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A Predictive Approach to Optimize a HHO Generator Coupled with Solar PV as a Standalone System

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Abstract: Production of hydrogen by means of renewable energy sources is a way to eliminate dependency of the system on the electric grid. This study is based on a technique involving coupling of an oxyhydrogen (HHO) electrolyzer with solar PV to produce clean HHO gas as a fuel. One of objectives of this study was to develop a strategy to make the electrolyzer independent of other energy sources and work as a standalone system based on solar PV only. A DC-DC buck convertor is used with an algorithm that can track the maximum power and can be fed to the electrolyzer by PV while addressing its intermittency. The electrolyzer is considered to be an electrical load that is connected to solar PV by means of a DC-DC converter. An algorithm is designed for this DC-DC converter that allows maximization and control of power transferred from solar PV to the electrolyzer to produce the maximum HHO gas. This convertor is also responsible for operating the electrolyzer in its optimum operating region to avoid overheating. The DC-DC converter has been tested under simulated indoor conditions and uncontrolled outdoor conditions. Analysis of this DC-DC convertor based on maximum power tracking algorithm showed 94% efficiency.

Keywords: electrolyzer; solar PV; convertor; HHO

1. Introduction

Demand of energy is peaking day-by-day relative to the available traditional fossil based resources [1,2]. Furthermore, the huge consumption of fossil fuels results not only in decreasing reserves but also increasing greenhouse gases [3,4]. While the ability to produce renewable electricity has achieved considerable technological maturity and dramatically lower costs in the past decade, it is now imperative to focus attention on reliable energy storage, transportation and deep de-carbonization of hard to electrify industrial sectors. Green fuels and their means of production are always a fascination for researchers to overcome both energy and environmental issues. On-demand HHO gas is considered as one of the alternative green fuel options. The HHO gas can be cost effectively generated and consumed on-demand in various engineering and combustion applications [5,6].

Various studies have proved the blending HHO with other fuels is an efficient and cost effective way to reduce the carbon footprint and improve the thermal efficiency of

combustion-related applications [7–13]. Combustion engines in particular show promising results towards increased efficiency of brake power and brake thermal by 5 and 7%, respectively, while reducing HC, NO_x and smoke by 88, 94 and 18% respectively. HHO gas can be used as a fuel to power catalytic boilers, gas powered heat pumps and direct flame combustion boilers that are more-or-less the same as natural gas boilers. A large variety of district heating techniques can be redesigned so they can use oxyhydrogen as fuel. HHO gas is not limited for use in combustion engines and industrial applications. It can also be used for house heating purposes. It is a beneficial substitute during thermal coating processes. It can be an alternative of plasma gas or can be mixed as an additive gas during thermal spray processes for depositing metallic or nonmetallic materials in a molten or semi-molten condition [14].

HHO gas has generally been produced by using an electrolyzer which is essentially a stack of multiple positive and negative plates so arranged to produce hydrogen at the cathode and oxygen at the anode when a direct current (DC) has been applied. No separator is used generally in between the cathode and anode to avoid separator-related resistive losses. Production is directly proportional to current as given in Equation (1):

$$V = [a_0 + a_1 T + b \cdot \ln(T) - (r_0/T)I]N_s \quad (1)$$

Here, V is voltage of cell which is normally kept as 2 Volt DC for electrolysis, I represents the current, T represents temperature, a_0 , a_1 , and b are electrolysis parameters which are determined experimentally depending on the type of electrolysis, r_0 is the initial resistance of the electrolyzer and N_s are number of cells. Also it was seen that in reality electrolyzer work as a non-linear load (resistance) [15] and will extract more current from the source during the period it remains turned on. This nonlinear behavior is dependent on the pressure, temperature and chemical structure of the solution which leads to a rise in temperature [16,17]. Studies shows that the optimal range of temperature for the electrolyzer is less than 70 °C [13].

Research is underway to use PV for energizing different applications like water pumps [18,19]. Direct coupling of PV with an application is always a challenge due to its intermittent nature. Recently, attempts have been made to directly couple electrolyzers (HHO generators) with solar PV due to the drive towards green energy and to minimize battery-related costs for on-demand HHO generation for various combustion-related applications [20]. Various studies have suggested pulse width modulation (PWM) as a useful technique for this purpose [21–25]. PWM is a control technique that helps to regulate the input current of electrolyzer by setting its duty cycle and frequency. The duty cycle of a PWM signal is defined as the ratio of “on” times over the full signal period [26,27]. By adjusting the duty cycle of the PWM, the input current can be regulated accordingly so that it can control the current of the electrolyzer. This PWM adjusts the operating voltage on the PV array I-V curve to keep its maximum power point and convert that power into voltage and current according to the requirements of the electrolyzer. A recent study concluded that electronic coupling of a PV by mean of an optimizer can increase the efficiency 5% more than other strategies [28], but the exact efficiency of electronic coupling over direct coupling of PV and electrolyzer is dependent on different parameters such as their I-V behavior, selection of PV, geographic location and scale.

The DC-DC buck convertor has also been used for efficiently connecting electrolyzers with a DC bus bar. Different topologies of DC-DC convertors were considered based on the conversion ratio [29–32]. Convertors with high conversion ratio have been deemed beneficial for electrolyzer applications due to their use of very low DC voltages compared to the high DC bus voltage [33]. The conversion ratio is not only an important parameter in designing of the convertor for electrolyzer applications. Some requirements should be taken in consideration which include: (1) the output current ripple that must be as small as possible in order to optimize the electrolyzer lifespan [34], (2) energy efficiency [35], and (3) cost [36]. Based on all these factors, the classic DC-DC buck convertor is the most mature and used topology to couple an electrolyzer with a DC bus bar

In this article a DC-DC converter has been designed to directly couple the HHO electrolyzer with solar PV. The prior performance has been investigated under simulated indoor and uncontrolled outdoor conditions. Furthermore, an attempt has been made to measure and adjust necessary parameters using specially designed solar simulator.

2. Design & Technique

The system was comprised of three main parts: (i) PV, (ii) converter, (iii) electrolyzer (model: 12 V, 30 plate, supplied by: greenfuelh2o, Orem, UT, USA, <https://www.greenfuelh2o.com/> accessed on 31 September 2021). As per the objective of the study, the electrolyzer has been directly coupled with solar PV. The converter is responsible for delivering the maximum available power from the PV to electrolyzer by keeping it in the operating region.

2.1. Experimental Setup

In this study a prefabricated electrolyzer has been used. This electrolyzer was coupled with solar PV by using an electronic converter. A complete schematic diagram of the system is shown in Figure 1. A 30% KOH solution has been used as an electrolyte which is fed to the electrolyzer from a container by means of gravity. A schematic diagram of internal architecture of the electrolyzer and the installed setup is presented in Figure 2a,b. Detailed specifications of the solar PV system are given in Table 1.

Figure 1. Schematic diagram of PV electrolysis.

Figure 2. (a) Configuration layout of the electrolyzer under test; (b) electrolyzer test rig.

Table 1. Specifications of the solar PV system under test.

Parameter	Value
Maximum Power	300 W
Voltage at $P_{\max}$	33 V
Current at $P_{\max}$	9.1 A
Short-circuit current I_{sc}	9.8 A
Open-circuit voltage V_{oc}	38.7 V

An electrolyzer as shown in Figure 2a,b was used with 30 plates of SS316 in such a configuration that they form six stacks comprising six cells each. From the literature it was established that the cells required from 1.8–2.2 volts [37] which depends upon the reversible thermodynamic decomposition voltage, anode over-potential, cathode over-potential and the inter-electrode Ohmic drop. The characteristic size itself is dependent on the cell configuration (such as cell and electrode geometry) and operational parameters (such as current density, electrolyte flow conditions, temperature and pressure). As the electrolyzer under investigation is comprised of six cells in each stack so it required between 11 volts to 13.2 volts for efficient working.

2.1.1. Indoor Setup

A simulated laboratory environment was used as shown in Figure 3.

Figure 3. Test rig for testing the PV-ELE system, coupled with a DC-DC convertor.

For irradiance on the solar PV system, 160 DECOSTAR halogen lamps (with UV filter, colour temperature 2950 K, Osram, Munich, Germany) of 50 Watts each were used. A HT SOLAR02 Remote Unit along with a HT HT304N reference cell (HT Italia srl, Via della Boaria, Italy) was used to monitor the irradiance level on the PV. Different irradiance levels were set by changing the light intensity of the bulbs.

2.1.2. Outdoor Setup

To test the system in a real environment, the whole setup was tested and investigated for four hours under Sun irradiance, as shown in Figure 4. The PV panel was exposed to the Sun and the working of the convertor and electrolyzer was continuously monitored to examine the real time performance of the converter.

Figure 4. Outdoor setup for real time testing of PV-EIE system.

2.2. Buck-Convertor Design

A classic buck convertor with a predictive control technique has been introduced in this study, to operate the electrolyzer in an optimum operating range by means of solar PV. This operating region is based on the design characteristics of the electrolyzer (as discussed in Section 3). A brief summary of the parameters of the electrolyzer in its operating region is shown in Table 2.

Table 2. Operating parameters of electrolyzer.

Parameter	Value
Voltage	10.8–13.2 Volts
Current	15 Amps
Optimum temperature	60 °C

The electrical characteristics of the buck converter (V_s , I_s Equations (2) and (3)) are related to those of the PV (V_{PV} , I_{PV}) according to the duty cycle of the signal which controls the converter:

$$V_s = DV_{pv} \quad (2)$$

$$I_s = \frac{I_{pv}}{D} \quad (3)$$

For developing this buck convertor, Arduino-nano is used as controller. This controller is responsible for reading and monitoring vital parameters like current, voltages and temperature. Upon looking at these parameters the controller will generate a pulse width modulation accordingly. The frequency of the controller is set to be 31 kHz. This PWM is

than feed to a MOSFET (IRF 4115, International Rectifier IR, El Segundo, CA, USA) with the help of a current driver (IR 2110, International Rectifier IR, El Segundo, CA, USA). A schematic diagram of the convertor is shown in Figure 5. Solar PV systems have non-linear behavior due to their intermittency because of the change in irradiance and temperature on the PV array, so this convertor is also responsible for tracking the maximum current that can be fed from the PV. In this way the electrolyzer can utilize the maximum power available from solar energy within its operating region (shown in Table 2). It also monitors the temperature of the electrolyzer and control the current in order to maintain the temperature of the electrolyzer to optimize HHO production so that it does not affect the quality of the HHO gas produced.

Figure 5. Schematic diagram of DC-DC convertor.

2.3. Control Strategy

When a traditional control is used for a buck-convertor by adjusting duty for achieving the required voltages and current, the convertor decreases the efficiency of the system. This happens because control of the convertor adjusts the duty of the convertor not only by keeping it in the operating region, but the intermittency of the PV was not taken into account. Therefore, an advanced strategy was used to track the maximum point of power that can be available from the PV by keeping the electrolyzer in its operating region while keeping the non-linear behavior (due to intermittency) of PV.

Normally for MPPT strategies of solar PV, monitoring of the parameters is done for PV in order to track the maximum power obtained from it. As the current system is a standalone and the electrolyzer is expected to work in its operating region as mentioned in Table 2, so this strategy was implemented in the electrolyzer by monitoring its parameters (current and voltage). This was done because the electrolyzer is required to run on the maximum available current (if under electrolyzer limitation of current) regulated by the operating voltage. Another reason to implement a control technique on the electrolyzer, because the electrolyzer itself is a non-linear load, so it is important to monitor the electrolyzer parameters in order to run it for maximum production of HHO gas. This control technique is represented in the flowchart shown in Figure 6.

For maximum power point tracking of the system a predictive approach was used. In this control technique, instant temperature and voltage is measured and kept in the operating range as mentioned earlier in Table 2. As the voltage is to be kept constant for working of the electrolyzer the current is to be taken into account for tracking the maximum power algorithm of the control measures instant operating current of the electrolyzer and compare it with last measured current. If the current is increased by the perturbation, then the current is kept changing by increasing of duty in the same direction. Otherwise the direction of perturbation is changed by decreasing the duty. As an increase or decrease of

duty cycle are dependent upon the limitations of the electrolyzer as well as the PV the step size remains constant throughout the algorithm. In this way by applying the algorithm on the load (electrolyzer) side, the maximum available power from PV can be tracked by keeping the electrolyzer in its optimum operating region.

Figure 6. Flowchart for the control strategy for the convertor.

3. Results

To determine the characteristics of the electrolyzer as well as PV, IV testing was performed to see the working behavior of the PV and electrolyzer. The IV curves of the solar PV and electrolyzer based on the tests, are shown in Figure 7a,b, respectively. From Figure 7b we can easily analyze the operating parameters of the electrolyzer.

To see the working of the electrolyzer coupled with the solar PV, the test rig shown in Figure 3 was allowed to run under different irradiance levels. Data of voltage, current and power for the PV and electrolyzer were recorded as seen in in Figure 8 by using an oscilloscope. Voltages and current for both PV and electrolyzer at different irradiances can be seen in (i) part of all figures in Figure 8. In the (ii) part of all figures of Figure 8, it

can be seen that electrolyzer power is following the power that is delivered from PV due to DC-DC converter. The system was allowed to run for an equal time interval for each irradiance until steady state was reached. Further data was analyzed and is summarized in Table 3. Power for the PV and electrolyzer was analyzed for the steady state by using a weighted moving average. This was used to calculate the efficiency of the converter and its working for tracking maximum power point. Although at 200 W/m^2 of irradiance, mathematically the converter was working at 89% but the system was actually not working, hence resulting in 0% yield of the HHO. This is because at this low level of irradiance the electrolyzer was not working in its operating region, so no HHO production occurred.

Figure 7. (a) IV curve for the solar PV under test; (b) IV curve for the electrolyzer under test.

Figure 8. Cont.

b. Irradiance at 1000 W/m² **c. Irradiance at 800 W/m²** **d. Irradiance at 600 W/m²**

Figure 8. Cont.

Figure 8. Voltage and current of the PV and electrolyzer monitored on oscilloscope and power was being calculated for each at different irradiance level: (a) 1200 W/m²; (b) 1000 W/m²; (c) 800 W/m²; (d) 600 W/m²; (e) 400 W/m²; (f) 200 W/m².

Table 3. Summary of the analysis of the convertor and PV-ELE based on different irradiance levels.

Irradiance (W/m ²)	PV Power (W)	Electrolyzer Power (W)	Efficiency of Converter (η_c)	HHO Production (LPM)	STH Efficiency (η_{STH})
1200	235.5	222	94.4%	0.885	12.60%
1000	195.5	185.6	94.9%	0.800	11.47%
800	146.1	140.6	96.2%	0.620	10.88%
600	105.7	101.2	95.7%	0.440	10.59%
400	67.57	64.23	95.0%	0.300	10.10%
200	32.88	29.37	89.3%	0.000	00.00%

From Figure 8 it was observed that the convertor was tracking the maximum power available from the PV to electrolyzer by keeping the electrolyzer in its operating region. As the irradiance was decreased the power output was lowered, which eventually lowered the power of electrolyzer and as a result decreased the production of HHO. For the overall efficiency, that is solar to hydrogen (STH) for this system, the total hydrogen production in moles and the size and design of the electrolyzer are required. As in this case the HHO production is dependent on the current and voltage of electrolyzer which is dependent

on its design (internal resistance, electrolyte, overpotential), the equation for STH can be written as follows:

$$STH = \frac{I_{Ele} \times V_{Ele}}{A_{pv} \times \rho_{sol}} \eta_{sys} \quad (4)$$

Here, I_{Ele} and V_{Ele} are the current and voltage of the electrolyzer that are required to split water, A_{pv} is the area of the solar PV system and ρ_{sol} is the irradiance in W/m^2 , while η_{sys} includes the efficiency of the panel, efficiency of the convertor and efficiency of the electrolyzer. For this instant values of the current and voltage of the electrolyzer were recorded as the outcome of all these efficiencies.

It is also seen from Table 3 that the maximum efficiency of the convertor is available when the solar PV is working in the electrolyzer operating range. Furthermore, IV-curves and power curves were analyzed to see the behavior of the working of the electrolyzer with the solar PV. Power curves and IV-curves were drawn in Figure 9 by keeping in view the actual data of the PV and the duty of the convertor at the respective irradiance in order to correlate the analysis with the electrolyzer curves. From Figure 9 it is more clearly seen that the convertor kept the electrolyzer to its operating region while tracking the maximum power of the PV. In all (i) parts of Figure 9, maximum point of power is tracked for a particular irradiance while keeping the electrolyzer in operating mode. On the other (ii) part of all figures in Figure 9, IV curve is drawn while displaying maximum operating point for electrolyzer. It can also further have determined from Figure 9, that control strategy for the convertor is not analyzing maximum power point of PV (in Figure 9, tracked power point is not on the tip of curve for this system as happens in case for traditional MPPTs) as it is dependent on operating region of electrolyzer as shown in Table 2. So it is determining the maximum operating point of electrolyzer from available PV power.

Figure 9. Cont.

Figure 9. Cont.

Figure 9. VI and Power curves of Solar PV and Electrolyzer under test: (a) 1200 W/m²; (b) 1000 W/m²; (c) 800 W/m²; (d) 600 W/m²; (e) 400 W/m²; (f) 200 W/m².

After 200 W/m² of irradiance, the PV system was unable to provide enough power for keep the electrolyzer working in its operating region. Although at this level of irradiance, the DC-DC converter tries to keep the electrolyzer operating, the electrolyzer does not operate (Figure 9f(i)) shows that less than 10.7 Volts are available for electrolyzer).

To see the effect of changing irradiance on runtime and tracking of maximum power, the test rig was allowed to run for 20 min while the irradiance was changed by changing the intensity of the bulbs. The intensity was thus gradually changed from 1200 W/m² to 200 W/m². This tracking power can be analyzed from Figure 10.

Figure 10. Voltage (left) and current (right) power; measured for PV and Electrolyzer in a 30mins continuous test (results from the indoor test rig). The shaded region shows the non-operating region of the electrolyzer.

From Figure 9 it can be seen that after a certain irradiance (in the experiment it was below 200 W/m²) the PV panel is not able to provide enough power for the electrolyzer to be in the operating region (the non-operating region is shown by shading). The same can be seen for higher irradiance, even though at 1200 W/m² more power was available for the electrolyzer and the converter was keeping the electrolyzer in its region of operation (i.e. 10.8–13.2 Volts and 15 Amps).

It was investigated that at lower irradiance, the converter was working at high duty regardless of the power of the PV in order to maintain the operating range of the voltages for the electrolyzer to work. At low irradiance, V_{pv} becomes so low that even at high duty, V_{ELE} does not remain in the operating range. This can be mathematically seen by using Equation (2). In this non-operating region the duty of the converter was fully increased up to 90%. This situation makes it difficult and very slow for the converter to reduce the duty

when the irradiance is again high after a low irradiance period. This is because of the slow response nature of the alkaline electrolyzer. This means that lower duty is more beneficial for the efficiency of the PV-ELE system.

Finally, a test of four hours under Sun irradiance was performed to see the behavior of the convertor and electrolyzer due to intermittency. The power of the PV system was recorded for each interval of time depending upon the intermittent nature of solar irradiance along with the power delivered to the electrolyzer due to convertor keeping the electrolyzer in its operating region. From Figure 11, it can be seen that the convertor is tracking and delivering the maximum power available in the PV system by keeping itself in the operating region of the electrolyzer. It was also concluded that at some instants not enough power is available from the PV system to energize the electrolyzer so in that instance the electrolyzer is not in its operating region and hence no HHO is produced.

Figure 11. Delivery of the maximum available power from PV to the electrolyzer by tracking the power while keeping the electrolyzer in its operating region (4 h under actual Sun irradiance).

4. Conclusions

This study helped determine an approach to use solar energy independently to power an electrolyzer with PV. It was seen that it is important to operate the electrolyzer in its operating region. The strategy of the convertor that was used in this study was successfully established with 94% efficiency by considering two objectives: (i) working of the electrolyzer in its operating region, (ii) delivering the maximum available power of the PV system to the electrolyzer directly by tracking the maximum power of the PV. It was seen that this strategy works in achieving these objectives. It was further explored that due to the slow response nature of alkaline electrolyzers it makes the convertor slow while the tracking power is in a high intermittency situation as it increases the duty to a high level. It was established that duty of the DC-DC convertor plays a crucial role for the system. It was further recommended that increasing in number of PV panels can help in lowering the optimized duty necessary for tracking the maximum power during high intermittency periods by keeping the electrolyzer in its operating region. Another solution is to use a hybrid system which include a battery to account for this intermittency effect.

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Data Availability Statement: The prepared samples to support the findings of this study are available from the corresponding authors upon reasonable request.

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References

- Manieniyar, V.; Thambidurai, M.; Selvakumar, R. Study on energy crisis and the future of fossil fuels. *Proc. SHEE* **2009**, *10*, 2234–2689.
- Fayaz, H.; Ahmad, M.S.; Pandey, A.; Abd Rahim, N.; Tyagi, V. A Novel nanodiamond/Zinc nanocomposite as potential counter electrode for flexible dye sensitized solar cell. *Sol. Energy* **2020**, *197*, 1–5. [\[CrossRef\]](#)
- Höök, M.; Tang, X. Depletion of fossil fuels and anthropogenic climate change—A review. *Energy Policy* **2013**, *52*, 797–809. [\[CrossRef\]](#)
- Watany, M. Variability in vehicle exhaust emissions and fuel consumption in urban driving pattern. *Am. J. Veh. Des.* **2015**, *3*, 31–38.
- Butt, O.M.; Ahmad, M.S.; Che, H.S.; Abd Rahim, N. Design of a small scale fluidized-bed incinerator for MSW with ability to utilize HHO as auxiliary fuel. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1127*, 012040. [\[CrossRef\]](#)
- Butt, O.M.; Ahmad, M.S.; Che, H.S.; Rahim, N.A. Usage of on-demand oxyhydrogen gas as clean/renewable fuel for combustion applications: A review. *Int. J. Green Energy* **2021**, *18*, 1–25. [\[CrossRef\]](#)
- Uludamar, E.; Tosun, E.; Tüccar, G.; Yıldızhan, Ş.; Çalık, A.; Yıldırım, S.; Serin, H.; Özcanlı, M. Evaluation of vibration characteristics of a hydroxyl (HHO) gas generator installed diesel engine fuelled with different diesel–biodiesel blends. *Int. J. Hydrogen Energy* **2017**, *42*, 23352–23360. [\[CrossRef\]](#)
- Ozcanli, M.; Akar, M.A.; Calik, A.; Serin, H. Using HHO (Hydroxy) and hydrogen enriched castor oil biodiesel in compression ignition engine. *Int. J. Hydrogen Energy* **2017**, *42*, 23366–23372. [\[CrossRef\]](#)
- Park, K.-H.; Kim, J.-Y.; Kim, C.-J.; Lee, E.-J.; Son, K.; Park, S.-H. The effect of hho gas on the performance of industrial diesel engine using biodiesel blended fuel. *J. Korean Soc. Mar. Eng.* **2011**, *35*, 1022–1027. [\[CrossRef\]](#)
- Thangaraj, S.; Govindan, N. Evaluating combustion, performance and emission characteristics of diesel engine using karanja oil methyl ester biodiesel blends enriched with HHO gas. *Int. J. Hydrogen Energy* **2018**, *43*, 6443–6455. [\[CrossRef\]](#)
- Krishna, V.M. Emissions control and performance evaluation of spark ignition engine with oxy-hydrogen blending. *Int. J. Heat Technol.* **2018**, *36*, 118–124. [\[CrossRef\]](#)
- Sharma, D.; Pathak, D.K.; Chhikara, K. Performance analysis of a four stroke multi-cylinder spark ignition engine powered by a hydroxy gas booster. *J. Aeronaut. Automot. Eng.* **2015**, *2*, 11–15.
- Bhardwaj, S.; Verma, A.S.; Sharma, S.K. Effect of Brown gas on the performance of a four stroke gasoline engine. *Int. J. Emerg. Technol. Adv. Eng.* **2014**, *4*, 300–307.
- Klein, D.J. Thermal Spray Coating Processes Using HHO Gas Generated from an Electrolyzer Generator. U.S. Patent US20080038478A1, 7 May 2008.
- Şahin, M.E.; Okumuş, H.İ.; Aydemir, M.T. Implementation of an electrolysis system with DC/DC synchronous buck converter. *Int. J. Hydrogen Energy* **2014**, *39*, 6802–6812. [\[CrossRef\]](#)
- Sudarmanta, B.; Darsopuspito, S.; Sungkono, D. Application of dry cell HHO gas generator with pulse width modulation on sinjai spark ignition engine performance. *Int. J. Res. Eng. Technol.* **2016**, *5*, 105–112.
- El Kady, M.; Farrag, A.E.F.; Gad, M.; El Soly, A.; Hashish, H.A. Parametric study and experimental investigation of hydroxy (HHO) production using dry cell. *Fuel* **2020**, *282*, 118825. [\[CrossRef\]](#)
- Jegha, A.; Subathra, M.; Kumar, N.M.; Ghosh, A. Optimally Tuned Interleaved Luo Converter for PV Array Fed BLDC Motor Driven Centrifugal Pumps Using Whale Optimization Algorithm—A Resilient Solution for Powering Agricultural Loads. *Electronics* **2020**, *9*, 1445. [\[CrossRef\]](#)
- Ba, A.; Aroudam, E.; Chighali, O.E.; Hamdoun, O.; Mohamed, M.L. Performance optimization of the PV pumping system. *Procedia Manuf.* **2018**, *22*, 788–795. [\[CrossRef\]](#)
- Niaz, H.; Lakouraj, M.M.; Liu, J. Techno-economic feasibility evaluation of a standalone solar-powered alkaline water electrolyzer considering the influence of battery energy storage system: A Korean case study. *Korean J. Chem. Eng.* **2021**, *38*, 1–14. [\[CrossRef\]](#)
- Arat, H.T.; Baltacioglu, M.K.; Özcanlı, M.; Aydın, K. Effect of using Hydroxy–CNG fuel mixtures in a non-modified diesel engine by substitution of diesel fuel. *Int. J. Hydrogen Energy* **2016**, *41*, 8354–8363. [\[CrossRef\]](#)

22. Baltacıoglu, M.K.; Arat, H.T.; Özcanlı, M.; Aydin, K. Experimental comparison of pure hydrogen and HHO (hydroxy) enriched biodiesel (B10) fuel in a commercial diesel engine. *Int. J. Hydrogen Energy* **2016**, *41*, 8347–8353. [\[CrossRef\]](#)
23. Kumar, S.S.; Kumar, K.S. Optimization and Control of Fuel by Producing Brown Gas by HHO Generating Device Controlled by VHDL and Implementing In FPGA. *Int. J. Mech. Eng. Robot. Res.* **2015**, *4*, 154.
24. Kumar, K.P.; Arora, N.S.; Mahesh, M. Development of constant current power system for hho cell operations to reduce fuel consumption. In Proceedings of the 2016 IEEE International Power Electronics and Motion Control Conference (PEMC), Varna, Bulgaria, 25–28 September 2016; pp. 273–279.
25. Worawat, S.-N.; AURASOPON, A. Application of microcontroller for controlling HHO dry cell in small trucks. *Maharakham Int. J. Eng. Technol.* **2015**, *1*, 10–13.
26. Butt, O.M.; Aslam, A.N.; Muazzam, H. DESIGN OF AN AC VOLTAGE STABILIZER BY USING INSULATED GATE BIPOLAR TRANSISTORS. *J. Fac. Eng. Technol.* **2015**, *22*, 45–50.
27. Butt, O.; Ahmed, M. Alternating Current Voltage Stabilizer by Using Pulse Width Modulation. *Int. J. Sci. Eng. Res.* **2014**, *5*, 928–931. Available online: <https://www.ijser.org/paper/Alternating-Current-Voltage-Stabilizer-by-Using-Pulse-Width-Modulation.html> (accessed on 31 September 2021).
28. Sriramagiri, G.M.; Luc, W.; Jiao, F.; Ayers, K.; Dobson, K.D.; Hegedus, S.S. Computation and assessment of solar electrolyzer field performance: Comparing coupling strategies. *Sustain. Energy Fuels* **2019**, *3*, 422–430. [\[CrossRef\]](#)
29. Tabanjat, A.; Becherif, M.; Emziane, M.; Hissel, D.; Ramadan, H.; Mahmah, B. Fuzzy logic-based water heating control methodology for the efficiency enhancement of hybrid PV–PEM electrolyser systems. *Int. J. Hydrogen Energy* **2015**, *40*, 2149–2161. [\[CrossRef\]](#)
30. Özgür, E.; Devrim, Y.; Albostan, A. Modeling and simulation of a hybrid photovoltaic (PV) module-electrolyzer-PEM fuel cell system for micro-cogeneration applications. *Int. J. Hydrogen Energy* **2015**, *40*, 15336–15342. [\[CrossRef\]](#)
31. Becherif, M.; Ramadan, H.; Cabaret, K.; Picard, F.; Simoncini, N.; Béthoux, O. Hydrogen energy storage: New techno-economic emergence solution analysis. *Energy Procedia* **2015**, *74*, 371–380. [\[CrossRef\]](#)
32. Blinov, A.; Andrianovits, A. New DC/DC converter for electrolyser interfacing with stand-alone renewable energy system. *Electr. Control Commun. Eng.* **2012**, *1*, 24–29. [\[CrossRef\]](#)
33. Guilbert, D.; Collura, S.M.; Scipioni, A. DC/DC converter topologies for electrolyzers: State-of-the-art and remaining key issues. *Int. J. Hydrogen Energy* **2017**, *42*, 23966–23985. [\[CrossRef\]](#)
34. Guilbert, D.; N'Diaye, A.; Lubarda, P.; Djerdir, A. Fuel cell lifespan optimization by developing a power switch fault-tolerant control in a floating interleaved boost converter. *Fuel Cells* **2017**, *17*, 196–209. [\[CrossRef\]](#)
35. Garland, N.L. US Department of Energy Fuel Cell Technologies Program. In Proceedings of the 18th World Hydrogen Energy Conference 2010–WHEC 2010 Proceedings Speeches and Plenary Talks, Essen, Germany, 16–20 May 2010.
36. Kolli, A.; Gaillard, A.; De Bernardinis, A.; Bethoux, O.; Hissel, D.; Khatir, Z. A review on DC/DC converter architectures for power fuel cell applications. *Energy Convers. Manag.* **2015**, *105*, 716–730. [\[CrossRef\]](#)
37. Subramani, V.; Basile, A.; Veziroglu, T.N. *Compendium of Hydrogen Energy: Hydrogen Production and Purification*; Woodhead Publishing: Sawston, UK, 2015.