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Fabrication and experimental study of transformer 400 V with a simple rectifier circuit design

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ABSTRACT

The demand for increased voltage in renewable energy sources is relatively high. This study examines the rapid development of technology considering the use of voltage-increasing transformers. Voltage regulator circuits are generally used to stabilize the output voltage of the rectifier according to the amount of input from the transformer. However, components for high-voltage stabilizer circuits are rare, which becomes an obstacle to the stabilization of the rectifier output. This study aimed to determine the performance of the designed rectifier circuit against a non-center tap step-up direct current (DC) 400 V transformer and compare the measurement results to manual calculations. The research method is a direct comparison between the input and output voltage values of the transformer after going through a rectifier circuit. This experiment was conducted using the repeatability method three to five times for each voltage variation on the transformer. The voltage variations successfully created are 0 to 50, 0 to 100, 0 to 200, and 0 to 400 V. The output test results from the DC transformer and rectifier circuit show linear results and an increase in peak-to-peak voltage data between the transformer and rectifier outputs by 3.8%.

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1. INTRODUCTION

The use of electricity is increasing day by day. Because non-renewable energy sources will run out in a few years. Many research developments are taking place on renewable energy sources to generate electricity [1]. The use of the electric current in everyday life in the household and industrial sectors has gone through generation and transmission in alternating current (AC). Energy can be stored in the field storage segment of interest (inductors, transformers) or the electric field storage section (capacitors) [2]. The sending and generating current of AC is more economical than that of direct current (DC) [3]. The transformer is one component that has an essential role in distributing electric current. The transformer is used to increase or decrease the AC voltage. The working principle of the transformer is based on the theory of AC electromagnetic induction [4]. The transformer can be applied to a high current with low voltage [5], [6]. Transformer life can be affected by transient currents that appear on it due to electromechanical forces [7].

The transformer is an important component of the power system, facilitating the economical transfer of power from generation to demand by changing its terminal voltage levels [8]. Transformers are used to decrease or increase the voltage sourced from power plants and can be raised to hundreds of kilovolts (kV).

At this time, the use of high voltage in renewable energy sources is very much needed. The high power demands are usually met by the advanced power electronics of the converter in some large utility and electric drive applications [9]. Renewable energy resources such as photovoltaics, wind turbines and fuel cells are widely used around the world [10]. In electricity production, solar photovoltaic plays an important role because it is widely available in almost all parts of the world, clean, reliable and scalable [11], [12]. One of the most important parts of a modern power system is a grid-connected photovoltaic (PV) system. Recently, this system has gotten a big revolution due to the introduction of transformer less inverter. It has the benefits of small size, low cost and high efficiency [13]. In the utilization of photovoltaic (PV), a DC voltage converter is needed as a voltage regulator output [14]. In order to increase the voltage level, it is important to design and study new high gain, efficient upgrade converters [15]. Several studies related to the use and testing of high-voltage transformer types have also been conducted [16]–[18]. The voltage will be distributed for various purposes after its increase.

One study has been developed on step-up converters by applying a single switch with a paired inductor and has a high-efficiency value [19]. DC-DC converters are increasingly important in several industrial applications [20]. Some common uses of DC-DC converters include controlling traction motors in electric car engines, forklift trucks, marine hoists, mine haulers, and trolley cars. This converter can be applied to improve energy conservation in transportation systems [21]–[23]. Very high gain step-up DC-DC power converters are commonly used in photovoltaic (PV) power generation systems and fuel cells [24]. In a micro converter, for example, the output voltage of each PV module (about 36 to 42 Vdc) must be raised directly to 400 Vdc [25].

Furthermore, the voltage-lowering type transformer reduces the distribution of high-voltage sources to meet household and industrial needs. The voltage drop generally reaches a voltage of 220/380 V [26]. In addition to the industrial and household fields, several researchers have examined the use of transformers, including that in the railway network [27], on a wireless temperature monitoring system as a producer of electrodynamic energy [28], in the copper production enhancement system [29], and that in the dielectric barrier discharge process [30].

The type of current in the transformer is AC. If a DC voltage is required for an electronic device, then converting AC into DC is necessary for operation. Generally the DC voltage generated by fuel cells is highly variable and of low magnitude; it is between 20 and 50 V at full load [31]. The nature of the DC supply lies in its stability and slight ripple coefficient, while the AC supply has minimal distortion. The circuit used to rectify AC into DC is called a rectifier circuit. The rectifier circuit is a wave rectifier, which is crucial in stabilizing the voltage in electronic circuits [32]–[34]. A wave rectifier on a power supply comprises four critical components: a voltage reducer (transformer), a wave rectifier (diode), a filter (capacitor), and a voltage regulator. The four main parts of the power supply operate to produce a stable DC. A DC power supply is vital in electronic devices because it can provide power that functions as energy for electronic circuits, such as amplifiers [35]. Previous research has developed a power supply designed for renewable-grid integration rectifier [36]. A block diagram of the rectifier location in a power supply circuit is shown in Figure 1.

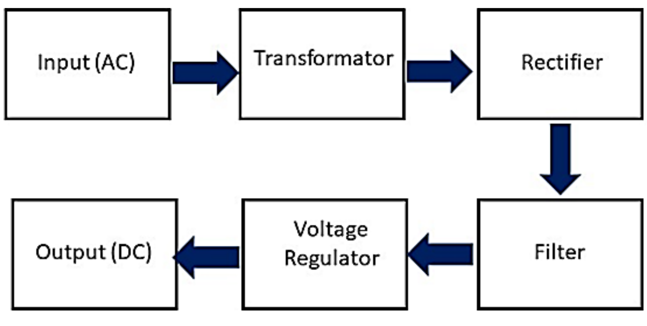

Figure 1. Power supply block diagram

Figure 1 shows that the position of the rectifier circuit is after the transformer and before the filter circuit. The rectifier position is critical because it provides DC for the following circuit block. A filter is needed to filter the waves after rectifying the transformer's voltage. The regulator circuit will stabilize the voltage value [37], [38]. The voltage regulator circuit generally aims to stabilize the output voltage of the rectifier according to the magnitude of the input from the transformer. However, components for high-voltage stabilizer circuits are rarely encountered, which becomes an obstacle to the output stabilization of the rectifier. The current research is focused on studying the fabrication of a non-CT 400 V transformer with four voltage variations and the fabrication of a rectifier circuit for further integration tests with and without a voltage regulator circuit. The transformer built in this study is a non-CT transformer with a voltage value of four variations from 0 V to 400 V, including 0 to 50, 0 to 100, 0 to 200, and 0 to 400 V. The concept of wave rectifier is divided into two types: half- and full-wave rectifiers. A full-wave rectifier is applied to an AC source from a zero transformer or a transformer with no center point (CT). The principle of a full-wave rectifier uses four diodes in the form of a bridge diode. A diode bridge is an arrangement of four diodes connected in a "bridge" manner. The diode bridge can be a compact packing with four legs or four separate diodes assembled as a diode bridge [39], [40].

DC voltage is the output of the rectifier circuit, which remains in the form of a substantially large ripple. The filter circuit is needed after the rectifier circuit to produce a low ripple DC voltage signal [41]. The filter circuit comprises a capacitor [42]. The type of capacitor commonly used for ripple filters is the electrolytic type of condenser. To produce a high voltage, a number of capacitors are connected in parallel to charge and then in series can produce a higher voltage during the off period [43]. The selection of capacitors as filters must meet the criteria. The adjustable gain converter switching capacitor is designed with multiple no-load voltages for higher efficiency over the voltage control range [44]. That is, the working voltage must be higher than the supply voltage and the capacitance value. These criteria determine the amount of ripple generated at DC voltage. The resulting DC ripple changes will remain unaffected When the capacitance is smaller. Conversely, if the capacitance value increases, the DC ripple will be smoother, approaching pure DC [45], [46].

The amount of DC voltage ripple in a transformer power supply is influenced by the value of the filter capacitor, load current, and frequency. The frequency value of the full-wave rectifier is similar to the input frequency of the transformer, namely 50 or 60 Hz. By contrast, the diode bridge rectifier has twice the input frequency of 100 or 120 Hz. To calculate the ripple voltage value, it is presented in (1),

$$\begin{aligned} V_{Ripple\ pp} &= \frac{V_{rect}}{f\ RL\ C} \\ &= \frac{V_{rect}}{f\ C}\frac{I_{load}}{V_{rect}} \\ V_{Ripple} &= \frac{I_{load}}{f\ C} \end{aligned} \quad (1)$$

where V_{Ripple} is ripple voltage (volts), V_{rect} is the peak voltage of unfiltered voltage, RL is the load voltage, I_{load} is load current (amperes), f is frequency (Hz), and C is value of capacitance (F).

The function of the capacitor is to suppress the ripple occurrence due to the AC wave rectification process. It is necessary to focus on being concerned about the output voltage ripple to obtain a pure output voltage. For a full-wave rectifier with a capacitor used to filter the input, the calculations to find the peak-to-peak ripple voltage and the value of the VDC filter output voltage are given in (1) and (2). Based on (1), the variable *Vp(rect)* is the peak voltage rectified without a filter. It can be illustrated that when the value of RL or C increases, the ripple voltage decreases, indicating that the DC voltage is rising. A DC Voltage is the DC (average) value of the filter's output voltage. A pure DC signal pure requires a substantial capacitance. Output voltage ripple can be reduced by choosing a large capacitor. The voltage ripple across each capacitor can be calculated by considering the decrease in voltage across the capacitor when the transistor is closed because the current is negative [47]. The output of this full-wave rectifier circuit will be a DC voltage after the capacitor is installed as a filter, which can be formulated as (2):

$$V_{dc} = \frac{2Vmax}{\pi} \quad (2)$$

where V_{dc} is DC voltage (volts), V_{max} is peak value of one rectifier diode (volts), and $\pi = 3.14$.

2. RESEARCH METHOD

The circuit design in this study requires several equipment and components, including tools and materials, to create a 400 V transformer, diodes, capacitor, voltmeter, connecting cable, printed circuit board (PCB) circuits, and others. The first step in designing a transformer is determining the specifications of the preferred transformer. The typical specifications of the transformer include determining the desired output voltage and the required components. The transformer created in this study is a non-CT transformer. The transformer and rectifier circuits can then be designed. The manufacture of a non-CT transformer requires a full-wave rectifier with four diodes, as shown in Figure 2. The figure shows the working principle of a full-wave rectifier with four diodes, which starts when the transformer output provides a positive-side voltage level: D_1 and D_4 are in the forward bias position, while D_2 and D_3 are in the reverse bias position. Furthermore, the positive peak-side voltage level will be passed through D_1 to D_4. D_2 and D_4 are in the forward bias position when the output of the transformer provides the negative peak-side voltage level, and D_1, D_2 are in the reverse bias position. Thus, the negative-side voltage level flows through D_2, D_4 [48].

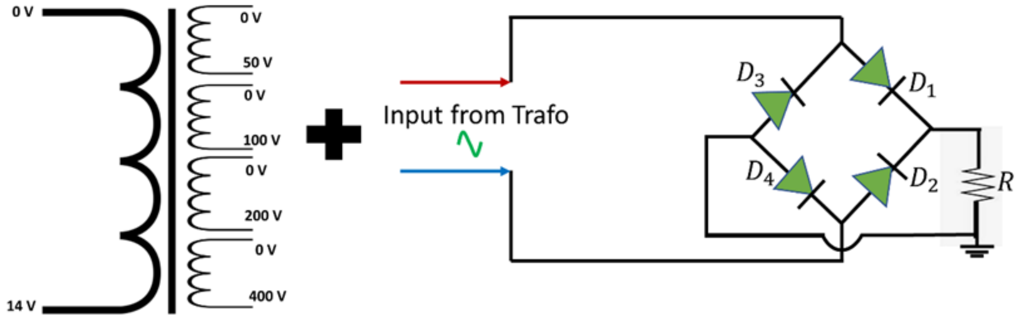

Figure 2. Full-wave rectifier with four diodes

Tests are conducted to determine the performance of the designed transformer and rectifier circuit. This test comprises two stages: precision testing on the transformer and integration testing on the rectifier circuit. The precision testing stage is performed at the input voltage from 0 to 400 V. The test results are then compared with measurements from theoretical calculations and multimeters and matched with variations in the initial voltage value on the transformer. Furthermore, the output of the rectifier is a DC voltage. The second test is the integration of the transformer with the rectifier circuit. The test scheme is shown in Figure 3.

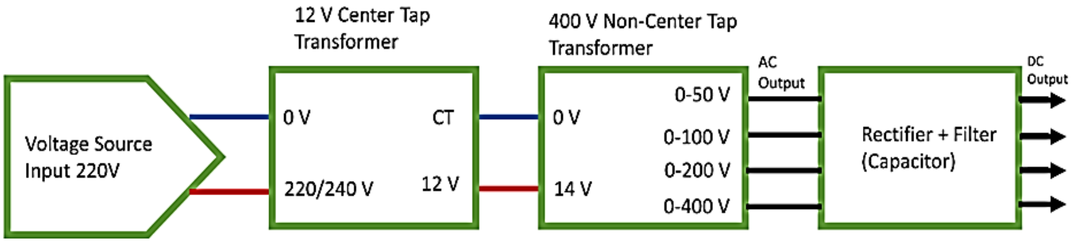

Figure 3. Schematic transformer integration test with a rectifier circuit

3. RESULTS AND DISCUSSION

The results of this study are in the form of a prototype design of a transformer and a rectifier circuit. The transformer comprises two or more iron cores wrapped in copper wire windings. AC will flow through the iron core; thus, the iron core can turn into a magnet. Figure 4 depicts a completed 0 to 400 V voltage transformer.

The transformer's voltage on the primary side comprises 14 V in this study. Four output voltage variations can be operated with a switch system, that is, switched on alternately on the secondary side, which includes the output of 50, 100, 200, and 400 V as shown in Figure 4. The winding of the wire in the transformer is created using enamel wire with a small cross-sectional area, and the current value is below 200 mA. The voltage level in the transformer can be changed by adjusting the number of wires turns in the transformer core, which can be used to calculate the voltage ratio in the transformer.

The manufacture of the transformer starts by creating cable/wire coils from the transformer core in the form of an iron plate and selecting the cross-sectional area of the cable/wire through the desired output current value. Electrical cables/wires have varying cross-sectional area sizes. A large cable cross-section indicates a substantial current carrying capability. The significant value of electric current that can be charged to an electric line is called the current conducting capacity (KHA). The manufacture of a transformer in this study uses a wire size of 2.1 and 0.35 mm for the primary and secondary sides, respectively. The cross-sectional area of the wire is based on the calculated current carrying capacity, which can be determined by calculating the power from the primary side of the required transformer. The necessary energy for the transformer is 154 VA. The power of 154 VA is then divided by the input voltage of the transformer of 14 V to produce a current value of 11 A. The KHA table reveals that a current of 11 A requires a wire with a cross-sectional area of approximately 2.5 mm to facilitate flow. Instead of modifying the transformer of a manufacturer, several reasons for creating a transformer design are as follows. Disassembling the transformer is difficult because the completed transformer contains resin and glue, which must be cleaned before modification. Another reason is that the magnet from the transformer may not adjust to the needs because the ready-made transformer is generally designed to follow the required size. Meanwhile, the designed transformer requires more magnets than ordinary transformer magnets.

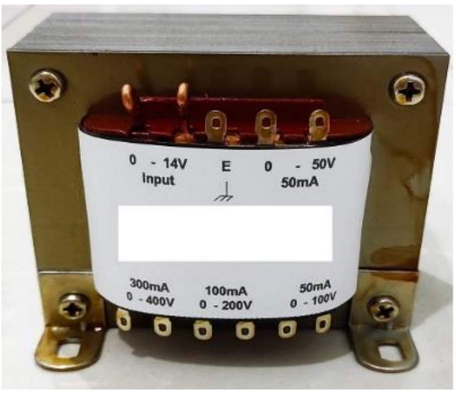

Figure 4. Transformer with a voltage variation of 0 to 400 V

3.1. Transformer test results

Testing the transformer prototype requires a 220 V AC voltage source from State Electricity Company (PLN). The output of the PLN electricity is forwarded to the step-down transformer from 220 to 12 V, and then the 12 V CT transformer output will be the input of the 400 V step-up transformer. The schematic and test results of the transformer are respectively shown in Figures 5 and 6.

Figure 5. Transformer test diagram

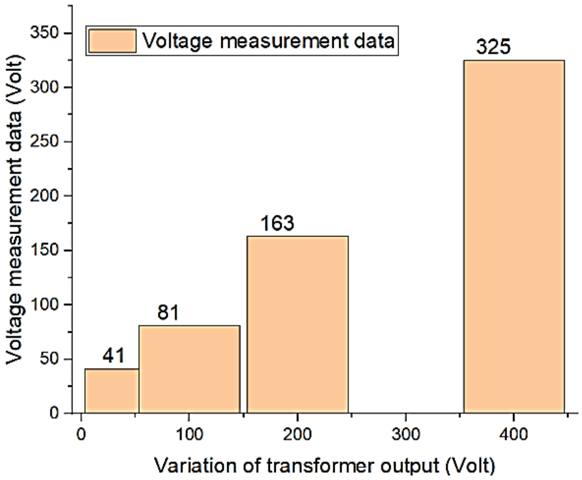

Figure 6. Graph of data from the test results for variations in transformer values

Table 1 shows the voltage drop from the voltage variation constant value in a non-CT transformer. The data presented are the average of the results of repeated measurements three times. The voltage drop is due to the voltage on the 12 V battery, which is only approximately 11.6 V. Therefore, the voltage data from the measured transformer output also decrease when the test is conducted.

Table 1. Transformer and rectifier circuit integration test data

Variation of step-up transformer output (Volt)	Transformer output (measurement) (Volt)	DC rectifier voltage output (Volts)
0	0	0
50	46.2	63.15
100	91.4	124.4
200	181	250
400	362	497.6

3.2. Rectifier circuit design and test

The rectifier circuit in the transformer amplifier comprises several components, which are presented in Figure 7. The specifications of this rectifier circuit contain four capacitors. Each capacitor is connected to the RS208 diode bridge. The rectifier circuit also comprises an input pin connected to the transformer's output and then rectified through a diode and filtered by a capacitor. Four diodes and capacitors each adjust to the needs of the variation of the transformer output: the 470 uf 160 V capacitor for the 50 and 100 V transformer output variations, the 470 uf 350 V capacitor for 200 V output variation, and the 470 uf 450 V capacitor for 400 V output variation.

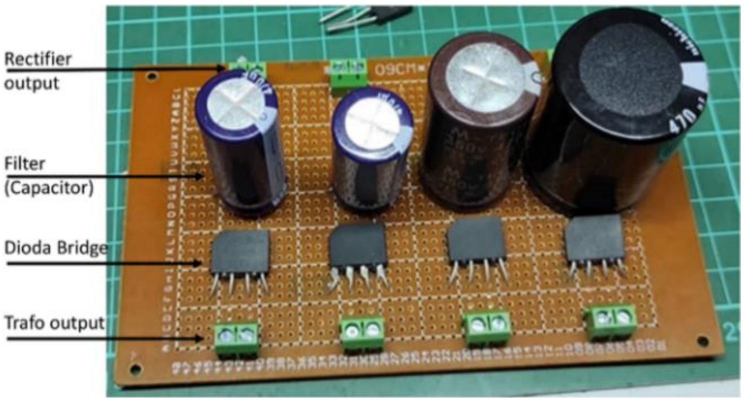

Figure 7. Rectifier circuit

The schematic of the integration test of the transformer and rectifier circuit is described in Figure 3. The test results data are then presented in Table 1. The transformer is integrated with a rectifier circuit using a 14 V DC voltage source. Table 1 shows an increase in the voltage value of the transformer output after going through the rectifier circuit. Theoretically, the transformer output voltage remains in the form of AC. If rectified to DC, then the voltage will increase. An AC scale Avometer is typically used when measuring AC voltage to determine the voltage value, and the data obtained by the Avometer include root mean square (RMS) voltage, not peak-to-peak (V_{PP}) voltage. Meanwhile, the voltage transforms into DC after being rectified using a rectifier diode and filtered by a capacitor (Elco). The DC voltage is then measured using an Avometer on a DC scale, and the voltage data obtained are the volt peak-to-peak (V_{PP}) voltage. This condition causes a difference in the voltage value when measured from the transformer input and rectifier output. Therefore, the measured voltage data have increased the value of the voltage data.

Calculating the safe voltage of the capacitor (Elco) in the rectifier circuit based on the data above is necessary. Therefore, the capacitor can work at a safe voltage, is durable, and is not easily damaged or dry. The conversion formula for RMS voltage to peak-to-peak voltage is written in (3):

$$V_{PP} = V_{RMS} + \frac{V_{RMS}}{3{,}14} \quad (3)$$

where V_{PP} is peak-to-peak voltage (Volts) and V_{RMS} is root mean square voltage (Volt).

The value of the transformer output voltage (V_{RMS}) has a difference of 24% from that of the V_{PP} based on the calculation results using (3). Figure 8 shows the graph of the relationship between the voltage variation on the transformer to the transformer output voltage in the form of conversion V_{RMS} to V_{PP} and the output voltage response in the rectifier circuit. The figure reveals that the output to the input voltage variation of 0 to 400 V shows a good linearity relationship. This finding indicates that the design is efficient. The test is conducted on the fluctuations in the output voltage value, namely for the output voltage with inputs of 50, 100, 200, and 400 V.

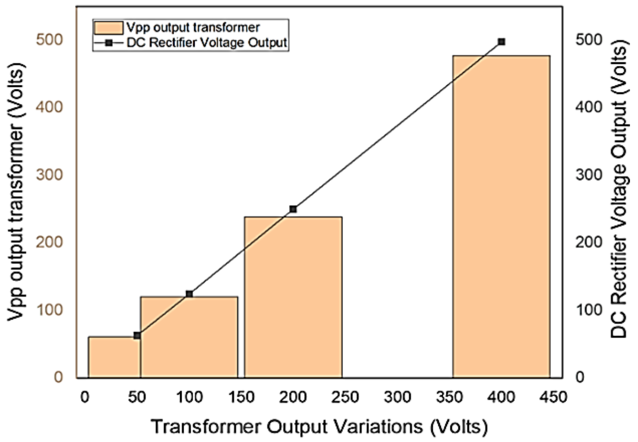

Figure 8. Voltage variation of the transformer on the results of the transformer and rectifier voltage measurements

4. CONCLUSION

This paper reports the successful design of a non-CT transformer and a 400 V DC high-voltage amplification rectifier circuit. The voltage variations successfully created are 0 to 50, 0 to 100, 0 to 200, and 0 to 400 V. The output test results from the DC rectifier transformer and diode circuit show linear results and an increase in peak-to-peak voltage data between the transformer output and the rectifier circuit by 3.8%.

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