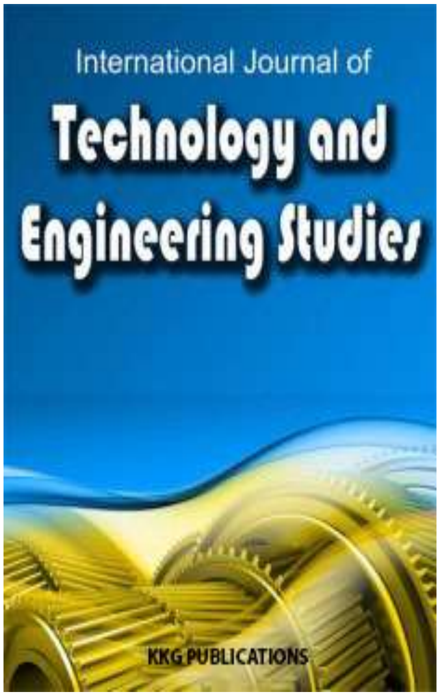


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# MODELLING AND SIMULATION OF HYBRID CONTROL SYSTEMS IN SOLAR CELL-BATTERY-SUPER CAPACITOR

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**Abstract.** Solar cell technology is very suitable to be applied to the power generation system. The dynamics of the slow solar cells must be compensated through hybridization with batteries and / or super capacitors by a DC-DC Converter. Solar cells are also very appropriate to be integrated on renewable energy schemes (Renewable Energy), such as wind turbines, fuel cells and so forth. In this study will be designed on the feedback control method of hybrid solar cells, batteries and super capacitors in which the use of such methods is to regulate the output voltage in accordance with the desired bus is 12 volts by using three sources mentioned above, each of which possessed different physical dynamics. The design of hybrid control includes hybrid systems modeling and design of state feedback control. The results of the control design is tested through simulation and implemented in the real system. The simulation results show that the hybrid control design goes well which produces a voltage output according to the desired bus is 12 Volts in which overshoot the closed loop system by 0.6% compared with the closed loop system by 1.0%.

## INTRODUCTION

In the energy and power systems research, solar cell needs to be designed so as to generate high power and able to deal with high load changes suddenly on the application [1]. Meanwhile, solar cell itself has a slow response to rapid load changes and the resulting power density is not high enough. For that, the solar cell requires other energy sources to improve the response. Additional energy source that is currently considered to be sufficiently effective to meet the above requirements are super capacitors and batteries [2].

Several previous studies, we need a state feedback control system by designing K using inequality LMI (Linear Matrix Inequalities) to regulate the flow of energy between the solar cell that acts as a primary energy source and other components which both as a source of additional energy.
Modeling on the solar cell, battery and super capacitor with each DC/DC converter is done with hybrid modeling before system design state feedback control is done [3], [7].

The purpose of this study is to design of state feedback control system for a hybrid system solar cell, battery and super capacitor and to evaluate of the overall system response to requests by the load power is used.

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## THEORETICAL BACKGROUND

Methodology to be achieved is the study of literature on the modeling of the solar cell, component-power electronics components forming a hybrid power system, and the control feedback. After that, the modeling of the solar cell, the determination of the working mode accompanied by a guard equations and design of feedback control results are validated by simulation using Simulink/MATLAB based HYSDEL (Hybrid System Description Language) [4].

Hybrid system is a combined system of continuous and discrete system consisting of the interaction between continuous dynamics (usually represented by differential equations) and discrete dynamics (represented by automata or Petri network). Hybrid systems commonly found in a variety of applications, especially on devices that use switching and computer algorithms in settings. Historically, the term hybrid system was introduced in 1966 by Witsenhausen [5]. Witsenhausen were studying continuous systems that interact with elements of discrete relay. The system that studied by Witsenhausen is a special case of the hybrid system in general. The method of analysis and control methods in general hybrid systems emerging in the early 80s who pioneered the science community and system control and computer science community who need a new framework in analyzing complex systems.

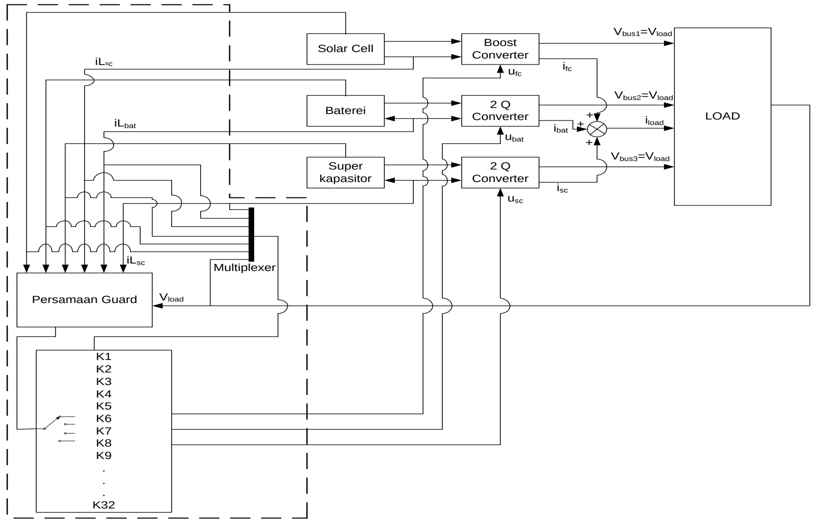


Fig. 1. Topology hybrid system solar cell/battery/super capacitor.

Figure 1 shows the overall topology of the hybrid system in which each component of the energy storage (batteries and super capacitors) has a DC/DC converter 2 quadrants and DC/DC boost converter for solar cell. The voltage on the solar cell, battery, super capacitors and load currents along each converter was installed so that the current and voltage sensors can be identified by the equation Guard which will be explained in section III that the Guard equation determines the mode controller should work[6], [8]. The controller will generate a duty cycle signal u for each converter. Because topology applied is parallel, then the sum of the output current of the third converter will supply the power required by the load. While the bus voltage equal to the output voltage of each converter. Equivalent circuit Solar cells, batteries and super capacitors represent the electrical circuit model that describes the dynamic behavior of cells, in the viewpoint of the electrical terminals with the following models:

$\dot{x} = -487.188x + 4.325\,u$ (1)

$y = -11x + 0.0654\,u$ (2)

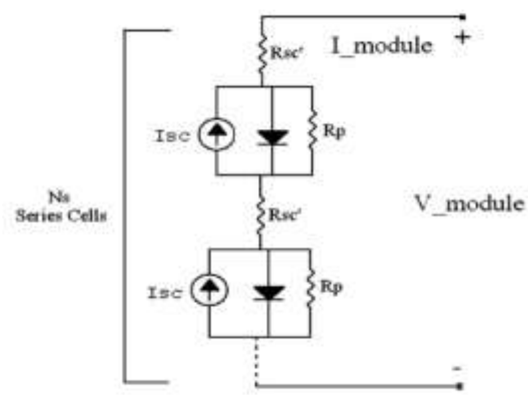


Fig. 2. Equivalent circuit solar cell

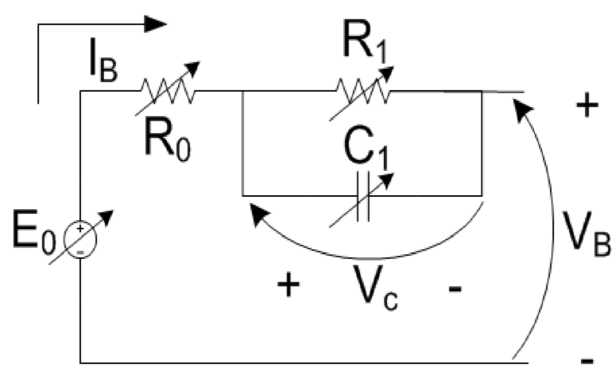


Fig. 3. Equivalent circuit batterie

Schematic of battery equivalent circuit shown in Figure 3 with the following models:

$E_0 - I_B R_0 - V_c - V_B = 0$ (3)

$\dot{V}_c = \frac{1}{C} I_B - \frac{1}{R_1 C_1} V_c$ (4)

While the equivalent circuit super capacitor as follows:

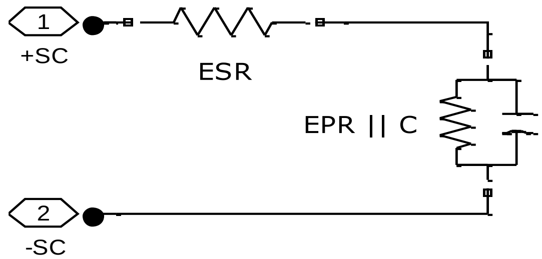


Fig. 4. Equivalent circuit of super capacitor

Working mode of hybrid system fuel cell, battery and supercapacitor stated in the following table.

**TABLE 1**
**REPRESENTATION OF WORKING MODE HYBRID SYSTEM**

| Mode | Switching | | | | | Kondisi | | | |
|---|---|---|---|---|---|---|---|---|---|
| | S1 SC | S1 bat | S2 | S1 | S2 | Charg | Discharge | Charge | Discharge |
| 1 | 0 | 0 | 1 | 0 | 1 | | D | C | |
| 2 | 0 | 1 | 0 | 1 | 0 | | D | C | |
| 3 | 0 | 1 | 0 | 0 | 1 | | D | C | |
| 4 | 0 | 0 | 1 | 1 | 0 | | D | C | |
| 5 | 0 | 0 | 1 | 0 | 1 | C | | | D |
| 6 | 0 | 1 | 0 | 1 | 0 | C | | | D |
| 7 | 0 | 1 | 0 | 0 | 1 | C | | | D |
| 8 | 0 | 0 | 1 | 1 | 0 | C | | | D |
| 9 | 1 | 0 | 1 | 0 | 1 | | D | C | |
| 10 | 1 | 1 | 0 | 1 | 0 | | D | C | |
| 11 | 1 | 1 | 0 | 0 | 1 | | D | C | |
| 12 | 1 | 0 | 1 | 1 | 0 | | D | C | |
| 13 | 1 | 0 | 1 | 0 | 1 | C | | | D |
| 14 | 1 | 1 | 0 | 1 | 0 | C | | | D |
| 15 | 1 | 1 | 0 | 0 | 1 | C | | | D |
| 16 | 1 | 0 | 1 | 1 | 0 | C | | | D |
| 17 | 0 | 0 | 1 | 0 | 1 | C | | C | |
| 18 | 0 | 1 | 0 | 1 | 0 | C | | C | |
| 19 | 0 | 1 | 0 | 0 | 1 | C | | C | |
| 20 | 0 | 0 | 1 | 1 | 0 | C | | C | |
| 21 | 0 | 0 | 1 | 0 | 1 | | D | | D |
| 22 | 0 | 1 | 0 | 1 | 0 | | D | | D |
| 23 | 0 | 1 | 0 | 0 | 1 | | D | | D |
| 24 | 0 | 0 | 1 | 1 | 0 | | D | | D |
| 25 | 1 | 0 | 1 | 0 | 1 | C | | C | |
| 26 | 1 | 1 | 0 | 1 | 0 | C | | C | |
| 27 | 1 | 1 | 0 | 0 | 1 | C | | C | |
| 28 | 1 | 0 | 1 | 1 | 0 | C | | C | |
| 29 | 1 | 0 | 1 | 0 | 1 | | D | | D |
| 30 | 1 | 1 | 0 | 1 | 0 | | D | | D |
| 31 | 1 | 1 | 0 | 0 | 1 | | D | | D |
| 32 | 1 | 0 | 1 | 1 | 0 | | D | | D |

The equivalent circuit in mode 1 is described as follows

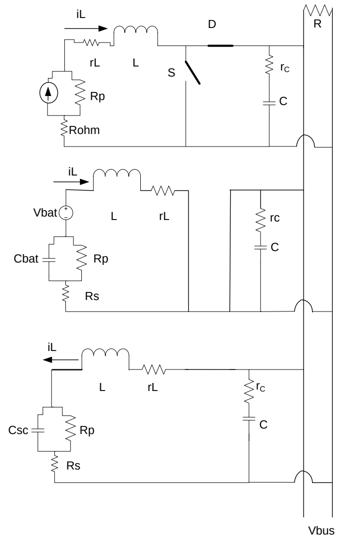


Fig. 5. Equivalent circuit mode 1

The state space equation as follows

$$A_1 = \begin{bmatrix} A_{SC} & B_{SC} & 0 & 0 & 0 & 0 & 0 \\ \frac{C_{SC}}{L} & \frac{D_{SC}-r_L}{L} - \frac{r_L r_c}{(r_L+r_c)L} & 0 & 0 & 0 & 0 & -\frac{r_c}{(r_L+r_c)L} \\ 0 & 0 & -\frac{1}{R_p C} & \frac{1}{C_{bat}} & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{L} & \frac{-R_S-r_L}{L} - \frac{r_L r_c}{(r_L+r_c)L} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{R_p C} & -\frac{1}{C_{sc}} & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{L} & \frac{-R_S-r_L}{L} - \frac{r_L r_c}{(r_L+r_c)L} & 0 \\ 0 & \frac{1}{C} - \frac{r_c}{(R+r_c)C} & 0 & -\frac{r_c}{(R+r_c)C} & 0 & \frac{r_c}{(R+r_c)C} & -\frac{1}{(R+r_c)C} \end{bmatrix}, \quad (5)$$

$$B_1 = \begin{bmatrix} 0 & 0 & 0 \\ \frac{C_{SC}}{L} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \frac{1}{L} & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \frac{1}{L} \\ 0 & 0 & 0 \end{bmatrix}, C_1 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

and derived by equation modeling

$i_{LSC} = i_{load} + i_{bus}$ (7)

$V_{SC} = V_L + V_{r_L} + V_{rbus} + V_{cbus}$ (8)

$i_{bus} = -i_{load}$ (9)

$V_{bat} = V_C + V_L + V_{r_L}$ (10)

$i_{bus} = i_{load}$ (11)

$V_{sc} = V_L + V_{r_L}$ (12)

Thus obtained 7 states of $x_{(t)}$ with 3 inputs of $u_{(t)}$

$x(t) = [V_{CSC}(t) i_{L_{FC}}(t) V_{Cbat}(t) i_{L_{bat}}(t) V_{Csc}(t) i_{L_{sc}}(t) V_{bus}]^T$
(13)

$u(t) = [Vu_{SC} Vu_{bat} Vu_{sc}]^T$ (14)

$V(x) = x^T P_i x \ \ \forall x \in \mathcal{X}_i$ (14)

Are having regard to Table 1 is based on the work system switching DC/DC converter that happens and it will obtain the equivalent circuits in 31 different mode.

## DESIGN OF FEEDBACK CONTROL

The design of feedback control is to find K (Gain) were stable through quadratic Lyapunov Function. Based on Lyapunov theory presented, the stability asimptotic PWA (Piecewise Affine) discrete-time systems can be checked through a quadratic Lyapunov function (Piecewise Quadratic Stability/PWQ Lyapunov) [9,11].

Relates to conditions that must be met in order for the system is stable asymptotic

$A_j^T P A_j - P < 0$ (15)

$P > 0,\ \forall_i \in I$ (16)

Where, I = {1, ..., n} is the set of states of cells (region) are formed.

To achieve stability in a design of the control of piecewise linear feedback control is expressed as follows

$uk = K_i xk \quad \forall xk \in \mathcal{X}_i$ (17)

Based on the topology in Figure 1 Guard obtained equation that represents the limits of the actual conditions in each mode so that the mode transition to another mode [10]. Having regard to the condition of the state, the equation Guard in mode 1 can be written as follow

$$G(m,1) = \left\{ \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \end{bmatrix} : x_1 \geq 5\,V \ \wedge x_2 \geq 0 \wedge x_3 \geq 6\,V \wedge x_4 \geq 0 \wedge x_5 \leq 7.5\,V \wedge x_7 \leq 12\,V \right\} \quad (18)$$

$$m = (2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32)$$

And the first mode transition toward 31 different modes and vice versa. The transition occurs due to the condition of different modes.

## SIMULATION

Open-loop simulation is shown in Figure 6 where the second 1-50, DC-DC converter at each voltage source is the condition that turns continuously switches and bus voltage is at less than the desired voltage 12 V when the conditions on the mode voltage bus is reduced occurs. However, there is a fairly common overshoot and output ripple voltage plant showed. Largest overshoot is 1.0 % occurred in the 14-18 second range in which it occurs when the mode with the condition of the bus voltage is greater 12 V. The bus voltage ripple occurs in the range of 5-15 seconds which shows the bus voltage drop during the process of charging the battery and super capacitors. In the 18-20 second range and the range of 40-45 seconds in the bus voltage is 12 V battery and super capacitor voltage which exceeds the nominal voltage of the solar cell so that it can help to supply the load.

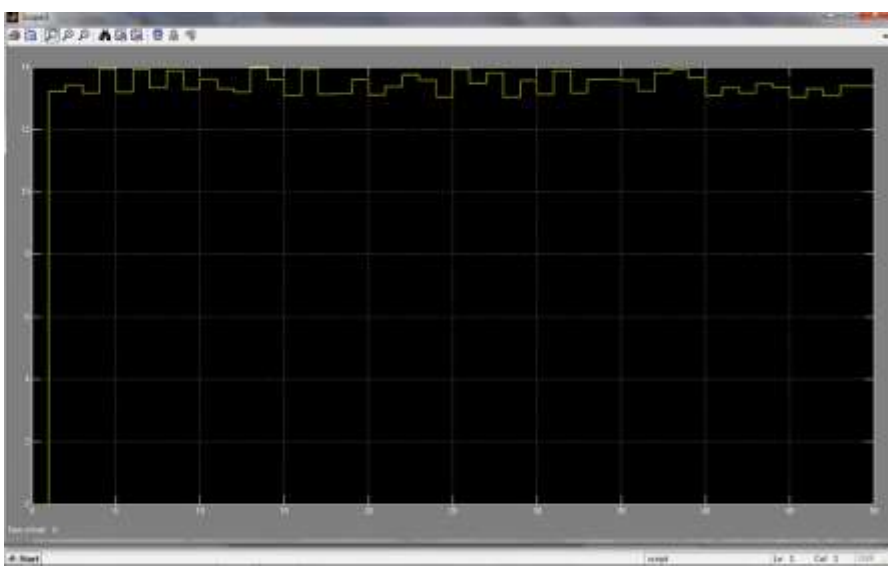

Fig. 6. Simulation of open loop

While the close loop simulation done by adding state feedback controllers computed into HYSDEL at the DA by substituting u(k) = K ix(k) in the equation x (k + 1) = Aix(k) + Bi u (k),so the output of the system is obtained as in Figure 7 below.

The simulation results illustrate that the system output is better though still often overshooting large enough, the bus voltage ripple that occurs can be minimized so little value mainly in the range of 5-25 seconds. Fairly large overshoot of about 0.6% occurred in the range of 30-45 seconds in addition there is also a bus voltage ripple is small enough compared to the simulation of the plant without the controller. In the 40-45 second range, there is no overshoot and a large bus voltage ripple.

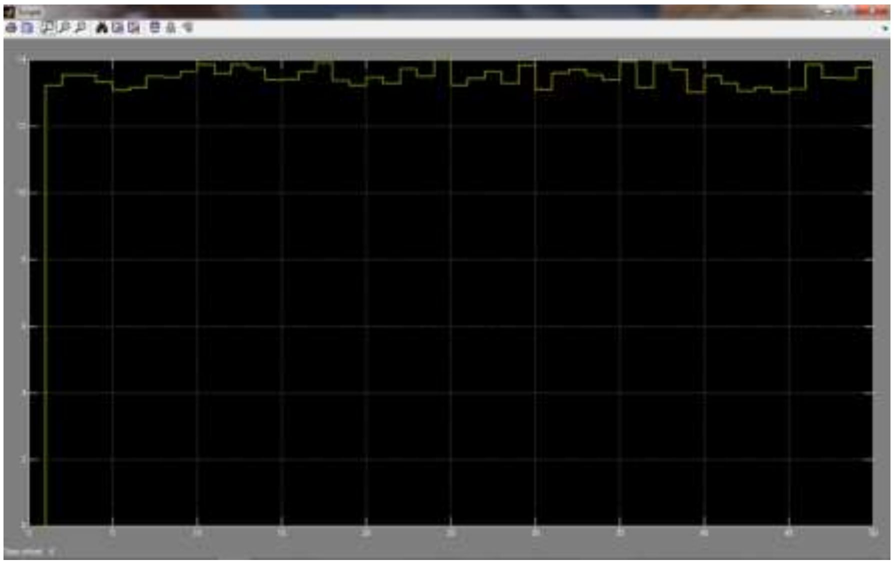

Fig. 7. Simulation close loop

**CONCLUSION AND RECOMMENDATIONS**

It can be concluded in this study are as follows: a hybrid energy source can be constructed from fuel cells with energy storage, ie batteries and super capacitors. State feedback control can be used keeping the bus voltage remains stable at the reference voltage. The simulation results obtained is that the design using state feedback controller generates an output voltage ripple of the system that are not so great that the overshoot of 0.6% compared with no state feedback controller and a small bus voltage ripple. Hybrid modeling combined with MLD and PWA models can exhibit discontinuous working modes that occur when there is movement of the working mode. This can be seen from the simulation results that show the change every time the bus voltage switches and voltage condition of each source is changed.

While the suggestion of this study to control the implementation process in real time, can be a great setting the gain to get better results. For implementation, necessary to design an observer at each voltage source capacitance. Need to optimize the control i (current) -v (voltage) by using the method of designing the control of Maximum Power Point Tracking.

For further development of the combined hybrid feedback controller state can be directed to other methods of control systems such as Robust Control and Optimal Control.

**Declaration of Conflicting Interests**

There are no conflicts of interest present.

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