Design and Implementation of Buck Converter for Fast Charging with Fuzzy Logic

Indhana Sudiharto  
Department of Electrical Engineering  
Politeknik Elektronika Negeri Surabaya  
Surabaya, Indonesia  
ishana@pens.ac.id

Ony Asrarul Qudsi  
Department of Electrical Engineering  
Politeknik Elektronika Negeri Surabaya  
Surabaya, Indonesia  
ony@pens.ac.id

Moch. Igam Rahadyan  
Department of Electrical Engineering  
Politeknik Elektronika Negeri Surabaya  
Surabaya, Indonesia  
mochigam@pens.ac.id

Abstract—This research presents a battery charger design that can charge faster than using a PWM type solar charge controller (SCC). SCC is often operated when the battery capacity is 80% so that the charging current that can be provided is only 10% to 20% of the battery capacity. The battery charging method applied in this study uses the principle of fast charging by adjusting the value of the current and the output voltage value of the buck converter. Fast charging has its own characteristic, obviously, the charging rate that is greater than the usual charging method, which is up to 1C of the battery capacity. The principle of fast charging in this study uses the constant current / constant voltage method. This converter is designed with the ability to produce current by the charging rate of 1C from a 12Ah battery capacity of 12 A and an output voltage of 16.8 V. To ensure that the output of the converter matches the setpoint, the duty cycle value is adjusted using fuzzy control. Based on the results obtained from the simulation, the control of this study obtained an output current 12 Amperes with error ripple current around 8.3%. The SOC on this battery increased by 75.74% in 45 minutes.

Keywords—fast charging, fuzzy, buck converter

I. INTRODUCTION

Electricity is a form of energy that has long been found and used for everyday life. Utilization starts with moving objects to light and many other things. Electrical energy can be generated from power plants that are now of many types such as solar power plants. It can be seen that the country of Indonesia is a country that has a tropical climate so that it has the potential to be able to utilize abundant solar energy. A solar cell (photovoltaic) is a device that can convert sunlight into electrical energy.

Solar is a potential energy source that can be renewed (renewable energy). By using solar cells, solar energy that had not been able to be used as alternative energy can be utilized as electricity that is friendly to the environment. A lot of research has been done to make solar cells as energy providers for battery charging, but not many have applied them using the principle of fast charging.

Research on the principle of fast charging has been carried out by several researchers, such as in research [1] using buck converter with the constant current method to make fast charging controllers used for charging batteries. Research [4] Battery Charging Method of Constant Current Constant Voltage Based on dsPIC30F4012. Research [5] of constant current method to charge batteries faster than PWM type SCC, which is often used for charging batteries with solar cell sources. Fig. 1 shows the design of the fast charging system on the battery.

Fig. 1. Overall system

The SOC on this battery increased by 75.74% in 45 minutes.

II. METHODS

A system design in this study will be shown in block diagram Fig.1. And, a system modeling will be explained in the following points.

A. System Design

A fast-charging system was created which can charge batteries faster than PWM type SCC, which is often used for charging batteries with solar cell sources. Fig. 1 shows the design of the fast charging system on the battery.

B. System Modelling

1) Lithium-Ion Battery

This Lithium-Ion Battery is capable of receiving a charging current greater than other types of batteries. This battery is capable of receiving a charging rate of 1C, which is the Ah capacity of the battery. The charging rate of fast charging is about 1C. Therefore this battery is suitable when fast charging is applied. The battery used in this study is 12 V 12 Ah.

SOC Battery Calculation as the following below, how to measure the State of Charge (SOC) of a battery can be done in 3 ways, that is:
1. Direct measurement, can be done if the battery can be charged at a constant value.

2. SOC from Specific Gravity (SG) measurements, this method depends on changes in measurements of the weight of active chemicals.

3. SOC estimation based on voltage is done by measuring the battery cell voltage as a basis for calculating SOC or remaining capacity.

And, how to find SOC batteries are as follows:

\[
\text{SOC} = \frac{(\text{Ah}_{\text{max}} - (\text{Ah}_{\text{in}} + \text{Ah}_{\text{out}}))}{\text{Ah}_{\text{max}}} \tag{1}
\]

Where:

- \( \text{SOC} \) = State of Charge
- \( \text{Ah}_{\text{max}} \) = Maximum Current / Hour
- \( \text{Ah}_{\text{in}} \) = Entering Current / Hour
- \( \text{Ah}_{\text{out}} \) = Exiting Current / Hour

Battery modeling includes the charging process based on the battery's State Of Charge (SOC). This battery model uses a Thevenin equivalent circuit based on the resistive and capacitive properties of the battery [8].

The equation of battery modeling is as follows:

\[
\text{Em} = R_0 \cdot I_t + R_1 \cdot I_t \tag{2}
\]

\[
I_{\text{ct}} = R_1 \frac{dI_{\text{rt}}}{dt} \tag{3}
\]

\[
\text{where:}
\]

- \( \text{Em} \) = Open Circuit Battery Voltage (V)
- \( I_t \) = Charging Current (A)
- \( R \) = Resistor (Ω)
- \( C \) = Capacitor (F)

2) Photovoltaic Module

Solar cells are energy converters made from semiconductor pieces of different square centimeters in size. Some solar cells are assembled into solar panels that can convert solar energy into dc (direct current) electrical energy with a certain capacity according to the type of material and the area of the solar panel. In terms of price when compared to other renewable energy power plants, solar panels have a relatively expensive price. Therefore, the use of more solar panels in areas that are not properly covered by the electricity flow of PLN or becomes a backup energy when the main electricity source is not available. The equivalent circuit of photovoltaic can be shown in Fig. 3.

The mathematical equation of the PV module can be expressed as:

\[
I_{pv} = N_p I_{ph} - N_p I_{o} \left[ \exp \left( \frac{-q(V_{pv} + R_s I_{pv})}{A K T N_s} \right) - 1 \right] - N_p V_{pv} + R_s I_{pv} \tag{5}
\]

where:

- \( I_{pv} \) = output power pv module (A)
- \( V_{pv} \) = output voltage PV (V)
- \( I_{ph} \) = generated current (A)
- \( I_{o} \) = current reverse diode (A)
- \( R_s \) = resistance series solar cell (ohm)
- \( R_{sh} \) = resistance shunt solar cell (ohm)
- \( N_p \) = number of parallel solar cell
- \( N_s \) = number of series solar cell
- \( Q \) = electron charge (1.6 x 10^{-19} C)
- \( K \) = constant boltzman (1.38 x 10^{-23} J/K)

Table I. Specifications of Photovoltaic

| Parameters               | Value       |
|--------------------------|-------------|
| Maximum Power (Pmax)     | 100 W       |
| Current at Pmax (Imp)    | 5.72 A      |
| Voltage at Pmax(Vmp)     | 17.5 V      |
| Short circuit Current(Isc)| 6.35 A     |
| Open circuit Voltage(Voc)| 22.0 V      |

Table I shows data on solar panels with a maximum power of 100 Watt peak below.

3) Modelling of Buck Converter

Buck converter is a special voltage-lowering converter that applies an SMPS (Switching Mode Power Supply) system. This converter has a higher efficiency when compared to an ordinary voltage-lowering power supply (linear system). The efficiency of this converter can reach more than 90%. The buck converter utilizes the nature of the inductor for high-frequency electric shocks and works in the presence of voltage pulses (as is the case with SMPS). Therefore, in a buck converter circuit, there are always signal generators, MOSFETs, diodes, capacitors, and inductors. The basic concept of the buck converter circuit in Fig. 4 is as follows.
Fig. 4. is the topology of the buck converter. From this picture can be analyzed how the operation of the converter. When the MOSFET is ON (closed), the electrical energy will pass through the MOSFET and the diode becomes reverse-biased so that the electrical energy is stored in the inductor in the form of current. The diode provides a path for the inductor current when the switch is opened and is reverse-biased when the switch is closed [9].

From basic operations, we can find out the value of the system duty cycle. It is assumed that the efficiency of the circuit is 100%. So the duty cycle value can be calculated using the equation:

\[
D = \frac{V_{\text{out}}}{V_{\text{in}}} \tag{6}
\]

Then what must be considered is the selection of components. The value of the selected component can be calculated using the equation:

\[
I_L = \frac{V_o}{R} \tag{7}
\]

\[
L = \frac{(1-D)\Delta V_o}{\Delta I_L} \tag{8}
\]

\[
I_{L,\text{rms}} = \sqrt{I_L^2 + \left(\frac{\Delta V_o}{\sqrt{3}}\right)^2} \tag{9}
\]

\[
C = \frac{(1-D)}{8L\Delta V_o V_o}\tag{10}
\]

Where:

- \(V_{\text{in}}\) = Input Voltage (V)
- \(V_{\text{out}}\) = Output Voltage (V)
- \(I_L\) = Load Current (A)
- \(R\) = Resistance (ohm)
- \(F\) = Switching Frequency (Hz)
- \(L\) = Inductor (H)
- \(\Delta I_L\) = Inductor Ripple Current (A)
- \(I_{L,\text{rms}}\) = Inductor RMS Current (A)
- \(C\) = Capacitor (F)
- \(\Delta V_o\) = Ripple Output Voltage (V)
- \(D\) = Duty Cycle

**TABLE II. RESULTS OF BUCK CONVERTER COMPONENT CALCULATIONS**

| Parameters                | Symbol | Value | Units |
|---------------------------|--------|-------|-------|
| Input voltage             | \(V_{\text{in}}\) | 35    | Volt  |
| Output voltage            | \(V_{\text{out}}\) | 16.8  | Volt  |
| Output Current            | \(I_{\text{out}}\) | 12    | A     |
| Inductor Ripple Current   | \(\Delta I_L\) | 2.4   | A     |

| Parameters                | Symbol | Value | Units |
|---------------------------|--------|-------|-------|
| Inductor RMS Current      | \(I_{L,\text{rms}}\) | 12.02 | A     |
| Voltage ripple            | \(\Delta V_o\) | 0.084 | Volt  |
| Switching Frequency       | \(F_{sw}\) | 40    | KHz   |
| Inductor                  | \(L\)  | 91    | uH    |
| Capacitor                 | \(C\)  | 89.28 | uF    |

4) *Modelling Fuzzy*

Fuzzy set contains elements that have varying membership values in a set. In contrast to the control system, the resulting value is defined definitively or in other terms, only logic 0 and 1 or work in the on and off regions so that an insignificant change is obtained in the fuzzy logic control system that works between 0 and 1 can be defined so that the controller can work such as the human nervous system that can feel the external environment that is less, somewhat, ordinary, very, or even obscure can be more than that category by adding linguistic factors that are collected in the degree of membership. So by using a fuzzy logic controller, we get conveniences that are not owned by conventional control systems. There are stages called fuzzification, determination of the rule base along with the database then defuzzification. The basic concept of fuzzy shown in Fig. 5.

![Fuzzy System Diagram](image)

**Fig. 5. The basic structure of the fuzzy system**

**a) Fuzzification**

Fuzzification is the process of changing the input from a crisp form into fuzzy (linguistic variable) which is presented in the form of a fuzzy set with each membership function. The membership function used in this system are shown in Fig. 6. and Fig. 7. The membership function consists of 5 triangles and 2 trapezoids.

![Variable Input Error](image)

**Fig. 6. Variable input error**

![Variable Input Delta Error](image)

**Fig. 7. Variable input delta error**

**b) Rule Base**

Because the output from the fuzzy controller issues a duty cycle value that adjusts to the setpoint, the rule base can be determined by looking at the error and delta error values used as fuzzy input variables. The rule base is used to determine the desired control according to the plant planned by the operator. The decision-making method used
in fuzzy is using the Takagi Sugeno Kang (TSK) method or what is commonly called the Sugeno Method where the rules are represented in the form of IF-THEN, and the output or system consequences are not in the form of fuzzy sets, but in the form of constants or linear equation. Table 3 shows the rule base used in this research.

| E/ΔE | NB   | NM   | NS   | Z    | PS   | PM   | PB   |
|------|------|------|------|------|------|------|------|
| NB   | NB   | NB   | NB   | NB   | NM   | NS   | Z    |
| NM   | NB   | NB   | NB   | NM   | NS   | Z    | PS   |
| NS   | NB   | NB   | NM   | NS   | Z    | PS   | PM   |
| Z    | NB   | NM   | NS   | Z    | PS   | PM   | PB   |
| PS   | NM   | NS   | Z    | PS   | PM   | PB   | PB   |
| PM   | NS   | Z    | PS   | PM   | PB   | PB   | PB   |
| PB   | Z    | PS   | PM   | PB   | PB   | PB   | PB   |

c) Defuzzification

The output from the rule base is still a fuzzy value, so the defuzzification part is needed to change the fuzzy value (linguistic variable) to a firm value which will then be sent to the system/plant. The defuzzification used in this system is the weighted average. In this method, each output membership function above the value indicated by each fuzzy output is truncated. Using the weighted average defuzzification method, the output singleton values are combined using average weights. This method applies to fuzzy sets with symmetric output membership functions.

III. RESULTS AND DISCUSSION

The purpose of this simulation is to test the performance of the system produced by fuzzy control. Fig. 9 shows the simulation of a buck converter. In this simulation, PVs are used as the power supply of the converter. The PV used in this simulation has a power of 200 WP each. This system uses 3 PVs and is arranged in parallel. So the result of the current PV output is around 17.16 Amperes and the output voltage of the PV is around 35 Volts.

Fig. 8. Membership function output

Fig. 9. Buck converter circuit

From Fig. 9, The system is simulated using 3 PVs with a power of 200 WP each. Actually 1 PV in this simulation has been set like 2 real PVs of 100 WP each installed in series. The Vmp voltage is 35 volts, and the Imp current is 5.72 amperes in each solar cell. This system is simulated using PSIM software. After simulating it can be seen the response of the system when using the control and when not using the control so that the form of the response can be compared. In this first simulation, a buck converter simulation without using control was carried out with a duty cycle of 48%. The response of the buck converter output current without control can be seen in Fig. 10 where the converter output current is not the same as the 12 A setpoint and the converter output voltage is also not the same as the 16.8 V.

Fig. 10. System response without control for current output and voltage output on a duty cycle 48

Fig. 11 shows the simulation of a buck converter using control in constant current mode when given a disturbance in two PVs on the irradiance side. Condition 1 is given disturbance at 0, 0.2, 0.4, 0.7, 1 seconds. The resulting output current response is stable when given a disturbance.

Fig. 11. Output current response when disturbed on the irradiance side

Fig. 12 shows the simulation of a buck converter using control in constant current mode when given a disturbance in two PVs on the irradiance side. Condition 2 is given disturbance at 0, 0.2, 0.4, 0.7, 1 seconds. The resulting output current response is stable when given a disturbance.

Fig. 12. Output current response when disturbed on the irradiance side

Fig. 13 shows the simulation of a buck converter using control in constant current mode when given a disturbance in two PVs on the irradiance side. Condition 3 is given disturbance at 0, 0.2, 0.4, 0.7, 1 seconds. The resulting output current response is stable when given a disturbance.
Fig. 13. Output current response when disturbed on the irradiance side

Fig. 14 shows the simulation of a buck converter using control in constant voltage mode when given a disturbance in two PVs on the irradiance side. Condition 1 is given disturbance at 0, 0.2, 0.4, 0.7, 1 seconds. The resulting output current response is stable when given a disturbance.

Fig. 14. Output current response when disturbed on the irradiance side

Fig. 15 shows the simulation of a buck converter using control in constant voltage mode when given a disturbance in two PVs on the irradiance side. Condition 1 is given disturbance at 0, 0.2, 0.4, 0.7, 1 seconds. The resulting output voltage response is stable when given a disturbance.

Fig. 15. Output current response when disturbed on the irradiance side

Fig. 16 shows the simulation of a buck converter using a control in constant voltage mode when given a disturbance in two PVs on the irradiance side. Condition 3 is given disturbance at 0, 0.2, 0.4, 0.7, 1 seconds. The resulting output voltage response is stable when given a disturbance.

Fig. 16. Output current response when disturbed on the irradiance side

In Fig. 17, we try to control the buck converter using PI control, where the PI value is obtained from the tuning process after running open-loop simulation. The current output response when using control produces a stable current. Fig. 18 shows the comparison of output current response between fuzzy controlled converter (red line) and PI controlled converter (blue line). The output response generated using the PI controller has a small overshoot while the output response from the fuzzy controller doesn’t. The error generated from the fuzzy control is 0.233% while the error generated from the PI control simulation is 0.258%.

Fig. 17. Buck converter circuit with PI control

Fig. 18. Comparison of output current response between fuzzy control and PI control

| TABLE IV. SYSTEM RESULTS USING THE FUZZY LOGIC CONTROLLER IN CONSTANT CURRENT MODE |
|---------------------------------------------------------------|
| **No.** | **Condition** | **Output(A)** | **Setpoint(A)** | **% Error** |
|--------|---------------|---------------|----------------|-------------|
| 1      | 1             | 11.97         | 12             | 0.25%       |
| 2      | 2             | 12.01         | 12             | 0.083%      |
| 3      | 3             | 11.98         | 12             | 0.167%      |

| TABLE V. SYSTEM RESULTS USING THE FUZZY LOGIC CONTROLLER IN CONSTANT VOLTAGE MODE |
|---------------------------------------------------------------|
| **No.** | **Condition** | **Output(V)** | **Setpoint(V)** | **% Error** |
|--------|---------------|---------------|----------------|-------------|
| 1      | 1             | 16.82         | 16.8           | 0.119%      |
| 2      | 2             | 16.809        | 16.8           | 0.053%      |
| 3      | 3             | 16.82         | 16.8           | 0.119%      |
### TABLE VI. COMPARISON BETWEEN PI AND FUZZY

| Condition | Parameter Output Response | Rise Time | Settling Time | Steady State Error |
|-----------|---------------------------|-----------|---------------|-------------------|
| PI        |                           | 0.008979  | 0.0318367     | 0.26%             |
| FUZZY     |                           | 0.025306  | 0.0293877     | 0.23%             |

From Table 4 and Table 5 the buck converter simulation results are obtained using fuzzy logic control. Where the simulation is given interference on the Irradiance side. With a setpoint current of 12 A in constant current mode and a set point of 16.8 V in constant voltage mode, a change in condition from condition 1 to condition 3 shows that the range of error percentage output current is between 0.083 - 0.25% and the range of error percentage output voltage is between 0.053 - 0.119%. The comparison between PI control and Fuzzy control are shown in Table 6. PI control has faster rise time than Fuzzy control but has slower settling time than fuzzy control. But Fuzzy control has smaller steady state error.

From Fig. 19, the simulation results of battery charging with fuzzy logic controller control show that PI control has faster rise time than Fuzzy control but has slower settling time than fuzzy control. But Fuzzy control has smaller steady state error.

From Fig. 20, the battery charging using buck converter simulation results are obtained using fuzzy logic control. Where the specified simulation time is 2700 seconds (45 minutes). The simulation starts when the SOC is 10.04% and at the end of the simulation time the SOC is 85.78%. Current ripple error was 8.3%.

### IV. CONCLUSIONS

Simulation of fast charging of buck converter with fuzzy logic control has been presented. The simulation results show that the system is functioning properly. Fuzzy control can accelerate the increase in time and keep the output of the buck converter stable. The system maintains a stable current in constant current mode and the system maintains a stable output voltage in constant voltage mode. This control has also been able to make the converter to produce current with a charge rate of 1C which is 12 Amps with decent precision. The contact type sensor installed parallel to the PD source location resulted in the impulse waveform that was more accurate than the nonparallel contact sensor. This indicates that the perfection level of impulse waveform may reveal the PD location in the oil-filled tank. The acoustic and current waveforms do not depend on each other. However, the closer electrode gap distance equivalently causes longer acoustic and current duration. In addition, the current is not influenced by the PD source location.

### V. ACKNOWLEDGMENT

Thanks to the supervisor who has guided the writer very well for the preparation of this research and to the Electronic Engineering Polytechnic Institute of Surabaya.

### REFERENCES

[1] Dwi Pratiwi, S.T, M.T, DRS. Maison, M.SI. PH.D, Dini Khusnul Yaqin, “Rancang Bangun Charge Controller Panel Surya Dengan Menggunakan Sistem Fast Charging”, UNJA, 2019.

[2] Galih Cahyo Adi, “Desain Pengisian Batere Metode Constant Current Constant Voltage Berbasis dsPIC30F4012”, UNIKA, 2015.

[3] Indhana Sudharto, Farid Dwi Muridianto, Irianto, Ayu Wulandari, “Adaptive Power Charge using PID Controller on DC Load Application”, 2019.

[4] Sutedjo, Ony Asrarel Qudsi, Andi Aribanto, Diah Septi Yanaratri, Suharwingsih, Moch. Darwis “Design and Implementation Buck Converter for 540WP Solar Charger Using Fuzzy Logic Control”, ASTECHNOVA, 2017.

[5] Ming-Wang Cheng, Shuh-Ming Wang, Yuang-Shung Lee, Sung-Hsin Hsiao, “Fuzzy Controlled Fast Charging System for Lithium-Ion Batteries”, IEEE, 2009.

[6] Jerzy Bakalarczyk, “Charging of PV Battery At Constant Current Mode By Using Fuzzy Logic Control”, IEEE, 2017.

[7] V.L. Teofilo, V.L. Mermitt and R. P. Hollandsworth, “Advanced Lithium Ion Battery Charge,” Battery Conference on Applications and Advances”, vol. 12, no. 11, pp. 227-231, 1997.

[8] Zhai Haizhou, “Modeling of Lithium-ion Battery for Charging/Discharging Characteristics Based on Circuit Model”, Ijoe, 2017.

[9] Daniel W. Hart. 2011. Power Electronics. New York. The McGraw-Hill Companies.