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Analysis of Matrix Converter as Solid State Transformer (SST) in Battery Charging Using Fuzzy Logic Control

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Abstract. *Technological advancements in the digital era have made electrical energy needs vital in the industrial world. The reliability of electricity supply certainly has serious challenges related to transmission system blackouts due to the failure of blackstart at the plant because the battery supply is not functioning optimally. To anticipate this failure, Matrix Converter (MC) modeling is carried out as a Solid State Transformer (SST) to replace conventional transformers to maintain voltage stability and change the voltage according to the needs for battery supply. The SVPWM methodology uses 9 bidirectional switches in the MC to modulate pulse width by comparing the duty cycle against high-frequency waves. This comparison can determine when each switch in the converter should be open or closed in each switching cycle. To control stable voltage and efficient current in the battery charging process, Fuzzy Logic control (FLC) is used. With a Rectifier as the converter (AC-DC), a stable voltage of 127.6 volts DC is obtained, so the battery charging process can work optimally and stably.*

1. INTRODUCTION

In the era of Industrial Revolution 5.0, rapid technological advancement and digitalization have made electrical energy indispensable to nearly all human activities. As a result, the demand for electricity plays a crucial role in supporting industrial development and economic growth. However, this growing demand also poses significant challenges in maintaining a reliable power supply, including potential system failures that may lead to blackouts or total outages in the electrical transmission network. [1].

During blackout conditions, power generation systems that have been disconnected from the grid are expected to recover and return to normal operation as quickly as possible through a black start process. During such events, most power generation units are unable to operate normally, resulting in a generation capacity significantly lower than the load demand. This imbalance can trigger Manual Load Shedding (MLS) and Under Frequency Load Shedding (UFLS) in the transmission network. A potential solution is to optimize alternative power plants, such as gas turbine generators, as backup power sources operated in synchronization mode with the main 150 kV transmission system to restore power supply to a wider transmission network. [2].

In this condition, the case study focuseson PLN’s Sebalang Generation Implementation Unit (UPDK Sebalang), which operates one Emergency Diesel Generator (EDG) with a capacity of 500 kW and a single conventional transformer. The facility also includes two steam power plant (PLTU) units, each rated at 100 MW, and one gas turbine power plant (PLTG) with a capacity of 15 MW. The PLTG serves as the power transfer unit to the 150 kV transmission system during blackout conditions and is designated as the black start generator for restoring the transmission system during a total shutdown.

However, in actual field conditions, the gas turbine power plant (PLTG) cannot operate as a black start unit if the battery (DC supply) does not function optimally [3]. Several factors may cause black start failures in power generation systems, including conventional transformer failures and battery malfunctions. Conventional transformers are prone to damage due to high harmonic distortion and voltage fluctuations caused by tap changer adjustments. Additionally, aging and poorly maintained batteries can experience a failure rate of up to 30%, significantly increasing the likelihood of malfunction during emergency blackout conditions. Therefore, a stable battery supply in the PLTG is essential to operate critical DC loads such as DC motors [4].

A Matrix Converter (MC) is a type of power converter that can be utilized as a Solid-State Transformer (SST) to replace conventional transformers. The MC can directly convert voltage and current without using energy storage components, offering high efficiency and compact size [5]. In battery charging applications, the MC can be used to convert voltage and current from the power source into suitable levels for the battery requirements.

However, the use of an MC as an SST in battery charging applications requires an effective control system to regulate the output voltage and current [6]. Fuzzy Logic Control is one control method that can be applied to manage the MC output [7]. This control strategy helps maintain voltage and current stability during the charging process, thereby minimizing battery failure [8].

In this study, a Matrix Converter is employed as a replacement for the conventional transformer, designed using the Space Vector Pulse Width Modulation (SVPWM) algorithm to generate the Emergency Diesel Generator (EDG) output voltage—converting from 380 volts to 126 volts as required—and applying fuzzy logic control to stabilize the voltage and regulate the current for improved charging efficiency.

2. LITERATURE REVIEW

2.1. Matrix Converter

This section describes the modeling architecture of a three-phase Matrix Converter used as a Solid-State Transformer (SST) to replace conventional transformers. The Matrix Converter replaces the rectifier (AC-DC) and inverter (DC-AC) stages with nine bidirectional switches capable of directly processing AC-to-AC voltage conversion using Space Vector Modulation (SVM) control [9][10]. In this study, Space Vector Pulse Width Modulation (SVPWM) is employed to control the Matrix Converter in transforming the three-phase input voltage directly to the output without passing through an intermediate DC stage as in conventional transformer converters [11] .

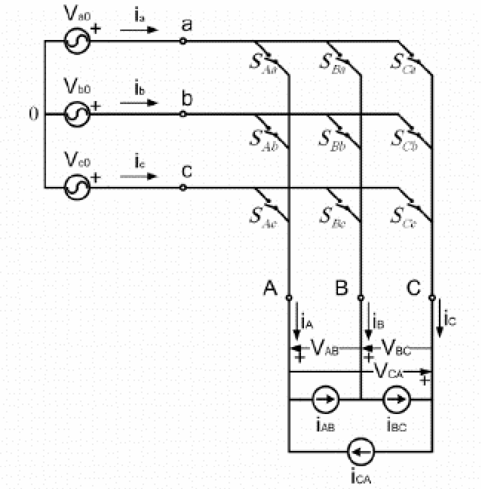


Figure 1. Matrix Converter circuit

The Matrix Converter can be represented using a 3×3 matrix equation, where the output voltage of the Matrix Converter can be mathematically expressed in equation (1) as follows :

$$\begin{bmatrix} V_a(t) \\ V_b(t) \\ V_c(t) \end{bmatrix} = \begin{bmatrix} S_{Aa}(t) & S_{Ba}(t) & S_{Ca}(t) \\ S_{Ab}(t) & S_{Bb}(t) & S_{Cb}(t) \\ S_{AC}(t) & S_{Bc}(t) & S_{Cc}(t) \end{bmatrix} \; X \; \begin{bmatrix} V_A(t) \\ V_B(t) \\ V_C(t) \end{bmatrix} \qquad (1)$$

$$\boldsymbol{V_o = Sx\, V_i}$$

Where V_0 enotes the output phase voltage; Vi represents the input phase voltage; S is the transfer switching matrix; A,B,C indicate the switching sequences, and a,b,c represent the phases.

The input current of the Matrix Converter can be expressed mathematically in equation (2) as follows:

$$\begin{bmatrix} I_A(t) \\ I_B(t) \\ I_C(t) \end{bmatrix} = \begin{bmatrix} S_{Aa}(t) & S_{Ba}(t) & S_{Ca}(t) \\ S_{Ab}(t) & S_{Bb}(t) & S_{Cb}(t) \\ S_{AC}(t) & S_{Bc}(t) & S_{Cc}(t) \end{bmatrix} x \begin{bmatrix} I_a(t) \\ I_b(t) \\ I_c(t) \end{bmatrix} \qquad (2)$$

$$\boldsymbol{I_o = Sx\, I_i}$$

Where I_0 is the output phase current, and; Ii represents the input phase voltage [7].

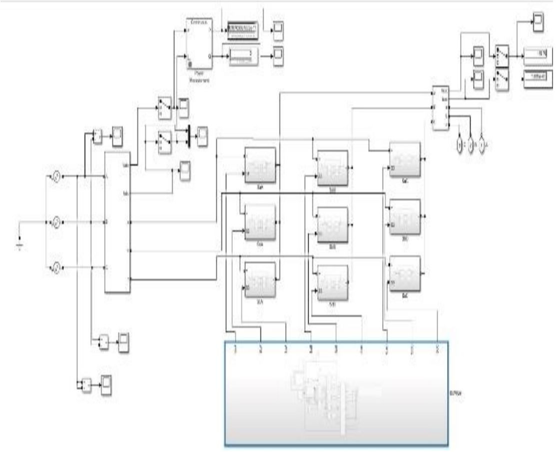


Figure 2. Modeling the Matrix Converter as an SST

2.2. Clarke and Park Transformation Equations

The Clarke transformation is a mathematical technique that employs a transformation matrix to convert a three-phase vector (a, b, c) into a two-phase vector (α, β), simplifying the control of electrical systems [12].

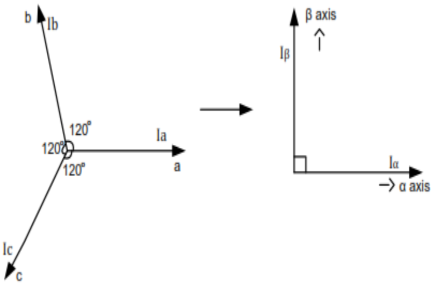


Figure 3. Clarke Transformation Coordinate

The current transformation equation for the Clarke transformation can be expressed as follows:

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos(\theta-120°) & \cos(\theta+120°) \\ sin\theta & \sin(\theta-120°) & \sin(\theta+120°) \\ 0.5 & 0.5 & 0.5 \end{bmatrix} . \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (3)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} . \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (4)$$

Meanwhile, the voltage transformation equation for the Clarke transformation can be expressed as follows:

$$\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \begin{bmatrix} \cos(\theta t) & \sin(\theta t) & 0 \\ -\sin(\theta t) & \cos(\theta t) & 0 \\ 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix} \qquad (5)$$

$$\begin{bmatrix} V_\alpha \\ V_\beta \\ V_0 \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \end{bmatrix} . \begin{bmatrix} V_{a1} \\ V_{b1} \\ V_{c1} \end{bmatrix} \qquad (6)$$

The Park transformation is a coordinate transformation that converts the stationary two-phase phase α and β system into a rotating d–q reference frame. The coordinate system is illustrated in Figure 4, and the corresponding equations are expressed as follows:

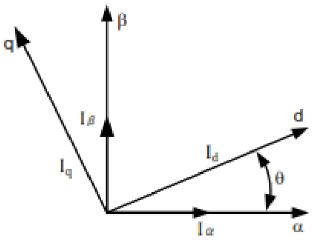


Figure 4. Park transformation coordinates

$$\begin{bmatrix} i_q \\ i_d \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} . \begin{bmatrix} i_q \\ i_d \end{bmatrix} \qquad (5)$$

The Park transformation diagram can be seen in Figure 5.

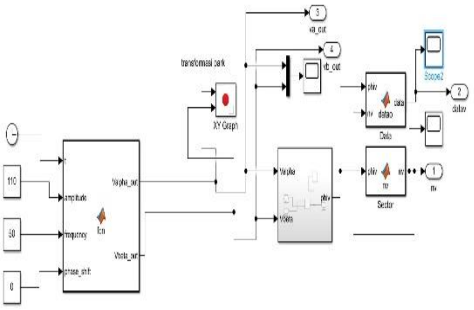


Figure 5. Park transformation

Thus,the block diagram is shown in Figure 6.

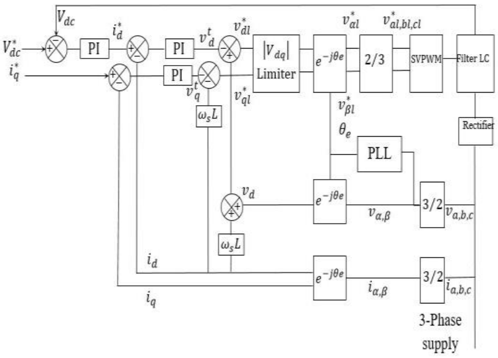


Figure 6. Vector control block diagram

2.3. *Modeling Of Space Vektor Pulse Width Modulation (Svpwm)*

Space Vector Pulse Width Modulation (SVPWM) is a PWM methodology that offers higher efficiency compared to other PWM techniques [13]. In the SVPWM algorithm, there are nine bidirectional switches that connect the three-phase inputs (A, B, C) to the three-phase outputs (a, b, c). The switching matrix, denoted as S_matrix, has a size of 3×3, where each element represents the duty cycle of each switch. A value of 0 indicates that the switch is always open, a value of 1 indicates that the switch is always closed, and intermediate values represent the proportion of time the switch remains closed [14].

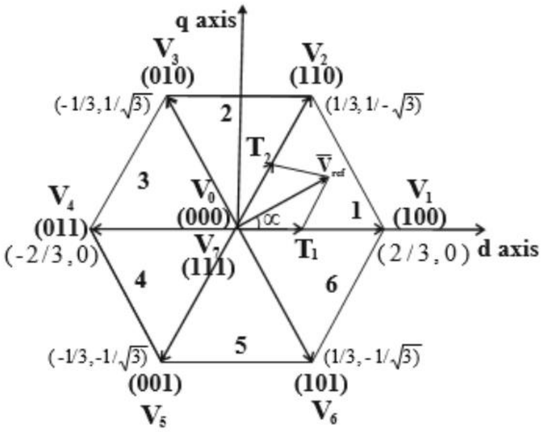


Figure 7. SVPWM Base Vector

To generate the switching signals, the system employs the Pulse Width Modulation (PWM) technique by comparing the duty cycle with a high-frequency carrier wave. The result of this comparison determines when each switch in the converter should be turned on or off during each switching cycle. In this system, the control of the switching signals ensures that the resulting sinusoidal output voltage exhibits minimal distortion.

Table 1 : Switching vector rule criteria

	a	b	c
A	S_1	S_2	S_3
B	S_4	S_5	S_6
C	S_7	S_8	S_9

Explanation:

- S_1 : SAa (switch between input A dan output a)
- S_2 : SAb (switch between input A and output b)
- S_3 : SAc (switch between input A and output c)
- S_4 : SBa (switch between input B and output a)
- S_5 : SBb (switch between input B and output b)
- S_6 : SBc (switch between input B and output c)
- S_7 : SCa (switch between input C and output a)
- S_8 : SCb (switch between input and outputb)
- S_9 : SCc (switch between input C and output c)

2.4 FUZZY LOGIC CONTROL

Fuzzy logic is a form of logic that incorporates uncertainty between true and false values. In fuzzy logic theory, a value can possess both truth and falsity simultaneously, where the degree of truth and falsity is determined by its membership function [15]. Fuzzy logic consists of several types of inference methods, including Mamdani, Sugeno, and Tsukamoto [16]. In this paper, the Sugeno method is employed as the basis for the fuzzy logic control system. Although the reasoning process in the Sugeno method is similar to that of the Mamdani method, the difference lies in the output. The Mamdani method produces fuzzy sets where the accuracy increases with the number of rule functions, while the Sugeno method generates outputs in the form of constant values or linear equations, maintaining good accuracy even with fewer rule functions [17].

3. RESEARCH METHOD

This study applies a case study approach to analyze the modeling of a Solid-State Transformer (SST) for battery charging at PLTU Sebalang, aiming to control voltage stability and optimize the charging process. The flow diagram of this research is presented as follows:

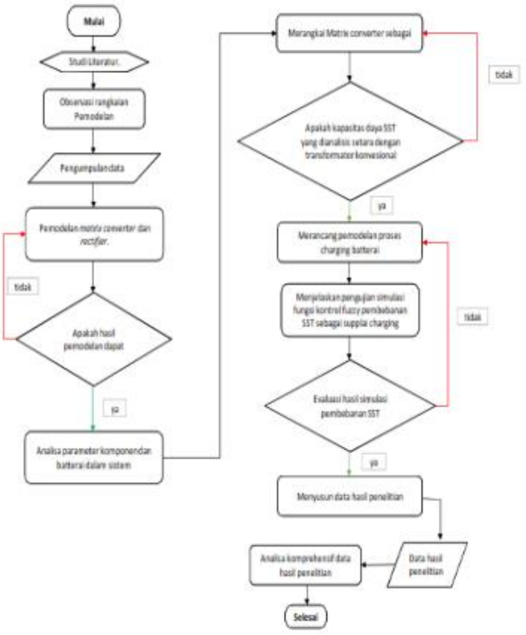


Figure 8. Research flow diagram

4. RESULT AND DISCUSSION

4.1 *Matrix Converter Modeling Data*

This simulation model is designed to observe the duty cycle of the Matrix Converter used as a replacement for the conventional transformer. The simulation block diagram is shown in Figure 9.

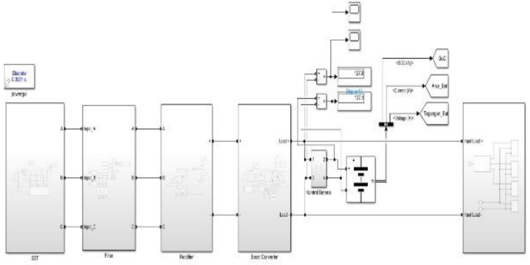


Figure 9. Matrix converter modeling

The following are the modeling parameter data for the Matrix Converter system used as a replacement for the conventional transformer:

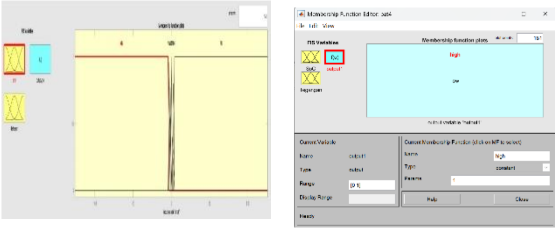
Tabel 2. Converter Matrix parameter

Parameter	Value
Grid voltage (RMS): V_{abc} /V	380
Fundamental frequency: f/Hz	50
Inductor filter: L_f/mH	0.04
Capacitor Filter: C_f/F	5,3
DC bus capacitor: C/mF	5.6
Battery voltage: V_b/V	126,3
Battery capacity: C_A/Ah	200
Battery Response time (s)	1
Motor load: I_l/A	150.25
Switching frequency: f_s/kHz	10
Sampling time: T_s/s	12

4.2 *Control Process of the Booster Converter and Battery Using Fuzzy Logic*

In this study, fuzzy logic with the Sugeno method is applied using a Multi-Input Single- Output (MISO) configuration, meaning the fuzzy system is designed with two inputs and one output. The inputs used in the booster control are error and change in error. The error value is obtained from the difference between the reference value and the actual value, while the change in error represents the difference between the most recent error and the previous one. For the battery charging control, the inputs consist of the State of Charge (SOC) and the output voltage from the booster. The SOC value is derived from the initial battery charging settings.

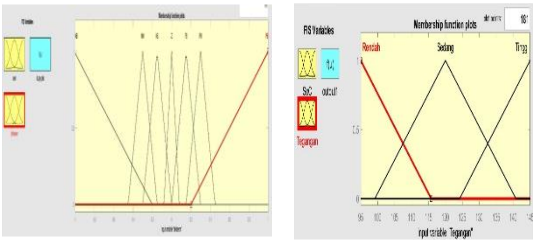
The membership functions for both the booster converter control and the battery charging control are shown in Figure 10. The booster converter control employs seven fuzzy rule functions with a value range between −300 and 300, namely: NB (Negative Big), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big). Meanwhile, the battery control uses three fuzzy rule functions with a value range between −145 and 145, categorized as low, medium, and high.



a b

Figure 10. (a) input error booster converter dan (b) input SOC baterai charging

Meanwhile, the membership function for the delta error variable is shown in Figure 11, consisting of seven fuzzy subsets with a value range from −300 to 300. The configuration of these variables includes dNB (Derivative Negative Big), dNM (Derivative Negative Medium), dNS (Derivative Negative Small), dZ (Derivative Zero), dPS (Derivative Positive Small), dPM (Derivative Positive Medium), and dPB (Derivative Positive Big).

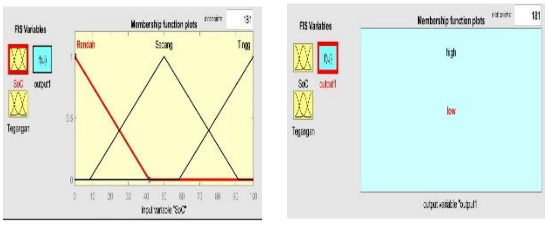


a b

Figure 11. (a) input delta error of booster converter (b) charging battery voltage input

The output of the fuzzy control logic is represented in the form of constant values or linear equations, as the applied fuzzy inference method is the Sugeno method. In this study, the fuzzy output is defined as constant values, meaning that each fuzzy variable has a single fixed value. The booster converter utilizes seven output variables, resulting in a rule base matrix of size 7 × 7. Meanwhile, the battery charging system employs three output variables, forming a rule base matrix of size 3 × 3. The configuration of the fuzzy logic output is illustrated in Figure 12.

After designing the membership functions, the next step is constructing the rule base. The rule base is a collection of IF–THEN rules, where each rule represents a conditional statement corresponding to predefined parameters and adjusted to actual system conditions. The rule base structures used in this study are presented in Table 3 and Table 4.



a b

Figure 12. (a) output of the booster converter and (b) output of the battery charging system

Table 3. Rule base sugeno inference system booster konverter

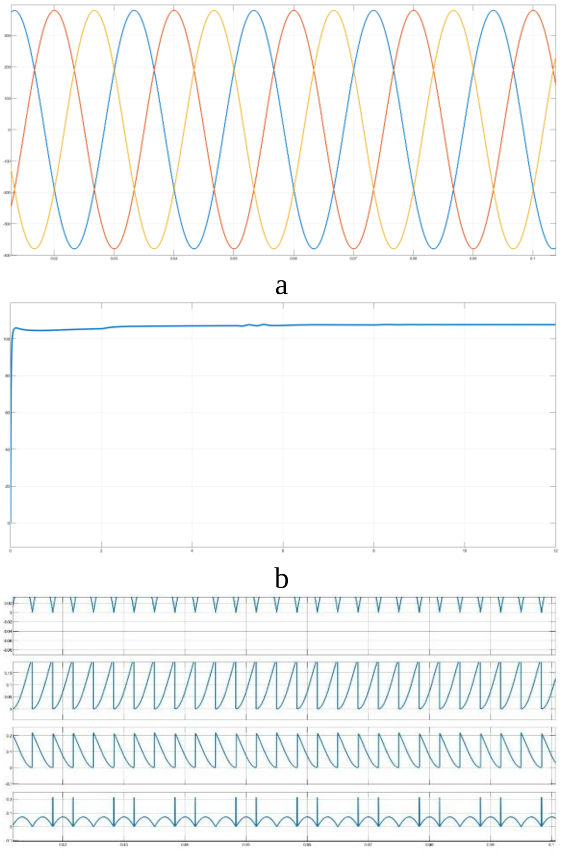
e/Δe	ΔNB	ΔNM	ΔNS	ΔZ	ΔPS	ΔPM	ΔPB
NB	B	B	B	B	M	S	Z
NM	B	B	B	M	S	Z	S
NS	B	B	M	S	Z	S	M
Z	B	M	S	Z	S	Z	B
PS	M	S	Z	S	M	B	B
PM	S	Z	S	M	B	B	B
PB	Z	S	M	B	B	B	B

Table 4. Rule base sugeno inference system charging battery

e/Δe	SoC Rendah	SoC Sedang	SoC Tinggi
Low Voltage	High	High	Low
Medium Voltage	High	Low	Low
High Voltage	Low	Low	Low

4.3 ***Simulation Results of the Model***

The modeling results of the Matrix Converter as a replacement for the conventional transformer, with a source voltage of 380 V AC converted by a rectifier into 110 V DC, are shown in Figure 14 below:



a

b

c

Figure 13. (a) Source voltage waveform, (b) Rectifier voltage waveform, (c) Duty cycle modulation signal.

From the simulation results shown in Figure 13 above, the Matrix Converter can function as a Solid-State Transformer, converting a 380 V source voltage into 110 V AC, which is then rectified into 110 V DC. Since the battery charging process requires a voltage of 126 V, a booster converter is utilized in this study to increase the voltage. The simulation results indicate an output voltage of 127.6 V, as illustrated in Figure 14 below :

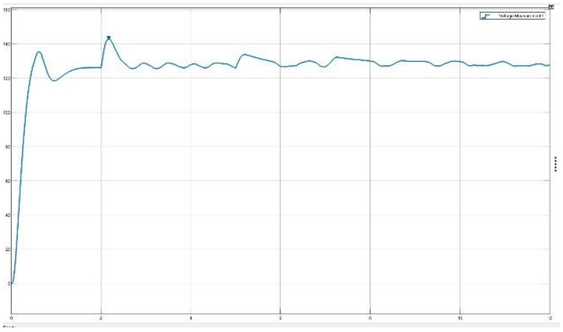


Figure 14. Battery charging output voltage waveform

From Figure 14, a single voltage ripple peak occurs at 2.17 seconds, reaching 142.9 volts. This ripple is caused by the switching process during motor load disconnection. Afterward, the voltage waveform stabilizes at 127.9 volts, which is used for the battery charging process.

5. CONCLUSION

The conclusions of this studi are as follows :

a. The Matrix Converter is proven to be an effective Solid-State Transformer (SST) replacement for conventional transformers, as demonstrated by its capability to convert a source voltage of 380 V into 110 V AC, which is then rectified into 110 V DC.

b. The fuzzy logic control using the Sugeno method successfully stabilized the voltage at 127.6 V, enabling the battery charging process to operate optimally and steadily. Consequently, the potential for black start failure in power plants due to charging malfunction can be mitigated.

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