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Modeling and Simulation of Integrated Solar PV/Battery/Hydrogen Hybrid System for Enhanced System

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ABSTRACT

This paper describes an ongoing engineering project and outlines the modeling and simulation of a Hybrid Energy Storage System (HESS) of an electric vehicle using fuel cells and batteries with the aid of MATLAB/Simulink. The key purpose of this research is to develop and demonstrate the hybridization compatibility between both devices to ensure overall system stability and minimize transient effects. At present, researchers have proposed several types of nonhybrid Energy Storage System (ESS) which mostly involves batteries, also referred to as Battery Energy Storage System (BESS). The problem with this conventional system is that the system itself is jeopardizing and not efficient enough to lower the rate of transient, resulting in a longer response time. On that account, the hybridization between two types of sources, which in this case is the fuel cell and battery, is required along with the presence of a network controller. The network controller proposed for the HESS is Artificial Neural Network (ANN) as it is suitable for capturing complex and nonlinear relationships data. In general, this research aims to increase the stability and reliability of the entire system performance.

1. Introduction

Over the course of years, Malaysia, a developing country has displayed an alarming increase in the rate of Greenhouse Gases (GHG) emissions, mainly Carbon Dioxide (CO_2) to the atmosphere [1-3]. As a result, the country was recognised as the leading CO_2 emitter in 2019 [4]. Statistically, transportation such as cars, trains and motorcycles account for one-fifth of the country's primary source of CO_2 emissions [5-8]. The transportation industry is the second-largest contributor to GHG emissions because most forms of transportation rely on fossil fuels such as gasoline or diesel as the primary energy source [4]. On that account, the process of importing and selling Electric Vehicles

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(EVs) which utilize green energy is considered one of the government's initiatives to decrease GHG emissions, promote low-carbon cities and prevent the adverse effects of climate change [9].

Solar energy, a well-known natural resource derived from the sun, naturally promotes the production of green energy [10]. The energy produced is responsible for charging the battery used by EVs whereas the fuel cell acts as a backup energy source [11,12]. The combination of a fuel cell and a lithium-ion battery creates a synergistic effect as both devices work well together [13]. A fuel cell, an energy device responds slower dynamically when there is an instantaneous increment in the load demands. Conversely, in the same situation, a battery, also referred to as an energy storage device can supply a high-power response to the load [14]. The union between these two different devices is commonly named hybrid power system or Hybrid Energy Storage System (HESS) [15]. This form of hybridization will minimize the overall cost of the Energy Storage System (ESS) inside the EVs. The storage system mentioned plays a significant role in supporting the entire charging system in the case of emergencies, where solar energy absorbed by the Photovoltaic (PV) panels during the day is insufficient or inadequate [16]. The ESS will be managed by the Energy Management System (EMS) [17]. On top of that, EMS assists both the fuel cell and battery in delivering the power demanded by the load at any time, increasing the system's life expectancy and efficiency as well as giving the system a better form of protection. Thus, ESS and EMS are equally important for the system because ESS can store excess energy while EMS can optimise the use of energy resources.

The objective of this research is to simulate and implement a smart energy management control strategy for fuel cell and battery hybrid system for the purpose of obtaining a more stable and efficient HESS with a lower transient rate as well as achieving a shorter response time to sudden changes due to the stated phenomena. EMS stability refers to the stability of the DC bus voltage and power under different loads [18]. Ergo, the hybrid power system should incorporate network controllers into the system design for the purpose of achieving a satisfactory level of EMS stability. Generally, unconventional control systems such as Artificial Neural Network (ANN) and fuzzy logic technology provide better results and performances compared to conventional ones, namely Proportional Integral (PI) controller [19]. Although a conventional or traditional approach is still viewed as an acceptable and sensible solution to this type of engineering problem due to its simplicity, a more modern technology is still preferable when the efficiency of the system is being considered [20,21]. ANN is defined as a type of network built based on the human brain's biological neurons that gives precise results compared to fuzzy logic technology [22,23]. Despite the fact that fuzzy logic does not produce a systematic result, this network controller is easier to comprehend [22]. Regardless, the selected network controller will be considered ideal if the controller is able to ensure that all potential combinations of input power from the sources either renewable energy or battery can meet the demand required by the load in real-time, resulting in a more effective hybrid power system [21].

Most existing research has proven the effectiveness of this idea to a certain level. Nevertheless, none of the research found is capable of providing a more accurate and faster forecasting response. One of the research projects discusses the stability analysis of fuel cells and batteries written by Huangfu *et al.,* [24], which illustrates that the output current and DC voltage became stable after a large disturbance but required an unnecessary longer period of time to maintain the stability and solve the transient issue and for this reason, the result was not entirely satisfactory. Nonetheless, both the fuel cell and battery respond smoothly when the load power changes. Thus, despite the unsatisfactory outcome, the operation of the fuel cell is undeniably stable and safe [24].

Another piece of research conducted by different authors, Liu *et al.,* [25] also discusses the stability of the hybridization between a fuel cell and battery for a fuel cell hybrid electric bus. This research utilizes Fuzzy Logic Control (FLC) as the nonlinear adaptive control system. Based on the results analysed, the stability of the system generated was validated as demonstrated using the quadratic Lyapunov function. The research was conducted to differentiate the different effects of using FLC compared to State Machine Control (SMC). By referring to the results of the simulation, the FLC-based system shows a fuel cell power variation rate that is coherently smoother than that of the SMC. The smoother the fuel cell variation rate, the lower the rate of transients and, therefore, the longer the lifespan of the overall system. The only drawback of the research is the lack of implementation of the system in real-time [25].

In addition, research performed by Tephiruk *et al.,* [26] mentions how a HESS is able to increase the efficiency of the renewable energy system performance. The hybridization is performed by combining a BESS and Solid Oxide Fuel Cells (SOFC) by using DIgSILENT PowerFactory software. Based on the results, simulations in transient condition show that BESS acts as a power agent to cope with sudden and rapid load changes whereas the simulation results under steady-state condition show that the SOFC can power the system to cope with fluctuations in renewable energy load or capacity which in turns improve the overall system. However, software such as MATLAB/SIMULINK is more preferable in controlling algorithms compared to DIgSILENT.

To sum it up, although the current system studies by other researchers can certainly meet the load demand and reduce the transient or fluctuating effects, the systems proposed and created by these researchers are not highly efficient. Therefore, one of the solutions to eliminate the problem faced is by generating and improving the algorithm needed by the network controllers. The algorithm will help the controllers to make intelligent-based decisions and is in charge of detecting faults and providing recovery for the controllers. Hence, this paper proposes the technical solution of the Fuel Cell/Battery-based HESS to increase the efficiency and enhance energy production and improve the dynamic stability of the entire system.

2. System Topology

The second section can be further classified into two subsections. The first subsection provides the description of the overall research design, which is illustrated using a block diagram. Next, the simulation model that was created based on the research design excluding the network controller is outlined in the following subsection.

2.1 Research Design

The illustration in Figure 1 outlines the block diagram of the proposed HESS. The solar array is known as the combination of solar panels that is formed through the grouping of solar cells. This solar array will send Direct Current (DC) to the fuel cell and battery via the Maximum Power Point Tracking (MPPT) solar charge controller. The input values obtained from both devices are then transmitted to the DC/DC converter. Subsequently, the DC/DC Converter will regulate the input value by stepping it up before transferring the data to the DC/AC inverter. The function of this inverter is to convert the input which is in DC form to Alternating Current (AC). After a period of time, the converted input data will finally be sent to the load at the end of the whole process. Fuel cells and batteries are similar in terms of the ability of these devices to produce DC inputs. However, one will act as the main energy source while the other will perform as a backup. Moreover, the difference between a conventional HESS and the proposed HESS is that the newly proposed system includes an EMS in its design which is responsible for allowing users to monitor, manage and regulate energy consumption and ensures optimal response to load demand by optimizing the performance of the fuel cell as well as the battery.

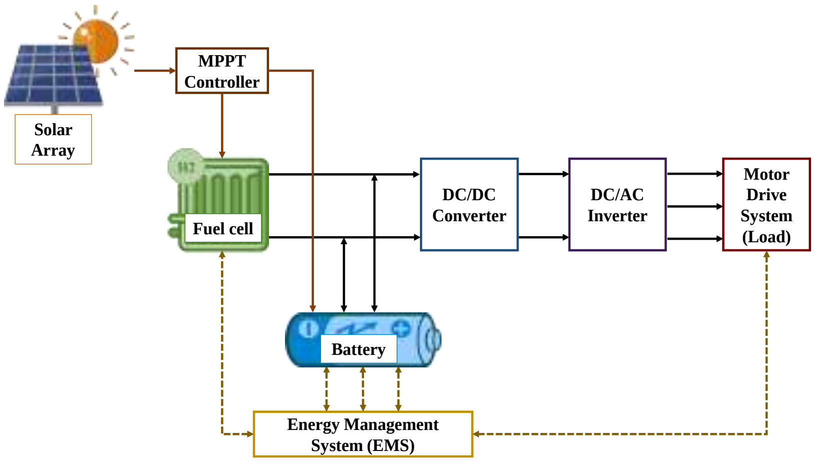

Fig. 1. Block diagram of proposed HESS

2.2 Simulation Model

Figure 2 displays the open loop HESS circuit constructed using Simulink. The circuit includes the solar array, electrolyzer and battery as the main devices as well as scope to view the results of the simulation after being run and tested. There will be four different graphs shown and each graph has distinct parameter readings which comprise voltages of battery and grid, currents of electrolyzer, storage and solar array, percentage of battery charge, and lastly, the mass of hydrogen produced.

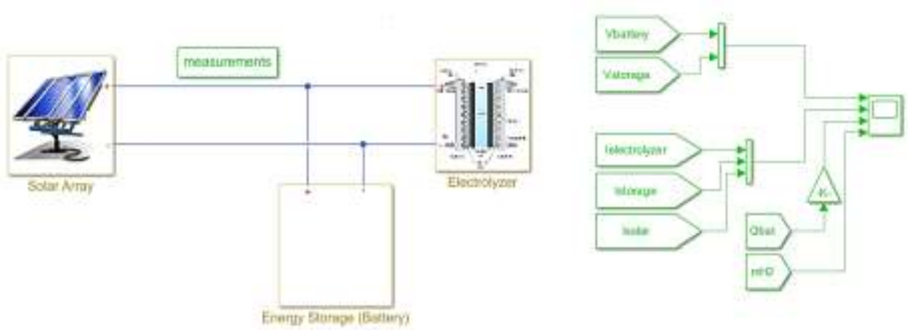

Fig. 2. Open loop HESS cicruit

2.3 Parameters

The parameters for the proposed HESS are tabulated in Table 1. The three main devices to be analysed are the solar cell, battery and hydrogen storage tank.

Table 1
Parameters of proposed HESS

Device	Parameter	Symbol	Values
Solar Cell	Diode saturation current	I_s , I_{s2}	$3.15 \times 10^{-7}\ A$, $0\ A$
	Solar generated current for measurement	I_{ph0}	$3.80\ A$
	Irradiance used for measurements	I_{r0}	$1000\ W/m^2$
	Quality factor	N, N_2	$1.4, 2$
	Series resistance	R_s	$0.00042\ \Omega$
	Parallel resistance	R_p	$10.1\ \Omega$
	Number of series-connected cells per string	N_{series}	700

	Number of parallel-connected strings	$N_{parallel}$	1
	First order temperature coefficient for $\mathrm{I_{ph1}}$	$T_{I_{ph1}}$	$0.000805\ 1/K$
	Energy gap	E_G	$1.14\ eV$
	Temperature exponent for $\mathrm{I_s}$	$TX_{I_{s1}}$	3.38
	Temperature exponent for $\mathrm{I_{s2}}$	$TX_{I_{s2}}$	3
	Measurement temperature	T_{meas}	$25°C$
	Device simulation temperature	T_{FIXED}	$25°C$
Battery	Nominal voltage	U_n	$240\ V$
	Internal resistance	R_s	$0.2\ \Omega$
	Cell capacity (Ampere-Hour (AH) rating)	Q_n	$50000\ hrA$
	Voltage V1 when charge is AH1	U_1	$210\ V$
	Charge AH1 when no-load voltage is V1	Q_1	$25000\ hrA$
Hydrogen Storage Tank	Chamber volume	$Volume$	$1000000\ cm^3$
	Number of ports	Num_{ports}	1
	Cross-sectional area at port A	$Area_A$	$0.01\ m^2$

3. Structural Design of Artificial Neural Network Control Topology

When designing the perfect topology for the ANN, there are several application-related information that will be required. Following this, the number of input as well as output neurons for each layer should be equal to the number of input and output connection control signals for each architecture. Figure 3 shows the suggested design of the ANN controller for the proposed integrated solar PV/Battery/Hydrogen hybrid system.

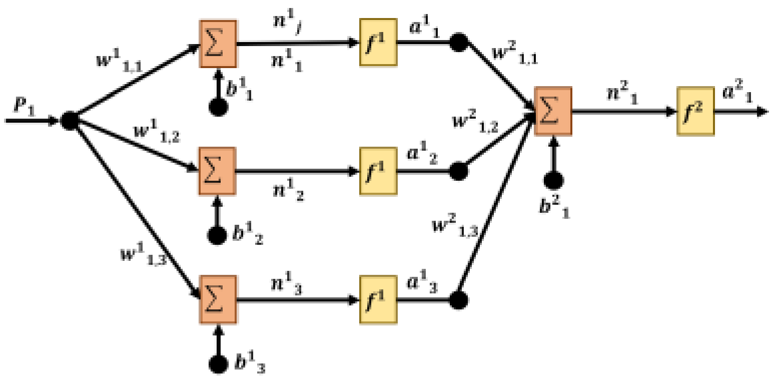

Fig. 3. Structural design of ANN Control Topology

The proposed control network incorporates 1-3-1 neurons as the structural design and this is actually based on the number of neurons available in each layer of the recommended ANN controller structure. The input layer contains neurons with multiple inputs. The input neurons represent error signals resulting from changes between the desired signals and the actual signals.

The connections weight parameter between j_{th} and i_{th} neuron at m_{th} layer is presented by w_{ij}, while bias parameter of this layer at i_{th} neuron is simply written as b_{mi}. The transfer function of the network of *the* neuron in m_{th} layer is given by

$$n_i^m = \sum_{j=1}^{S^{m-1}} w_{ij}^m a_j^{m-1} + b_i^m \tag{1}$$

The neuron output function at m^{th} layer is defined as

$$a_i^m = f^m(n_i^m) \tag{2}$$

where f is noted to as the activation function of the neuron. The activation function for the output layer and the hidden layer are respectively known as a unity and a tangent hyperbolic function in this design. The activation function of the hidden layer is written as

$$f^m(n_i^m) = \frac{2}{1+e^{-2n_i^m}} - 1 \quad (3)$$

The upgraded version of the connection weight and bias parameters are provided below

$$w_{ij}^m(k+1) = w_{ij}^m(k) - \alpha \frac{\partial F(k)}{\partial w_{ij}^m} \quad (4)$$

$$b_i^m(k+1) = b_i^m(k) - \alpha \frac{\partial F(k)}{\partial b_i^m} \quad (5)$$

where k is the sampling time and α is the learning rate. On the other hand, F is referring to the performance index function of the network.

After the process of modeling and designing of the ANN structure, the next step is to update the network parameters, also referred to as the network learning models. The designing and developing procedures of an online learning Back propagation algorithm are carried out. The performance index sum of square error is written as

$$F(k) = \frac{1}{2} \sum_i e_i^2(k) \quad (6)$$

$$e_i(k) = t_i(k) - a_i(k) \quad (7)$$

where t_i is the target signal and a_i is the output signal existed on the last layer.

The gradient descent of the performance index against to the connection weight is presented by

$$\frac{\partial F}{\partial w_{ij}^m} = \frac{\partial F}{\partial n_i^m} \frac{\partial n_i^m}{\partial w_{ij}^m} \quad (8)$$

Next, the sensitivity parameter of the network is given by

$$s_i^m = \frac{\partial F}{\partial n_i^m} \quad (9)$$

$$s_i^m = \frac{\partial F}{\partial a_i^m} \frac{\partial a_i^m}{\partial n_i^m} \quad (10)$$

The gradient of the transfer function to the connection weight parameter is defined as follows

$$\frac{\partial n_i^m}{\partial w_{ij}^m} = a_i^{m-1} \quad (11)$$

Then, substitute equation (9) and (10) into (4). The updating connection parameter is given by

$$w_{ij}^{m-1}(k+1) = w_i^{m-i}(k) - \alpha s_i^m(k) a_i^{m-1}(k) \quad (12)$$

With the same substitution technique, the updating bias parameter is addressed as

$$b_i^{m-1} = (k+1) = b_i^{m-i}(k) - \alpha s_i^m(k) \quad (13)$$

4. Results and Discussion

In Section 4, the results obtained from the open and close loop tests are discussed. Open loop test is referred to as the experimental procedure conducted on a circuit or simulation without the presence of control network whereas close loop test is conducted with the presence of control network. Results are presented from Figure 4 to Figure 11. As mentioned previously, the HESS was constructed and simulated using MATLAB/Simulink and results were analysed based on the various graphs presented inside the scope. Since the results are clear and can be inspected, this means that the hybridization between the fuel cell and battery is successful. The details of these results are discussed and elaborated according to the subtopics written below.

4.1 Voltage of Battery and Grid

First and foremost, Figure 4 shows how the voltages of the battery and grid change over a period of time, specifically after 7 days, which is also equal to $604800\ s$ or $6.05 \times 10^5\ s$. The yellow line represents the battery voltage (Figure 4a) whereas the green line is the grid voltage (Figure 4b). Based on Figure 4a, the maximum value of battery voltage recorded was at $1.18 \times 10^5\ s$ with a value of $235.3\ V$. On the other hand, the minimum voltage recorded for the battery is $215.6\ V$ at $6.02 \times 10^5\ s$. The battery voltage is lower during the first, fourth and seventh days but higher during the second, third, fifth and sixth days. Therefore, the voltage of the battery increases and then decreases tremendously after two intervals and this occurrence depends on the changes or fluctuations in the load. Thus, when the ESS is supplying the power demanded by the load, the voltage will drop and discharging occurs. The same can be said for the grid voltage in Figure 4b. When the load demand is low, the grid voltage rises. However, the changes in grid voltage value remain consistent throughout the simulation as the voltage will increase up to a maximum of 243.6 V daily. Grid instability can also affect the changes in the grid voltage.

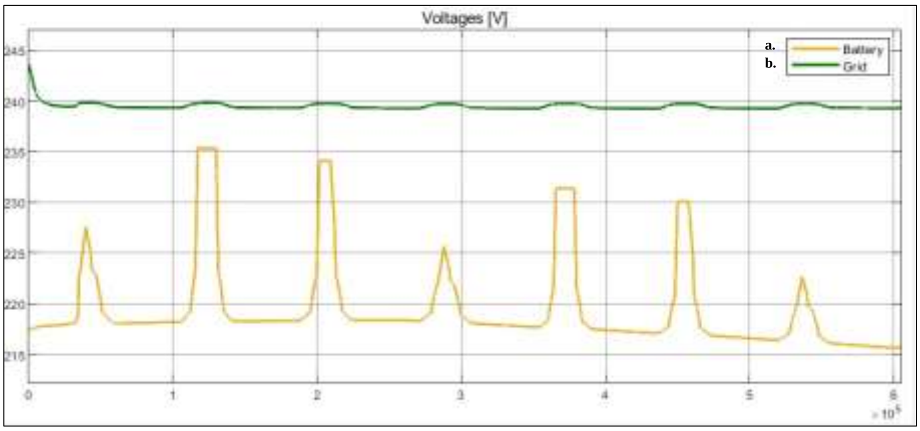

Fig. 4. Voltages of battery and grid

4.2 Current of Electrolyzer, Storage and Solar Array

The currents of the electrolyzer, storage and solar array are illustrated in Figure 5. The purple line characterizes the current of the electrolyzer (Figure 5a) and the blue line represents the current of the storage (Figure 5b). On the other hand, the current of the solar array is portrayed by the orange line (0c). Based on these figures, both the electrolyzer and solar array show an increase in value of the currents when there is demand at the load. The maximum currents for both are $814.2\ A$ at $1.22 \times 10^5\ s$ and $663.0\ A$ at $3.71 \times 10^5\ s$ respectively. Contrarily, the current for the storage drops during power absorption and records the lowest value at $4.58 \times 10^5\ s$ which is $81.6\ A$. The reasons why the currents increase for both the electrolyzer and the solar array but decrease for storage is because, in the case of electrolyzer, the device requires a higher amount of current to produce the desired amount of hydrogen gas during an increase in the power demand. Correspondingly, the solar array also needed to produce electricity. Current is directly proportional to power and due to this, when the power demand increases, the current also increases. However, as for the current of the storage, it depends on the voltage regulation. The higher the load demand, the lower the current as the voltage regulators will try to lower the output current value of the storage to maintain the required voltage.

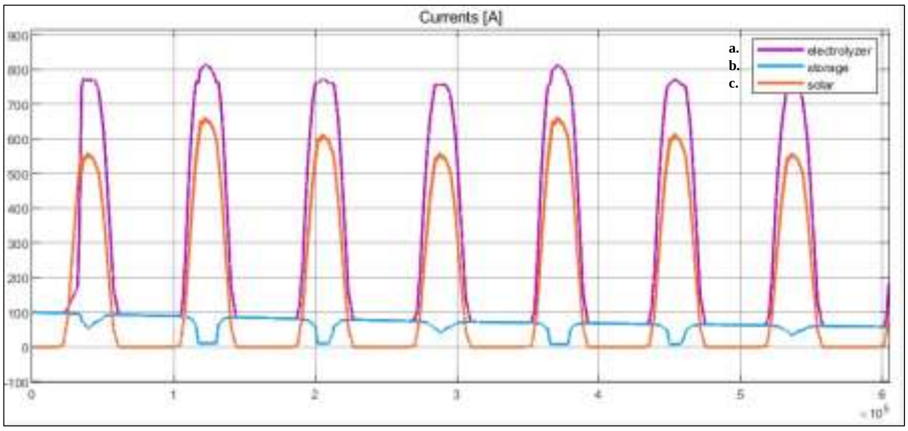

Fig. 5. Currents of electrolyzer, storage and solar array

4.3 Percentage of Battery Charged

Figure 6 displays the percentage of battery charge. At $0.00\ s$, the battery is fully charged at 100% and percentage drops slowly after a week. During the seventh day, which is at $6.05 \times 10^5\ s$, it shows that the battery charge percentage is 74.79%, which means that the percentage drop is only 25.21%. The percentage is dropping over time due to self-discharging as experienced by all types of batteries.

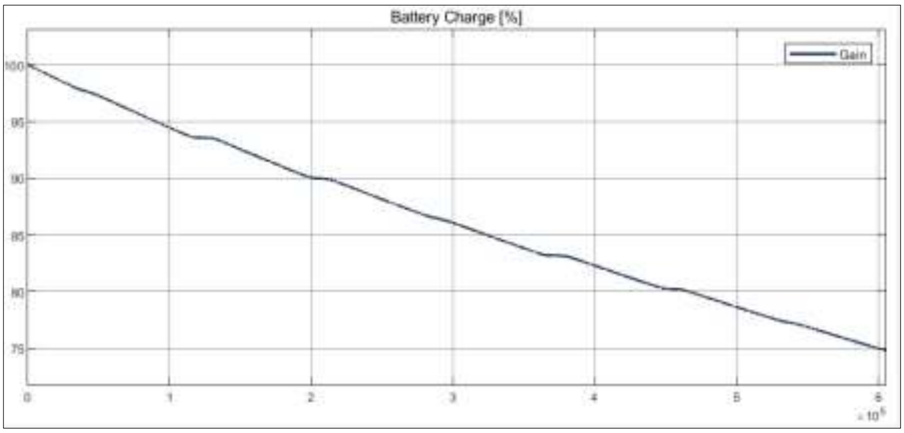

Fig. 6. Percentage of battery charge

4.4 Mass of Hydrogen Produced

The mass of hydrogen produced steadily escalates from $0.00\ s$ to 6.05×10^5 s with the highest value achieved is $89.52\ kg$ as viewed in Figure 7. The electrolyzer operates over a considerably long period of time as shown beforehand in Figure 5a. This causes the electrolyzer to continuously consume water and produce hydrogen gas. The mass of hydrogen produced is directly proportional to the operation time of the electrolyzer, so the longer the electrolyzer is operating, the more hydrogen that will be produced.

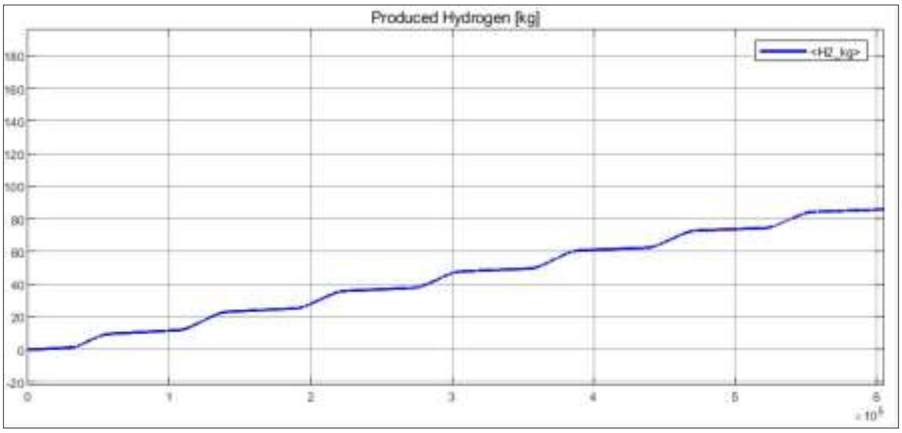

Fig. 7. Mass of hydrogen produced

4.5 Open Loop Voltage Regulation Capability

For the first stage of simulation analysis, the proposed multi-input converter has been tested without controller in steady-state condition. Thus, the converter is being assessed with mismatched input voltage sources. Afterwards, the output voltage regulation capability of the proposed converter is evaluated in order to verify the capability of the proposed converter to regulate the output voltage with different reference values. The simulation results of voltage regulation capability for the proposed converter in open loop circuit are shown in Figure 8.

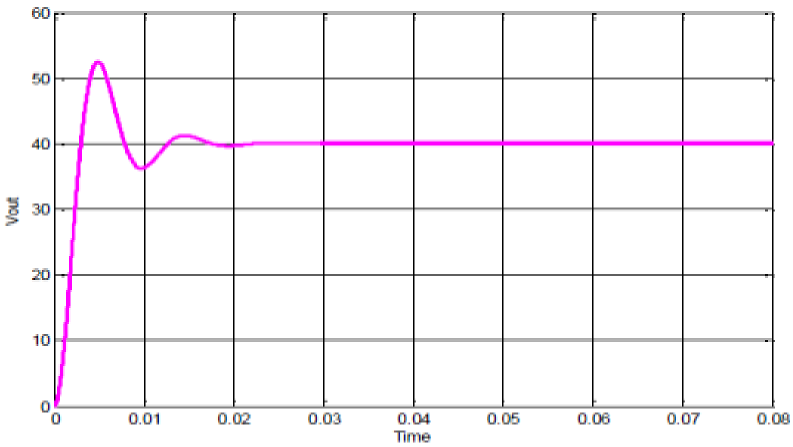

Fig. 8. Voltage regulation capability of the proposed converter when the output voltage is being stepped up to 40V

4.6 Close Loop Dynamic Response

Figure 9 represents the close loop HESS Circuit with ANN control topology. The output voltage regulation capability and output voltage tracking capability are further explained in the following subsections 4.6.1 and *4.6.2.*

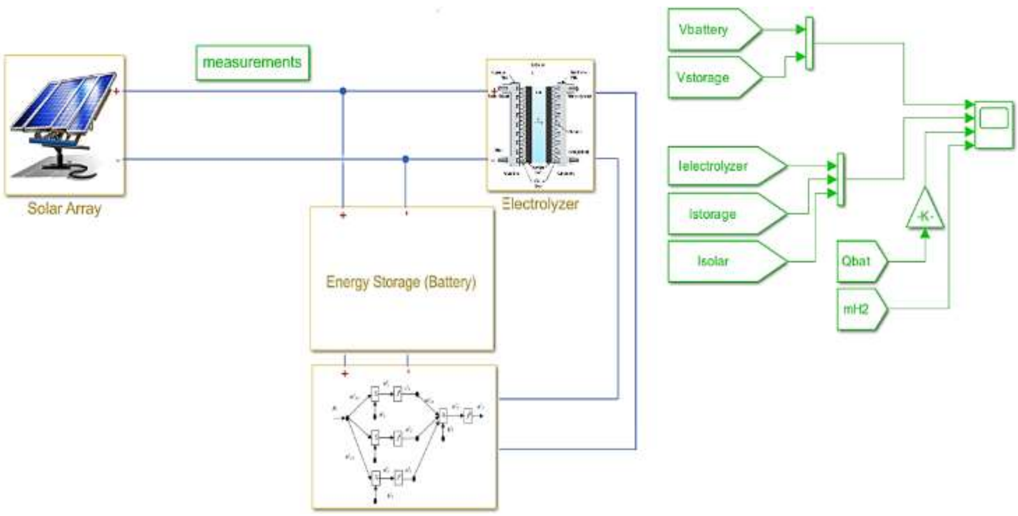

Fig. 9. Close Loop HESS Cicruit with ANN control topology

4.6.1 Output voltage regulation capability

Simulation result in Figure 10 have proved the capability of the proposed controller to regulate output voltage at 40V with shorter setting rise time around 0.06sec and eliminated overshoot.

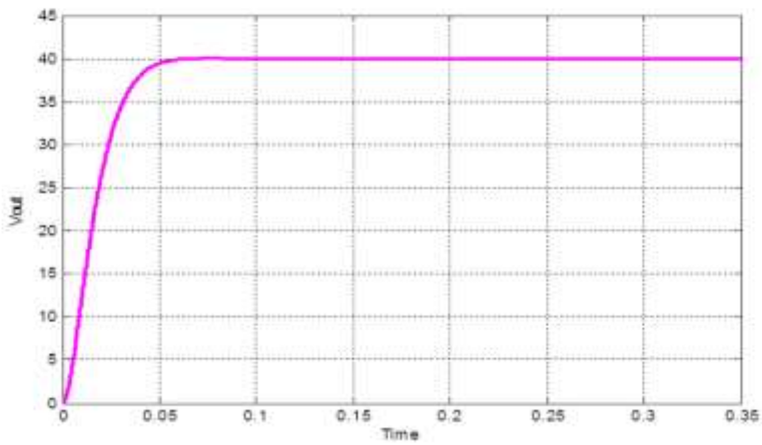

Fig. 10. Voltage regulation capability of the proposed converter with single reference testing when the output voltage is being stepped up from 0V to 40V

4.6.2 Output voltage tracking capability

Simulation result presented in Figure 11 shows the dynamic response of the proposed HESS circuit when the output voltage is being commanded to step up.

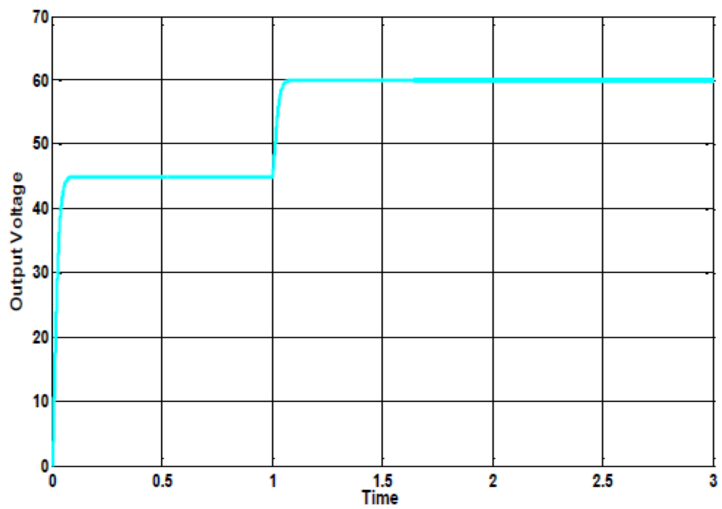

Fig. 11. Dynamic response of the proposed converter when the output voltage is being stepped up from 0V to 45V to 60V

By referring to the same figure, when the output voltage tracking capability was verified, the simulation result shows that the output voltage transient displays an exceedingly small rise time and negligible overshoots.

5. Conclusion

As conclusion, the purpose of this engineering project is to achieve specific results as outlined in the research design. While the project is still yet to be completed, significant progress has been made, and several key findings and insights have emerged. The HESS was constructed and executed using a simulation software referred to as MATLAB/Simulink. There are three main devices that were required in the Simulink design, mainly the electrolyzer, solar array and battery as the energy storage and results could be obtained from the scope. In the final analysis, various types of graphs were shown and able to be examined and explained. The fact that clear and proper results can be attained demonstrates that the fuel cell and battery can be hybridized and operationally combined. From the discussion, the battery and grid voltages are either rising or declining based on the changes at the load.

When the ESS is operating to satisfy the demand, there will be growth in the value of the voltages. Furthermore, the currents of the electrolyzer and solar array are directly proportional to the power demanded by the load while the storage current is inversely proportional to the load demand. The battery which acts as the storage has a self-discharging tendency and eventually causes the percentage of battery charge to decrease over time. Last but not least, the hydrogen produced is dependent on the operation time of the electrolyzer and therefore, the longer the electrolyzer is operating, the more the amount and the heavier the hydrogen produced will be. Thus, a hybrid system can indeed be formed using the combinations of PV, hydrogen and battery. In addition, as the voltage output is being commanded and instructed to step up, the simulation results show a significant difference when the circuit is either open or closed loop. When ANN controller is present and the circuit is closed loop, the rise time is observed to be very low whereas vice versa when the circuit is opened loop. Hence, it is proven that a network controller does help in minimizing transient and avoiding overshoots.

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