure 3 (b). The obtained voltage is a smooth sinusoidal signal, and there is a small peak because of switching.

3.2. The PV Array Operation

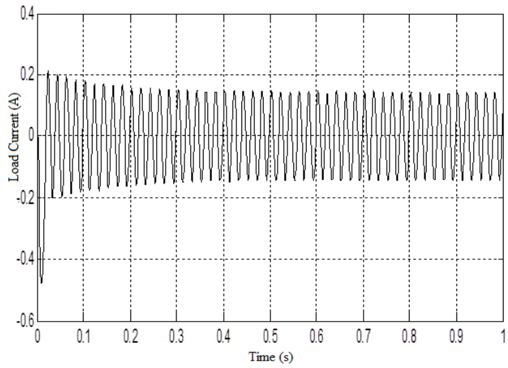
The developed model is also simulated with the single operation of the PV array. Figure 4 shows the simulation results obtained from the proposed model when the load is resistive (40 W). The output voltage of the PV array is indicated in Figure 4 (a) and the load current in Figure 4 (b). There is a small fluctuation in the load current, but the current provides the stability in a short time.

4. DEVELOPED ENERGY MANAGEMENT SYSTEM

The proposed control system checks the PV power or FC power to provide a sustainable power to the load. PV power is directly related to weather conditions. Besides, FC power is directly related to amount of generated hydrogen. Thus, if the PV power is not sufficient, FC power is selected by the control system to generate desired load power demand. This condition is valid for PV power when the FC power is not sufficient to supply the load demand. The control system is switched off both the PV power and FC power is not sufficient.



(a)



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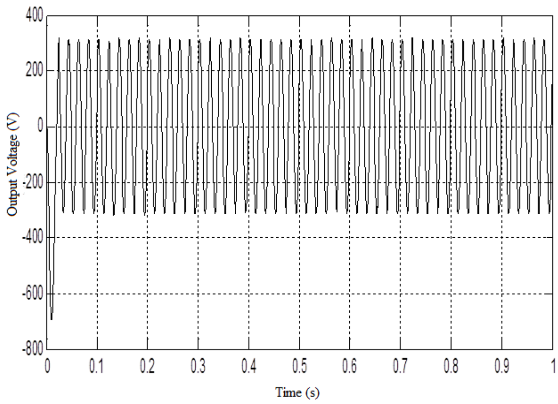
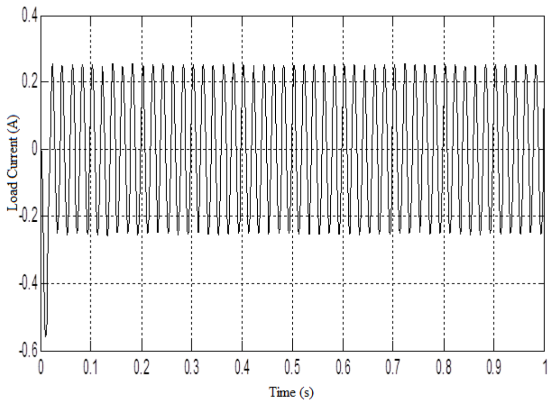


(a)



(b)

Figure 4. (a) Output voltage of load, **(b)** the load current

The developed EMS is implemented in real-time by developed Labview software that monitors each side of the hybrid power system (hybrid power system, inverter and load). The voltage, current, frequency, active power, the phase angle and the peak values are determined in the developed software, and the hybrid system is monitored in real time.

The developed Labview software evaluates the analog inputs transmitted from electrical measurement circuits. According to these parameters, it monitors the electrical parameters of the solar-hydrogen hybrid system. Figure 5 shows the general structure of the developed software. The implemented electronic control card manages the active power flow of the hybrid system to provide a sustainable power demand of the local load. The current energy demand of the residential power plants can be viable in the lack of the sun or hydrogen, due to the developed EMS.

is not sufficient. The PV system is the main source in this condition. Figure 6 (b) indicates the output of the PV inverter voltage and current waveforms obtained from the EMS. The distortion of the output current of the inverter is also indicated in Figure 6 (b).

4.2. Operating the PV System with A Different Load Condition

The developed EMS has also been researched for the different load conditions. In Figure 7, active, reactive and apparent power changes of the inverter side when an inductive load connected to the PV system is shown. All the powers on the grid side while the hybrid system was running could be seen in real time in Figure 7 (a) due to the developed EMS. Active and reactive power of the load in real time is also shown in Figure 7 (b).

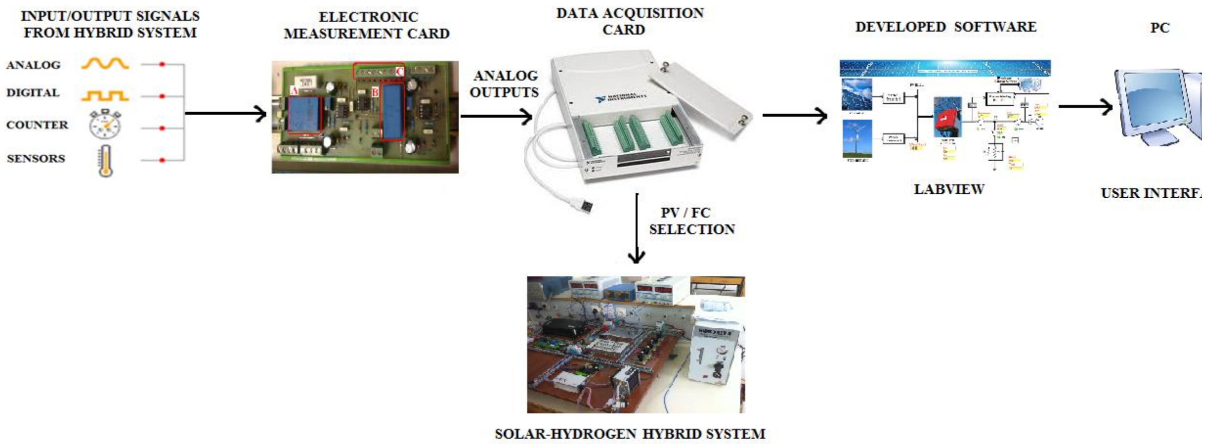
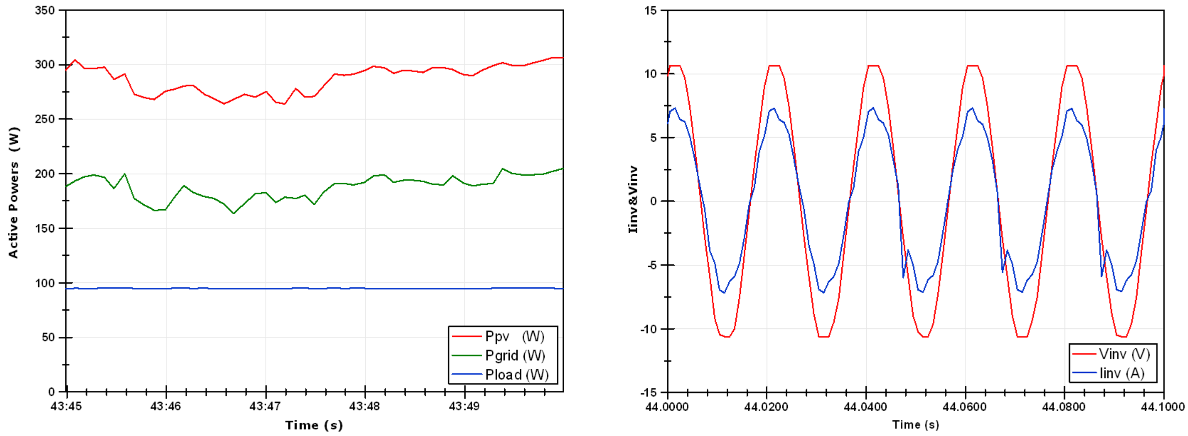


Figure 5. The general structure of the developed EMS

4.1. Operation of the PV System

The active power changes of the inverter output and the load are shown in Figure 6 (a) when the FC stack power



(a) (b)

Figure 6. (a) The active power changes of the PV system, **(b)** The waveforms of the current and voltage of the inverter

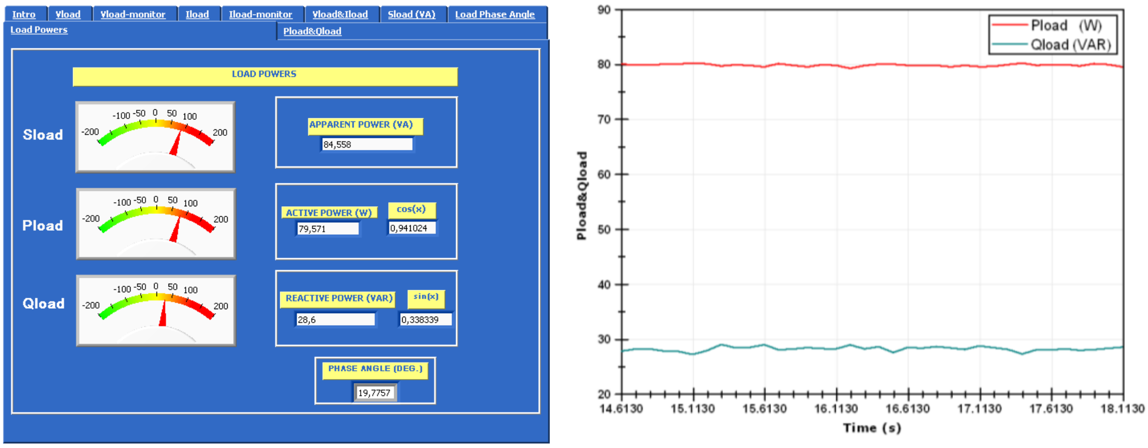


Figure 7. (a) The power and phase angle of the inverter, **(b)** The load power in real-time

5. CONCLUSIONS

This study focuses on developing a new energy management system for residential solar-hydrogen hybrid systems. In the study, the developed EMS to supply the required energy demand of the hybrid power plant is simulated by using Matlab/Simulink. An experimental solar-hydrogen hybrid power generation system is also performed in the laboratory to realize the proposed system. The experimental results show that the proposed EMS provides a sustainable energy infrastructure for the residential hybrid power plants, and it is also easy implemented and suitable for residential real system applications.

The total energy demand of the hybrid power plant is controlled by the developed EMS. The EMS operates the solar power plant or the hydrogen energy based power plant to provide a sustainable power for the local load. A new control card is developed and a real-time EMS is performed in Labview for controlling and monitoring the hybrid system. The proposed control system controls the PV or FC power to supply a sustainable power. Unlike FC power, PV power is directly related to weather conditions. The FC power is depended on amount of generated hydrogen. By this way, if the PV power is not sufficient, FC power is selected by the control system to generate desired load. This condition is valid for PV power when the FC power is not sufficient to supply the load demand. Thus, the current energy demand of the residential power plants can be applicable in the deprivation of the sun or hydrogen.

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