A MULTI-PURPOSE MINI HYBRID FUEL CELL-BATTERY-SOLAR PORTABLE DEVICE FOR RURAL APPLICATIONS: LABORATORY TESTING

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ABSTRACT

In this study, a novel multipurpose portable PEM fuel cell-solar-battery system was custom designed, constructed and laboratory tested, specially aims for applications in the rural areas remote from conventional electric power grid. We obtain encouraging results which show the applicability of such system for used as a multipurpose kit for portable applications. Our study shows that various power sources namely solar cell, battery and PEM fuel cells can combine harmoniously to obtain higher power voltage, whilst maintaining their individual advantages – such as good startup performance. Our typical results show that the maximum power of the PEM fuel cell/solar/battery with load is in the range of 2.4W-2.7W which can be maintained continuously. Apart from good cold start characteristic, the portable system also exhibits stable voltage, compact in size and acceptable in weight, hence suitable for rural power application at places remote from conventional grid.

Keywords: *Applied hybrid energy, Multi-purpose energy systems, Energy resources, Fuel cells, Solar energy*

1. INTRODUCTION

It is a growing concern that there is a lack of grid-based electricity supply to rural areas in developing countries [1-2] and that alternative energy sources such as solar, wind and biomass must be developed [2, 3]. Broader application of fuel cell technology promises significant contribution to sustainable global economic growth, but requires intelligent improvement to size, cost, fuel flexibility and operating flexibility [4-5]. Also, for fuel cell to be sustainable, one of the feasible solutions is that the hydrogen (H_2) fuel must come from water using alternative energy to generate it.

Fuel cell of its definition is an electrochemical device that produces electricity via inverse electrolysis. A chemical reaction and electrical charge transfer occurs within the fuel cell. This is very similar to the way a battery produces electricity. Unlike a battery, a fuel cell produces electricity as long as there is a continuous supply of fuel [2, 6]. Simple definition of a fuel cell is that it is an electrochemical device that reacts hydrogen and oxygen to produce water and electricity.

A 2.24 kW hybrid photovoltaic (PV)- Proton exchanged membrane (PEM) fuel cell generation system employing an electrolyzer for hydrogen generation was designed and simulated by El-Shatter [7]. The system was reported to be applicable for remote areas or isolated loads such as pumping for irrigation. Shapiro et al. [8] investigated a system consisted of a PEM electrolyzer, high-pressure hydrogen, oxygen storage and a PEM fuel cell, without battery. This system was reported to be able to provide reliable, environmental benign power of around 4 kW to remote installation. The hybrid fuel cell systems mentioned above, however, are mainly designed for non-portable applications.

Lee et al. [9] studied and analyzed a 40W direct methanol fuel cell (DMFC) combined with battery hybrid power for portable application. The DMFC was used for main power source at average load while the battery was applied for auxiliary power at overload. The experiments were done on hybrid DMFC using a lead-acid battery, Ni-Cd battery and Ni-MH battery. Typical result shows that a stable transient characteristic for some seconds in the beginning of the load growth.

To meet pulse-power demand, in which the power demand is impulsive rather than constant, a design and experimental tests of control strategies for active hybrid fuel cell/battery power source had been investigated by Jiang et al. [10]. These control strategies were implemented in Mathlab/Simulink and then tested under the pulsed-current load condition through experiments. The same actively controlled fuel cell/battery hybrid was studied by Gao et al. [11] to meet pulsed power demands. The fuel cell was controlled to satisfy the load average power requirement over a long time while the lithium-ion battery is used to serve high pulse power requirement in short intervals. The results showed that the hybrid power source can achieve much greater specific power and power density than the PEM fuel cell alone. Another fuel cell/battery hybrid power source for pulse power applications had been investigated by Jones et al. [12]. The investigation was done on the combination of specific energy performance from the fuel cell system with the specific power and response time of a lead-acid or nickel/cadmium battery. These hybrid systems were reported successfully operated continuously for several weeks under load profiles that the fuel cell alone could not sustain. However, the lead-acid battery (1.2 Ah) operated between 13.8V and 11.4V at 20°C, without charging, was reported to have lasted a maximum of 3 hour 20 min.

A power coordination consisting of a low cost, light weight and compact solid state power distribution in a fuel cell-battery hybrid power source using commercial power controller circuits was investigated by Blackwelder & Dougal [13]. The miniature power regulator integrated circuits with appropriate modification allowed the interconnection of fuel cell systems and batteries having dissimilar operating voltages and also impose a power sharing strategy that elicits peak performance from each part of the device.

Suppes [14] had done an investigation on plug-in hybrid fuel cell battery charger which used an on board regenerative fuel cell (RFC) stack as a battery charger. The RFC's electrolyser was able to use grid electricity to produce hydrogen and oxygen during overnight charging process. The combination of a RFC stack and battery pack resulted in a lower cost compared to using battery pack or fuel cell stack alone.

In this study, a novel hybrid energy system namely Hybrid Power Source Multipurpose Emergency Kit (HPSMEK) comprising three energy sources namely PV, battery and fuel cell was designed, constructed and laboratory tested. A design load in this research is a multipurpose and portable emergency kit which is consisted of a small radio, fan, two lamps and a USB port for USB devices applications. The applications described here are specially designed aim to help the local rural communities for portable or emergency power accesses. Here it is to be noted that due to an overall high local humidity, clouds are inevitable sometimes, and this has often resulted in a random amperage and voltage of the PV cells. For this reason, fuel cell is also included in the hybrid energy scheme compared to the conventional PV-battery or PV-wind energy schemes.

2. MATERIALS, EXPERIMENTAL SET-UP AND PROCEDURE

The prototype (Figure 1) was custom constructed in the Faculty of Engineering, UNIMAS, which consist of few components. It consists of a PV solar cell which is generated by a 20W light bulb for solar light simulation purpose. The PV panel drives a PEM electrolyzer (input voltage: ~ 1.5 - 3 V d.c.), which breaks water into H_2 and O_2 into a limited on-demand ~ 24 ml and ~12 ml gas tank, respectively. The gases thus obtained are used to run a 5W PEM fuel cell (Thames & Cosmos®, US), producing on-demand electricity to power a load. The gases are obtained from electrolysis process generated by an ETM500 PV solar cell with maximum d.c voltage thus generated ~ 3V. To increase the voltage, a DC-DC converter is then connected in series. After the conversion, the d.c voltage had increased to 5V. A 12V rechargeable lead acid pack was employed in this system. The lead acid battery pack is used to connect in series to the solar PV/fuel cell after the conversion. The maximum d.c voltage from which the hybrid system could now provide approximately13V. The voltage regulator is connected to the system to divide the voltage from hybrid solar/fuel cell/battery to the fixed voltage i.e. 5V, 9V and 12V. Finally, a hybrid solar/fuel cell/battery power system is thus constructed and is able to supply for the emergency multi purpose kit or other devices. The overall size of the prototype is ~ 24cm x 37 x 9 cm. Detail design of the prototype system and the associated electronics set-up is given in ref [15].

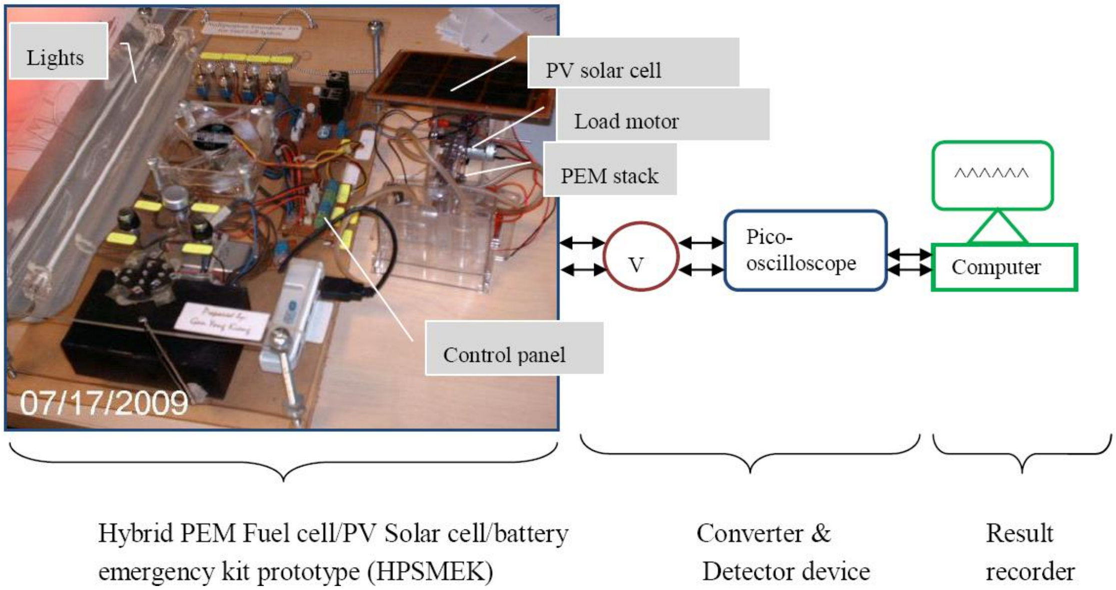


Figure 1The prototype and the schematic of the associated experimental setup. The experimental rig essentially consists of three sections i.e. the prototype, converter & detector device and the computer result recorder.

The prototype (Figure 1) was tested with load and without load; under dual hybrid and triples hybrid i.e Dual hybrid fuel cell and solar, fuel cell and battery, hybrid solar and battery and also triples hybrid fuel cell, solar and battery respectively. The specifications of the load (motor) considered in this study are given in Table 1. A Pico-oscilloscope and a personal computer were used for performance evaluation and result recording (Figure 1). The specification of Pico-oscilloscope (Model: ADC212D) used is given in Table 2.

Table 1. D.C. Motor Specifications

Specification	Value
Operating range	1.5-3V
Nominal	3V
At No load:	
Speed	12511 rpm
Current	0.29A
At max efficiency:	
Speed	10012 rpm
Current	1.16A
Torque	15.7 gcm
Output	1.61W
Eff.	42.36%

Table 2. Specifications of Pico-oscilloscope (model ADC212D)

Specification	Value
Voltage range	± 20mV to ± 20V in 9 ranges
Spectrum range	0-76 Hz (min)
Channels	2 BNC, 1MΩ ac/dc; 1 BNC external trigger
Accuracy	±1%

3. RESULTS AND DISCUSSION : EXPERIMENTAL STUDY

3.1 Materials for Hybrid Power Source Multipurpose Emergency Kit (HPSMEK)

Figure 2 is a schematic diagram of the HPSMEK system designed and built in the present study, which includes PV Solar Cell, PEM fuel cell, lead acid battery and a DC-DC converter. The DC-DC converter is used to step-up the voltage produced by solar cell and PEM fuel cell. Lead acid battery is used to combine with the voltage after the DC-DC converter to gain higher voltage for supplying enough electricity to the HPSMEK.

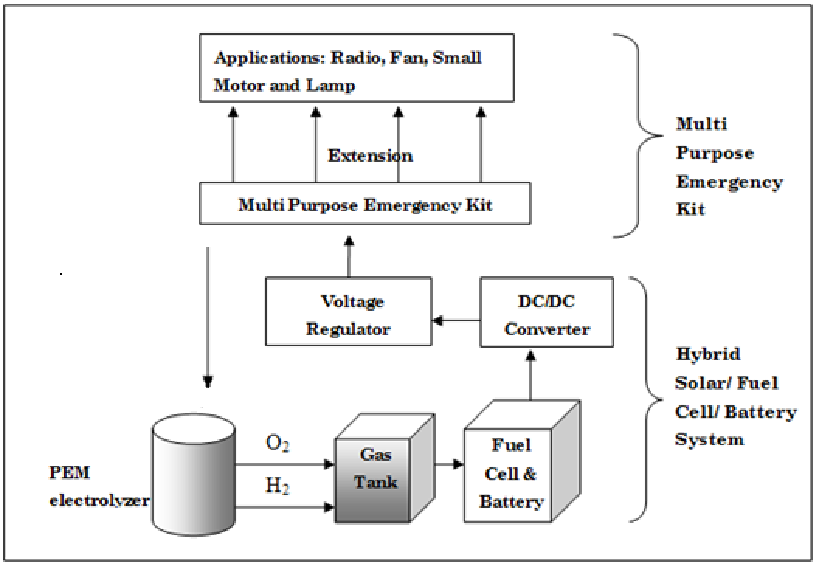


Figure 2 Schematic diagram of the HPSMEK device system

The micro-electronic materials used for the circuit construction for the HPSMEK system includes resistor, fixed resistor, variable resistor, capacitor, light emitting diode (LED), LM78L05 fixed voltage regulator, LM317 adjustable voltage regulator, switches, heat sink, strip board and breadboard. All of the materials are combined based on the schematic diagram and the circuit diagram of the multi purpose emergency kit as shown in Fig. 3(a) and Fig. 3(b), respectively. The HPSMEK system is subsequently connected to the electrical appliances such as radio, fan and lighting bulb.

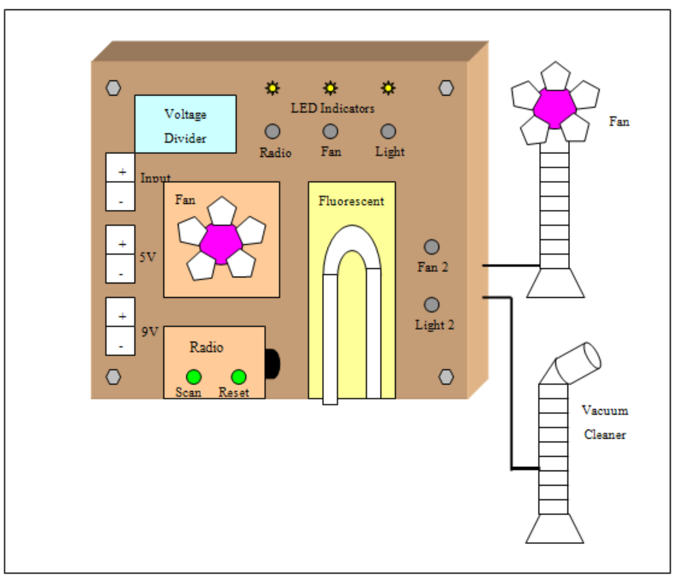


Figure 3(a) Schematic diagram of the prototype (HPSMEK)

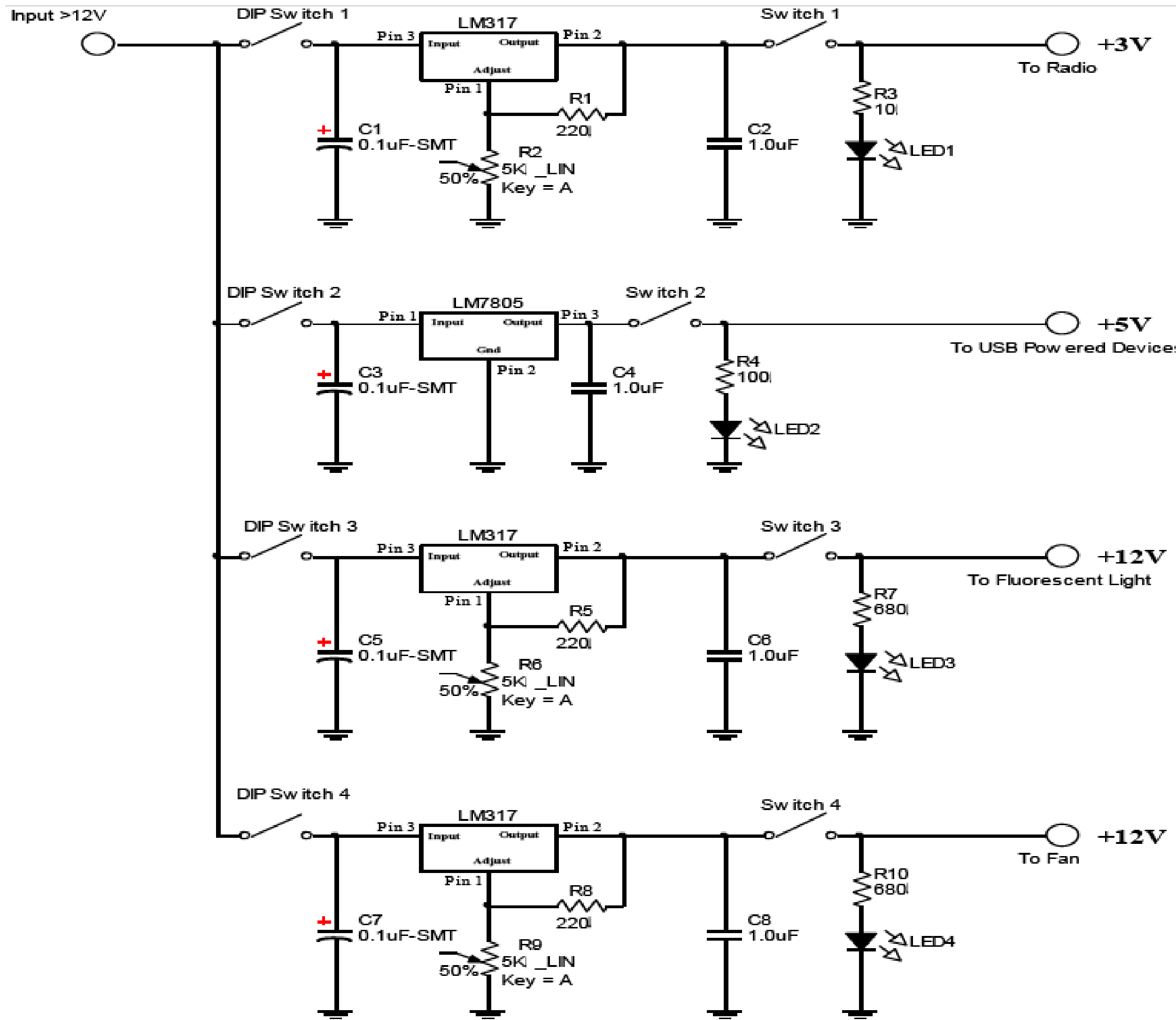


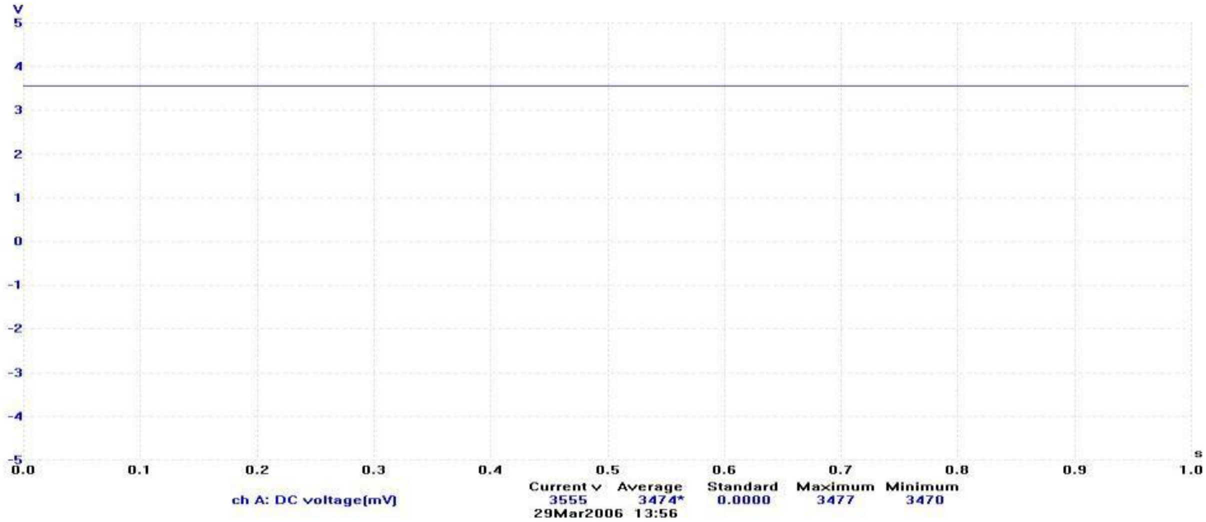
Figure 3(b) Circuit diagram of the prototype (HPSMEK) system.

3.2 Standalone power source without load study

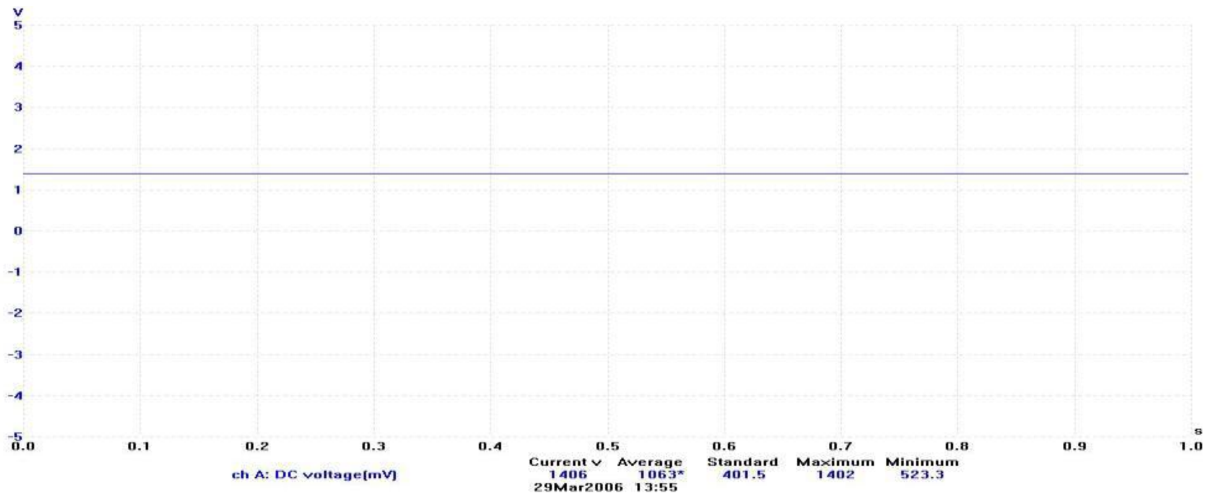
Figure 4 presents the performance of the power source characteristic profiles with load for lead acid battery, PEM fuel cell without load and solar cell without load, respectively. From these figures, it had been observed that all power sources are producing stable d.c voltages, indicated by the stable continuous signal waves. These three power sources had shown different voltage levels: the voltage designed for lead acid battery carries maximum 12V; the solar cell produces up to 5V; and the fuel cell is the lowest source which generates up to approximately 3V. The voltages thus attained are due to the base design capacity of the sources used (Table 3).

Table 3.Base design capacity of the power sources

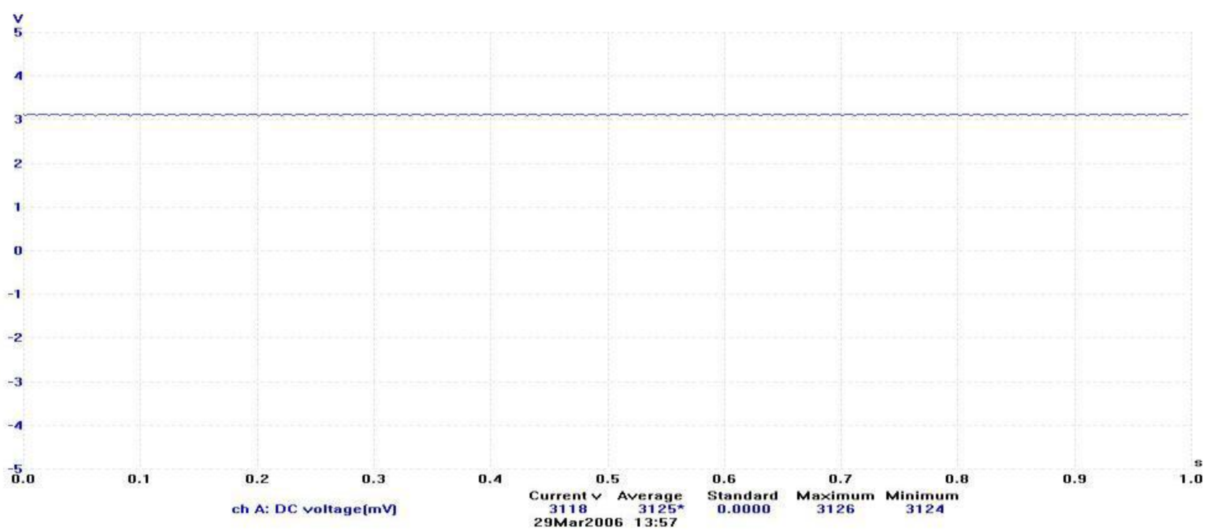
Energy resources	Base Capacity
Lead acid battery	12V
PV Solar cell	5V
PEM fuel cell	3V



4(a)



4(b)

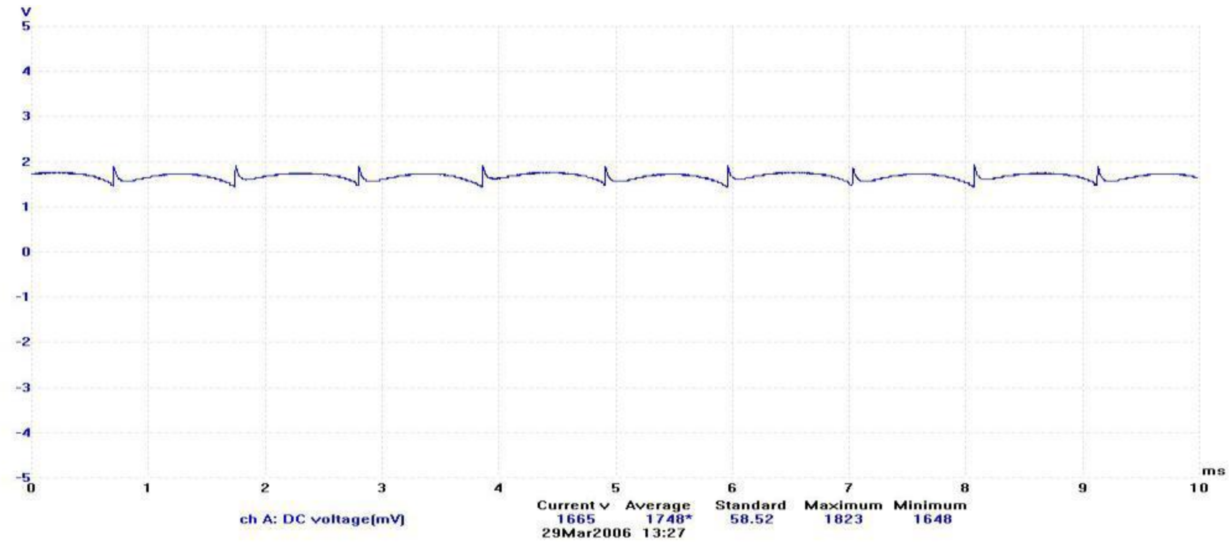


4(c)

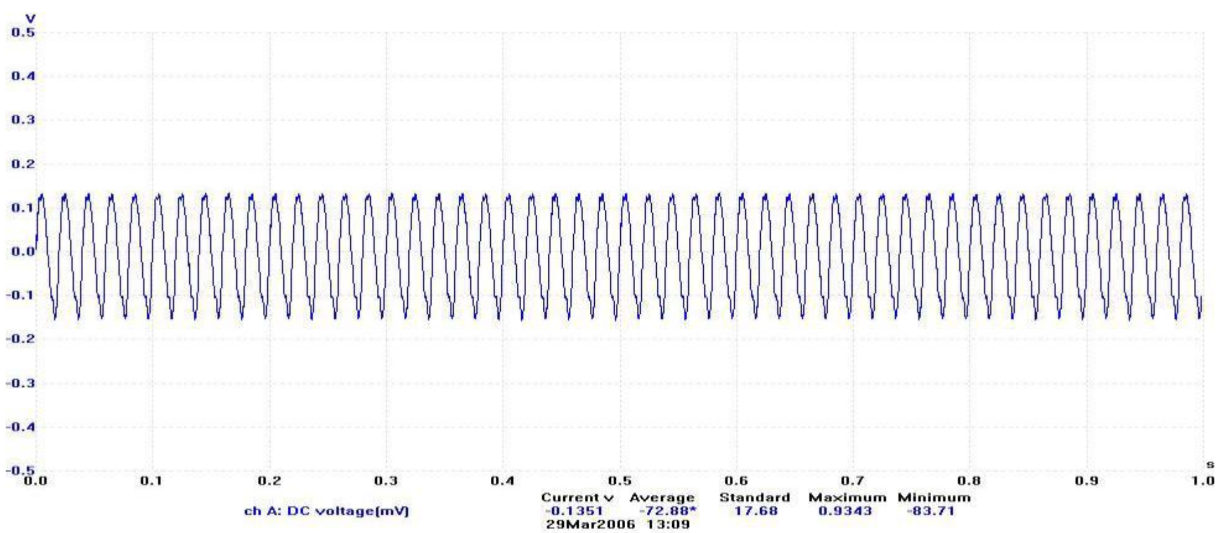
Figure 4. Pico-oscilloscope screen output showing the performance characteristic of (a) lead acid battery (with load). (b) PEM fuel cell (without load). (c) PV Solar cell (without load).

3.3 Standalone power source with load study

Figure 5 shows the performance characteristic of the individual lead acid battery, PEM fuel cell and PV Solar cell with load motor, respectively. Signal from the lead acid battery (Figure 5(a)) is shown displaying different in pattern from the other two sources. Also, the cycle distance of the lead acid battery's sinusoidal waves is more than the other two sources. As a result, lead acid battery could enable cold start (immediate start up without warming) operation while PEM fuel cell and PV solar cell are still in the stage of warming up [10,12].



5(a)



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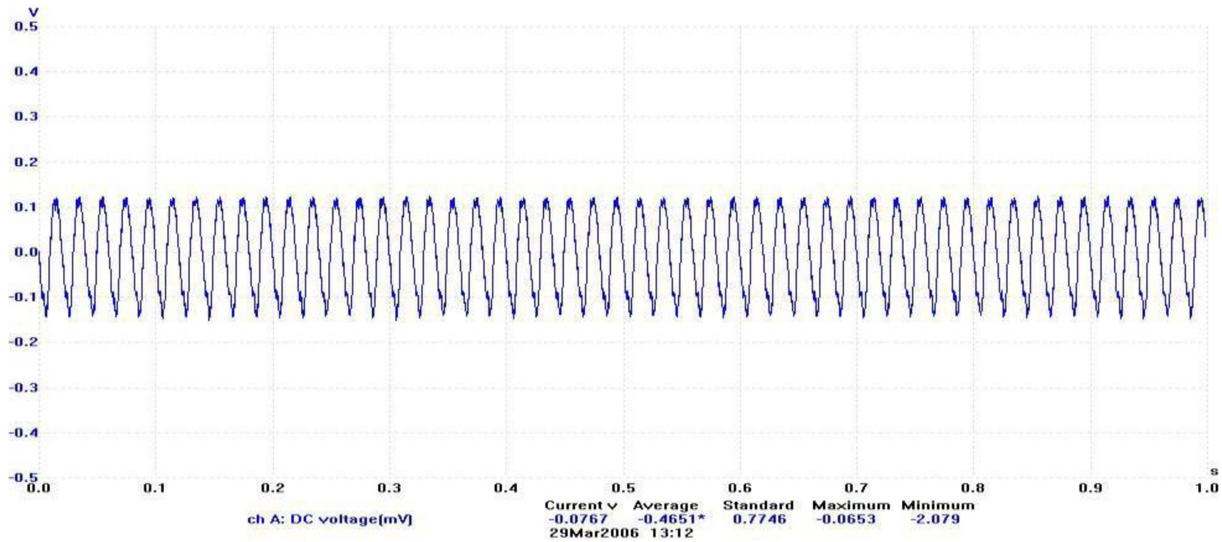


5(c)

Figure 5. Pico-oscilloscope output showing the performance characteristic of (a) lead acid battery (b) PEM fuel cell; and (c) PV Solar cell, with load motor.

3.4 Hybrid dual power source system characteristics

Figures 6(a) and 6(b) are the performance characteristic of hybrid solar-PEM fuel cell without and with load motor, respectively. The PV solar cell and PEM fuel cell are combined in series so that the d.c voltage can be increased. The pattern of the hybrid PV Solar cell/PEM fuel cell without load motor is almost same to individual PV Solar cell power system but the magnitude of voltage is higher. The pattern of this hybrid cells with load motor (Figure 6(b)) is similar to lead acid battery alone with load motor (Figure 5(a)); suggesting that the hybrid PV Solar cell-PEM fuel cell is almost equal to the lead acid battery alone. As a result, the combined sources can enable the cold start operation with applied load.

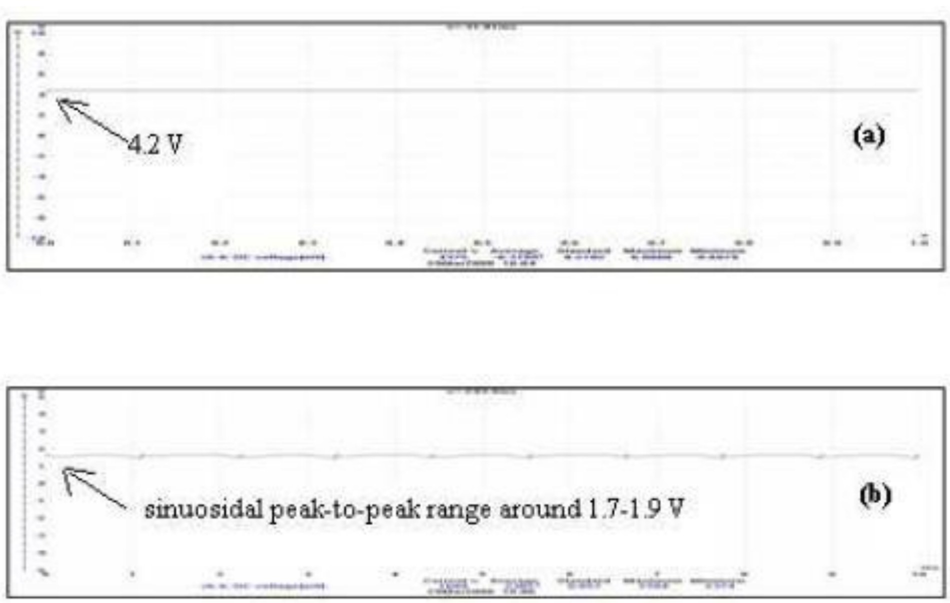


Figure 6. Pico-oscilloscope screen output showing performance characteristic of (a) Hybrid PV solar cell-PEM fuel cell without load (b) Hybrid PV solar cell-PEM fuel cell with load.

Figures 7(a) and 7(b) illustrate the performance of the hybrid PV Solar cell-lead acid battery without and with load motor, respectively. The pattern of PV Solar-lead acid battery without motor (Figure 7(a)) is almost similar to individual cell but exhibit an increment of d.c voltage because of series combination. Figure 7(b) shows the hybrid

PV Solar cell/lead acid battery with load motor, the pattern of which is much different from the other two hybrid systems. This indicates that solar cell is a relatively slow start up cell; whereas lead acid battery is a relative fast start up cell. However, when lead acid battery is combined with solar cell, the hybrid evolves to become a combined relatively fast start up hybrid cell, enable cold start operation in shorter period compared with both the hybrid PV Solar cell-lead acid battery and the lead acid battery alone.

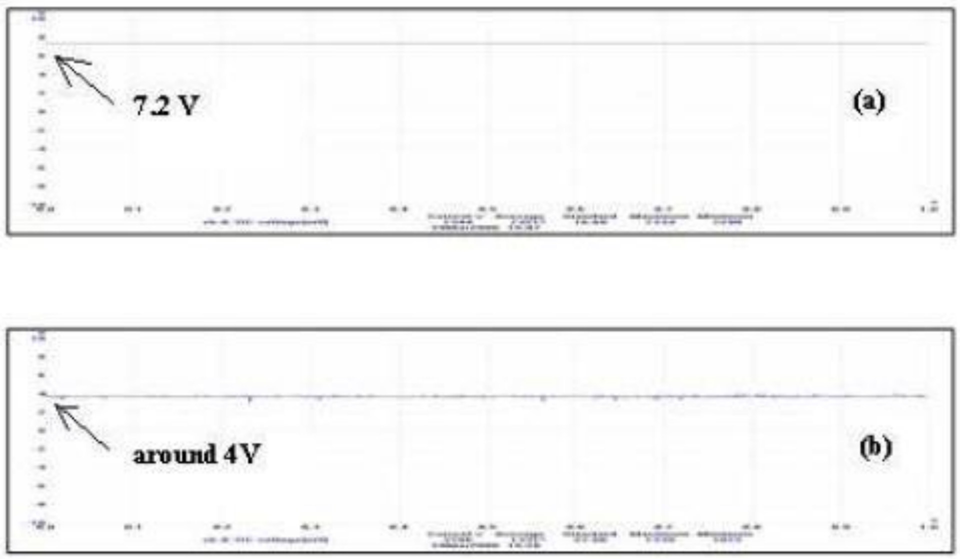


Figure 7. Pico-oscilloscope screen output showing performance characteristic of (a) Hybrid PV solar cell- lead acid battery without load (b) Hybrid PV solar cell-PEM fuel cell with load.

The hybrid PEM fuel cell- lead acid battery system, without and with load motor, is given in Figure 8(a) and Figure 8(b), respectively . The hybrid PEM fuel cell- lead acid bat ery system is quite similar to isolated cell performance and the above two just mentioned hybrid cells. In addition, the pattern of hybrid PEM fuel cell-lead acid battery (Figure 8(b)) is a bit similar to hybrid PV solar cell-PEM fuel cell (Figure 7(b)); they differ mainly only in the distance of sinusoidal wave. The distance of sinusoidal wave at Figure 8(b) is about half of chart of Figure 7(b), which means that hybrid PEM fuel cell-lead acid battery enable cold start operation faster than hybrid solar cell-lead acid battery. In other words, PEM fuel cell can enable cold start operation faster than PV solar cell, as far as present hybrid systems used are concerned.

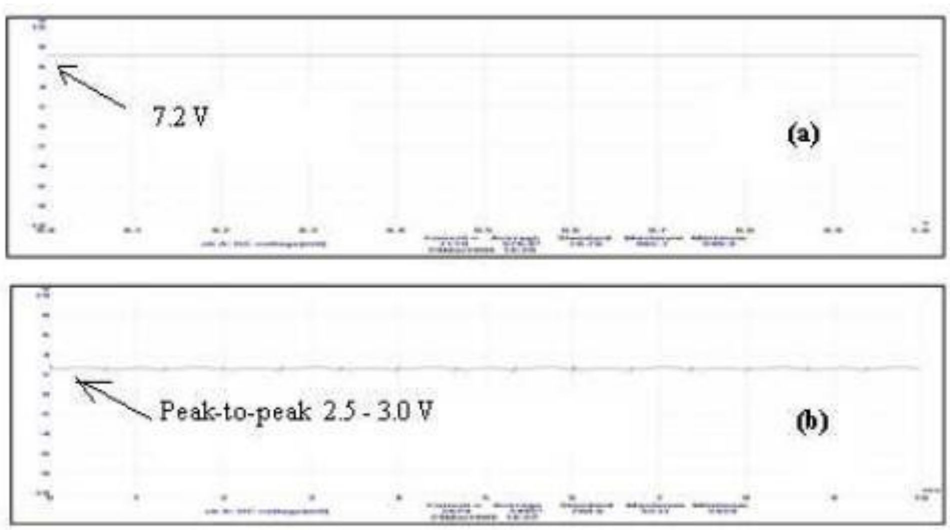


Figure 8. Pico-oscilloscope screen output showing performance characteristic of (a) Hybrid PEM fuel cell - lead acid battery without load (b) Hybrid PEM fuel cell- lead acid battery with load.

3.5 Hybrid triple power sources system characteristics

The performances characteristics of the hybrid triple power sources, viz. PV Solar-PEM fuel cell-Lead acid battery, without and with, load motor are presented in Figures 9(a) and 9(b), respectively. Both tests are conducted without H_2 and O_2 storage. Figure 9(a) shows the maximum d.c voltage with the combination of three power sources in series, after the cells have been discharging for approximately 10 minutes. Therefore, it shows only at around 6V d.c voltage. The pattern is almost the same as individual power source and combination of two power sources. The pattern of hybrid triple power sources with load motor (Figure 9(b)) is similar to hybrid PEM fuel cell- lead acid battery pattern as shown in Figure 8(b). In summary, the results obtained show that a combined PV solar-PEM fuel cell to that of lead acid battery, increases the d.c voltage thus obtained although there have not much effect or improvement on the cold start operation.

Figure 10(a) shows the voltage versus time of hybrid PV solar-PEM fuel cell- lead acid battery with the portable application as it supplies to the multipurpose emergency kit, with full loading (supplying two mini fluorescence lights, a radio and a fan with total maximum nominal capacity = 2.73 W). The plot in Fig. 10a clearly shows that the hybrid system could sustain a maximum voltage of around 7V for about 40 minutes (without battery, H_2 and O_2 storage), as far as the current study is concerned. The voltage drops to half in value (around 4.5V) thereafter, two minutes before it comes to flat in profile.

Figure 10(b) shows the current versus time plot of the hybrid PV solar-PEM fuel cell-lead acid battery with portable application (without H_2 and O_2 storage). The figure shows the constant current at around 0.39A for 25 minutes. Then, it drops to 0.38A until it reaches 35 minutes. The next 5 minutes is the measured current at around 0.37A and then it drops to 0.25A at 42 minutes.

The power versus time behavior of this hybrid system is presented in Figure 10(c). The starting power generation of this hybrid system with portable application is around 2.73W. It is maintaining until 25 minutes and thereafter drops to 2.66W. After running for another 10 minutes, the power reduces to 2.59W. And, it finally it becomes 1.25W at 42 minutes.

It is to be noted that the experiments mentioned above are conducted essentially to simulate difficult situations, i.e., when limited energy is available. When continuous supply of H_2 and O_2 storage, or solar is (are) available, once the system reaches steady-state operation, the power output is essentially constant throughout.

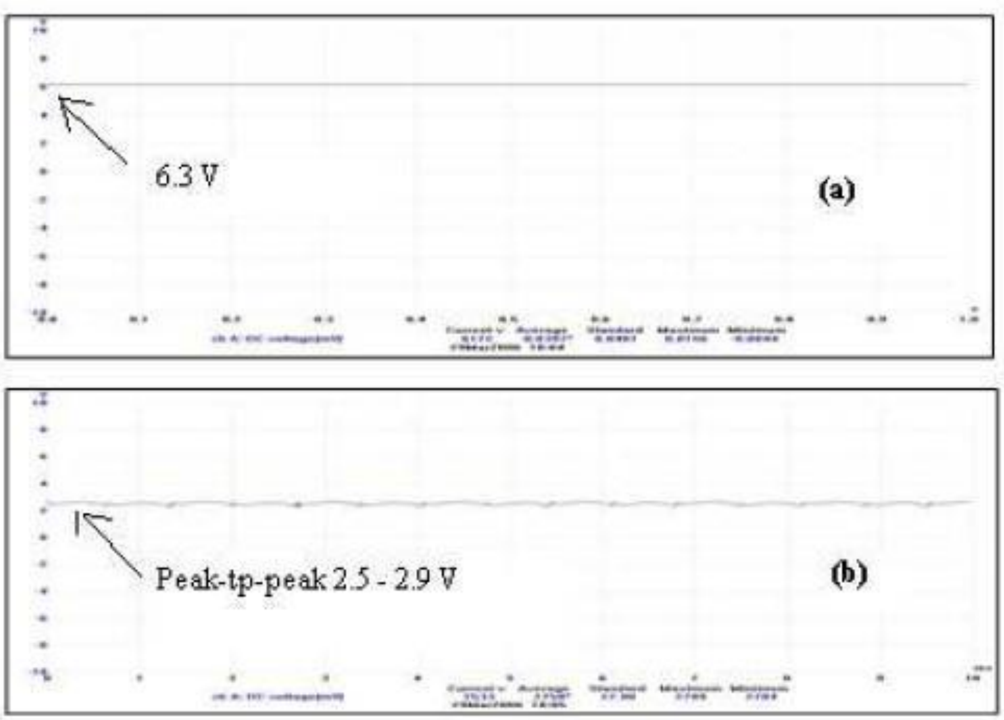
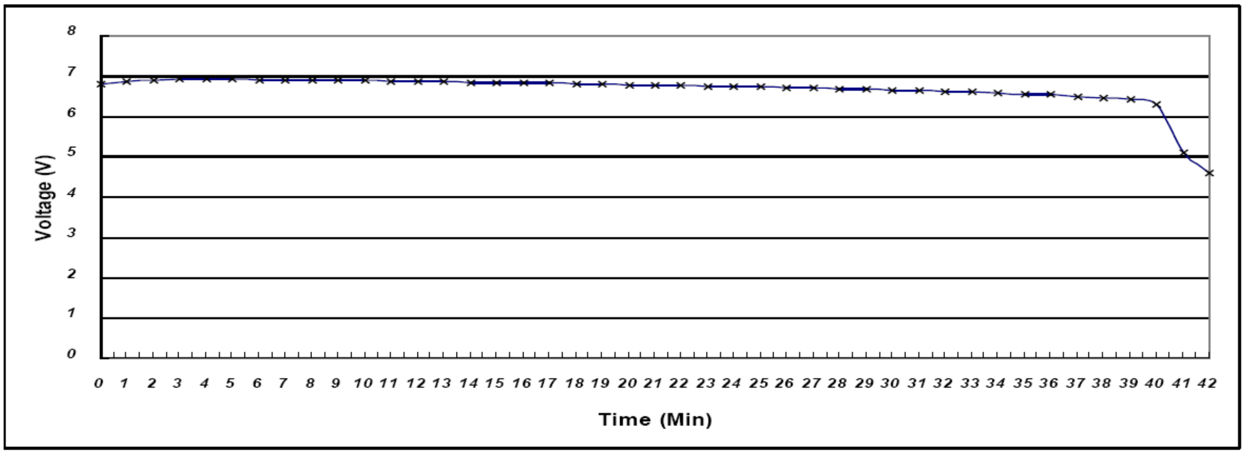
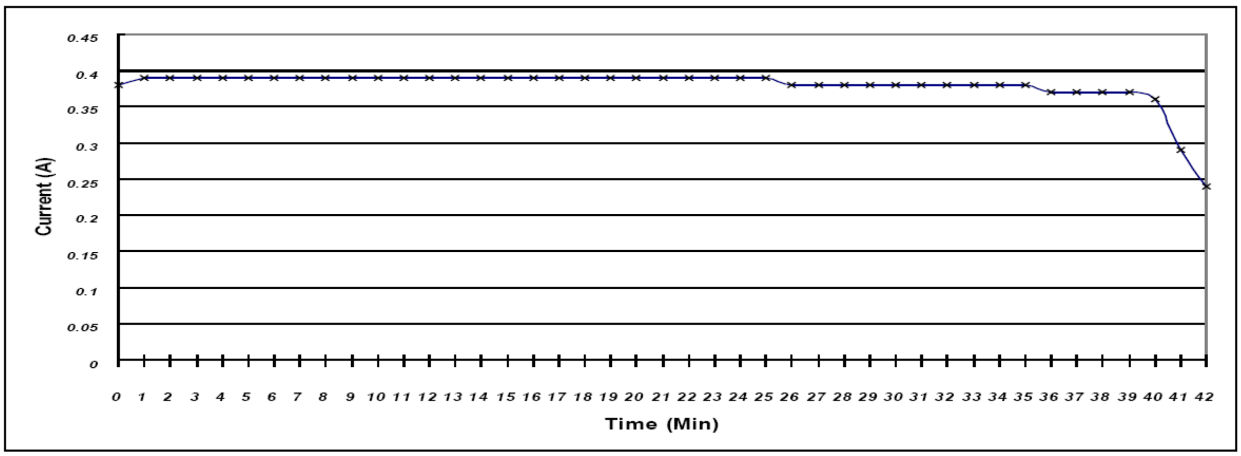


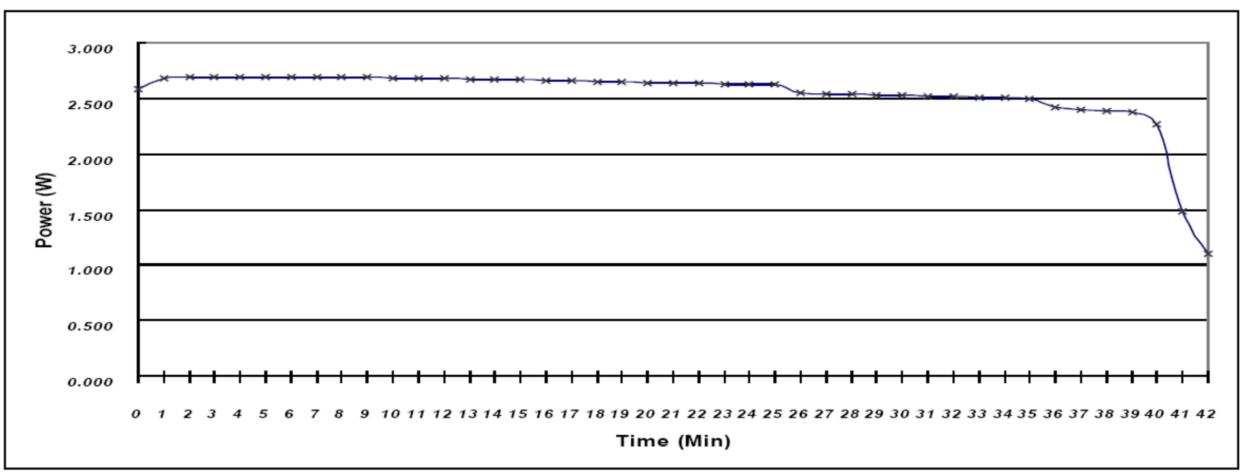
Figure 9. Pico-oscilloscope screen output showing performance characteristic of (a) Hybrid three power sources without load (b) Hybrid three power sources with load



10(a)



10(b)



10(c)

Figure 10. Pico-oscilloscope screen output showing prototype performance characteristic (a)Voltage versus time plot of the hybrid triple power sources with load (b) Current versus time plot of hybrid three power sources with load (c) Power versus time plot of hybrid three power sources with load.

4. RESULTS SUMMARY

Figure 11 summarizes results of the present study in various plots i.e. voltage versus current density, voltage versus current, power versus current density and power versus current of the hybrid fuel cell – battery – PV solar cell. The plot of voltage versus current density was found to exhibit similar pattern to the study reported on a hybrid PV/ PEM fuel cell without the use of battery, but slight voltage rise was reported with elapsed time [8]. Thus the voltage stability of the present study has the advantages for multipurpose and small power applications. The plot of power versus current of the present study was found to show same pattern to a study on a hybrid 40W DMFC Fuel cell/ battery system [9]. Nevertheless the power obtained and the associated device sizing reported in ref [9] is too big or exceeding in power necessary for the present study intended application.

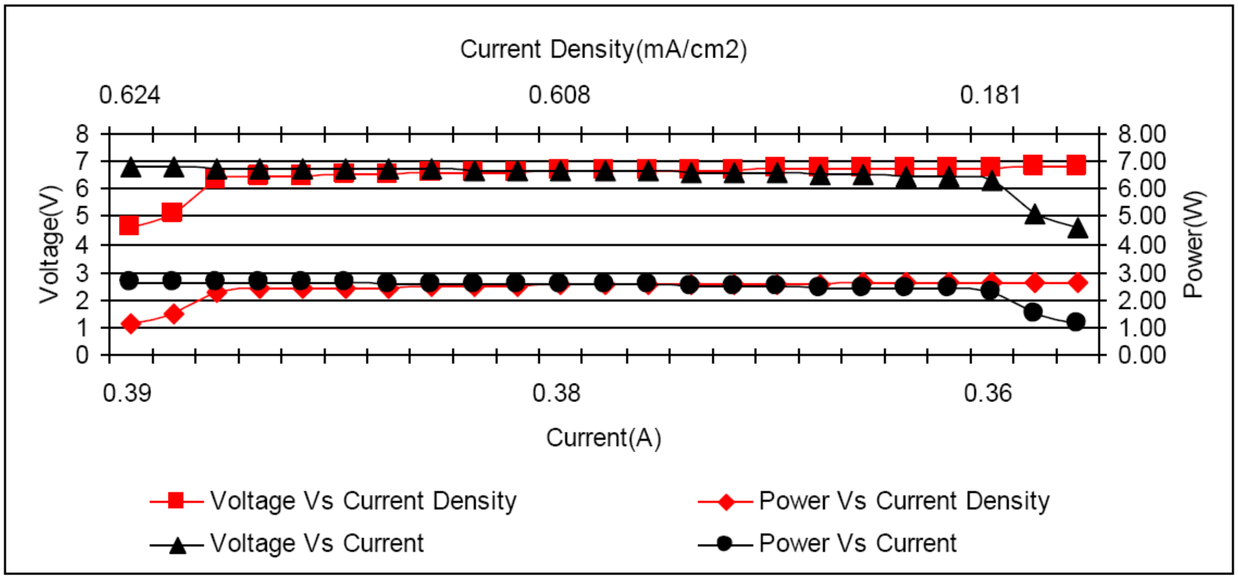


Figure11. Overall result summary

For small portable power applications especially for use at rural areas, remote from conventional electric grids, the present system has shown encouraging performance characteristics such as acceptable size, low weight and it exhibits stable voltage, as well as having acceptable cold start characteristics (Table 4).

Table 4. System Characteristics

System characteristics requirement for a portable multipurpose hybrid power system	The Prototype (HPSMEK) system characteristics
1. Overall system must be as small as possible i.e. compact	Acceptable size for portable application. Overall size: ~ 24cm x 37 x 9cm
2. Overall system must be low weight	Light weight ~ 1.12 kg (including casing).
3. The system must exhibit stable voltage At No load:	Stable system voltage characteristics (can be further improved)
4. The system must have good cold start characteristics and durable in application.	System have good cold start characteristics

To sum up, it had proven that the multipurpose emergency kit constructed herein is essentially able to power by the triple hybrid power system for an extended period of 42 minutes (without H_2 and O_2 storage or that of solar and battery). The current study also shows that various power sources (triple power sources) i.e. solar cell, battery and PEM fuel cells could be combined together to obtain higher power voltage, whilst maintaining their individual advantages. Other influencing parameters, such as operating temperature and pressure, which may affect the performance of the system however, is not studied in the present study.

5. SUMMARYAND RECOMMENDATION FOR FUTURE STUDY

In this study, it had experimentally proven that the multipurpose emergency kit (HPSMEK) designed and constructed herein is able to power by the triple hybrid power system. With available of energy resources, the prototype could work continuously as long as there is a continuous supply of the resources. The current study also shows that various power sources (triple power sources) i.e. solar cell, battery and PEM fuel cells could be combined together, coupled with suitable DC-DC converter and voltage regulator, to obtain higher power voltage, whilst maintaining their individual advantages. The performance of the present system could be further improved such as in lowering the overall weight, and betterment of battery managment; however, it has almost reached a practical state. As future work, we also would like to apply Artificial Intelligent (AI) techniques, i.e., fuzzy controller, neural network and genetic algorithms, to our developed system to further improve the overall performance and for system optimization.

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