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Analysis of the Effect of Capacitor Installation and Rectifier Circuit on the Reciprocating Load of a Single-Phase AC Generator

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Abstract

The role of rectifier circuits in electronic technology has long been known and often discussed. However, in its application, there is still a lot of potential that can be modified from this rectifier series so that the output produced becomes more optimal and can be applied in daily use. The rectifier circuit serves to convert alternating current (AC) into direct current (DC) [3]. Generators are also a component that is popularly used as an object of experimentation and research in the field of power electronics. A single-phase AC generator consists of a stator that generates electric current, a rotor to create a magnetic field, and an air gap between the stator and rotor [1]. With this construction, this generator is able to convert mechanical energy into electrical energy which produces alternating voltage (AC). This study discusses the analysis of the influence of uncontrolled capacitor installations and half-wave rectifier circuits on recisive loads in single-phase AC generators. In the experiments conducted, the installation of capacitors had a significant impact on the output waveform produced by the rectifier circuit. The sinusoidal waves generated by the single-phase AC generator will be straightened by the diode, and the installation of capacitors in parallel with the recisive load can reduce the noise generated in the output waves, so that the output is closer to the properties of pure direct current (DC) [2]. These findings provide a new understanding of the application of capacitors in improving the quality of power output generated by single-phase AC generators, which has the potential for further applications in the field of small electric power systems.

Keywords: Generator, Sinusoidal Wave, Rectifier, Phase.

1. Introduction

Electricity and human life today are inseparable. The role of electricity can be said to cover almost all aspects of human life in daily activities. Therefore, electricity has become a very important unit in human life and technological development.

In this industrial era, the development of electronic technology has an important role in small, medium, and large scale industries. One of the closest electronic technologies to our lives is the rectifier circuit. A rectifier is a power electronics circuit that can convert an alternating current (AC) voltage source into a direct current (DC) voltage source (Nugraha et al., 2022). These rectifiers can be found in a variety of electronic devices that we often encounter, such as mobile phone charging adapters and various other applications.

The rectifier serves to convert alternating current into direct current. Diodes are a very important component in rectifier circuits because they are semiconductors, but not much is known about the characteristics and performance of these rectifier circuits. Therefore, research and experiments were conducted on a series of rectifiers (Jones et al., 2018; Sharma et al., 2021).

No less important than the rectifier circuit, a synchronous generator or commonly called an alternator is an electrical machine that functions to convert mechanical energy into electrical energy by following the working principle of electromagnetic induction or fluctuation (Adhi et al., 2019; Wang et al., 2022). In its application, synchronous generators or alternators act as power plants on a small or large scale that produce alternating voltage or AC (Smith et al., 2020). In Indonesia, PLN (State Electricity Company) uses the generator function as an alternative power generation tool that utilizes renewable energy from nature, such as hydroelectric power plants (PLTA) that utilize the flow or flow of river water to drive water turbines (Lee et al., 2023), as well as wind power plants (PLTB) that utilize the speed of wind flow to drive wind turbines (Tanaka et al., 2023). The mechanical energy produced will be converted into alternating voltage electrical energy by AC generators which then go through several distribution processes to homes.

The installation of a single-phase AC generator or alternator as an alternating voltage source in an uncontrolled half-wave rectifier circuit with a recisive load faces several problems. One of them is that the voltage generated still requires a filtering process or filter to produce a voltage that is close to the nature of direct current (DC) so that it is safe to use in small electronic equipment that only requires a direct voltage source.

In an uncontrolled single-phase half-wave rectifier circuit, the component that plays an important role is not only the diode as the rectifier component, but also the capacitor mounted in parallel as a filter component to reduce the ripple voltage generated by the rectifier circuit (Smith et al., 2020; Nugraha et al., 2022). Therefore, a study is needed that explores how the working principle of each component in the rectifier series, which is presented in the form of analysis results through experiments and research that has been carried out to obtain the necessary data.

2. Material and methods

2.1. Material

2.1.1 Synchronous Generator

A synchronous generator is a machine that converts mechanical energy into electrical energy. This generator operates based on the principle of electromagnetic induction, as described by Faraday's Law of Induction: "If the number of magnetic lines of force through a coil changes, an electromotive force (emf) is induced in the coil. The magnitude of the induced emf is directly proportional to the rate of change of magnetic flux through the coil" (Smith et al., 2020).

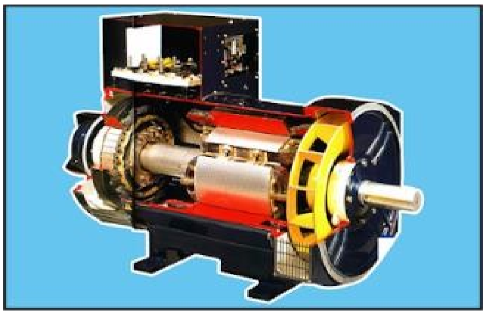

Figure 1. Synchronous Generators

The generator consists of a rotor with a field winding powered by direct current. This current produces a rotating magnetic field that matches the speed and direction of the rotor's rotation. The rotating field in the rotor induces a changing magnetic flux in the stator coils, leading to the generation of an emf at the coil's terminals (Jones et al., 2018).

2.1.2 Working Principle of Synchronous Generator

In a synchronous generator, there are two primary components: the field coil on the rotor and the armature coil on the stator. The field coil can take various forms, such as shoe poles or cylindrical types, while the armature coil is designed similarly to those in induction machines (Taylor et al., 2019; Brown et al., 2017).

The generator operates as follows:

a. The excitation source connected to the rotor supplies direct current to the field coil, which generates a constant magnetic field over time.
b. The prime mover coupled with the rotor rotates at a constant speed, inducing a rotating magnetic field that is transferred to the stator.
c. The rotating magnetic field induces a time-varying magnetic flux in the stator coils, which leads to the induction of voltage (emf) according to Faraday's Law (Clark et al., 2016).

The emf can be mathematically described as:

$$E = -N\left(\frac{d\Phi}{dt}\right) \quad (1)$$

where N is the number of turns in the coil and Φ is the magnetic flux. The induced emf is proportional to the rate of change of the magnetic flux (Bennett et al., 2015).

DOI xxxxxx

2.1.3 Diode

A diode is a two-electrode device that allows current to flow in one direction only, essential for rectifier circuits. Initially developed by J.A. Fleming in 1904, diodes serve as the core component in converting alternating current (AC) into direct current (DC) (Fleming et al., 2020).

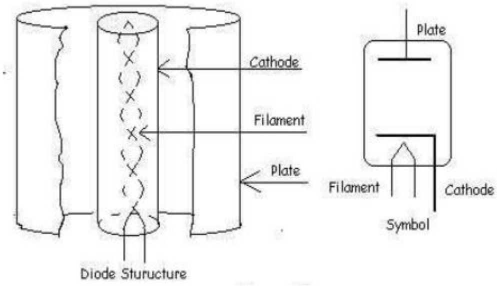

Figure 2. Diode Structure

2.1.4 Role of Electromotive Force in AC Generators

In single-phase synchronous generators, electromotive force (emf) plays a critical role in inducing current in the armature coil. When a metal is placed in an electric field, the free electrons move, creating an opposing electric field, thus generating an emf. The emf continuously drives the movement of electrons, ensuring the flow of current (Miller et al., 2020).

The emf source, which is typically a battery or another voltage source, maintains a potential difference across the coil, ensuring that the current flows continuously and the induction process remains active (Jones et al., 2018).

2.1.5 Synchronous Generator Anchor Reaction

When operating under no-load conditions, a synchronous generator does not have any current flowing through the stator coils. However, when a load is applied, the stator current generates its own flux, which interacts with the rotor's magnetic field, causing a shift in the terminal voltage. This effect is known as the anchor reaction (Li et al., 2020).

The anchor reaction can either strengthen or weaken the field flux, depending on the load and the power factor of the system. This reaction influences the synchronous reactance Xs and can be described as:

$$V = E - I \cdot Z \tag{2}$$

where V is the terminal voltage, E is the induced emf, and Z is the total impedance (Xu et al., 2017).

2.1.6 Synchronous Generator Construction

A synchronous generator consists of three main components: the stator, rotor, and air gap. The stator is stationary, while the rotor rotates within it, and the air gap separates these two components (Jones et al., 2018). In brushless synchronous generators, the rotor contains the field windings and the stator remains fixed. This configuration eliminates the need for brushes, commonly used in traditional synchronous machines (Zhao et al., 2021).

2.1.7 One-Phase Half-Wave Uncontrolled Rectifier Circuit

A half-wave rectifier circuit uses a diode to convert AC to DC. This circuit only allows one half of the AC waveform to pass through, resulting in a pulsed DC output (Green et al., 2022). The half-wave rectification process allows only the positive half of the sinusoidal wave to be conducted, while the negative half is blocked.

2.1.8 Electrolytic Capacitors (Elco)

Electrolytic capacitors are polarized passive components used in various electrical circuits. These capacitors store and release energy as needed, playing a crucial role in stabilizing voltage fluctuations in power supplies (Davis et al., 2019).

DOI xxxxxx

2.2 Methods

The methodology of this research was carried out at the Power Electronics Laboratory in June 2022. The equipment used includes hardware in the form of a laptop with AMD Ryzen 3 3200U processor specifications (2.6 GHz) with Radeon Vega Mobile Gfx, 8 GB RAM, 512 GB SSD, 14" Full HD backlight IPS LCD LED screen (1920 x 1080 pixels), and Windows Home x64 operating system. The electronic components used include single-phase semi-controlled wave rectifier modules, single-phase AC generators (alternators), AC/DC voltmeters, AC/DC ammeter, transformers, resistors, diodes, electrolyte capacitors (Elco), oscilloscopes, and connecting cables. The simulation was carried out using the Power Simulator (PSIM) software, which was chosen because of its ability to simplify the analysis of output waves and network characteristics. The research procedure includes the preparation of tools and materials, designing circuits based on the schematic, determining the parameter values for each component, and measuring parameters such as RMS input voltage, RMS input current, DC output voltage, DC output current, RMS output voltage, and RMS output current. Input and output voltage waves are observed using an oscilloscope, and the measurement results are compared with theory to determine the percentage difference. Furthermore, an analysis of the characteristic parameters of the series is carried out to produce conclusions. This research utilizes a half-wave rectifier circuit with a capacitor filter designed using a single-phase AC generator as a voltage source. The transformer is used to lower the voltage before entering the rectifier, which then converts the AC voltage into a half-wave DC voltage. The system block diagram includes the assembly stages of an AC generator with a transformer, the design of a half-wave rectifier with a resistive load, the addition of capacitors as filters, and the reading of the results using voltmeters, ammeteres, and oscilloscopes to evaluate the performance of the system. This methodology is relevant for publication in journals or engineering proceedings because it provides a detailed analysis of the performance of power electronic systems in energy conversion, with the support of empirical data and simulation validation.

3. Results and discussion

3.1. Design and Analysis of Source Voltage Step-Down System

At this stage, the voltage drop system from a single-phase AC generator source with an initial voltage of 220 V is designed to be lowered using a transformer. The transformer configuration is specified to produce an output voltage of 30 VAC. The calculation of the number of secondary turns (Ns) is carried out with the transformer formula as follows:

$$N_s = \frac{V_s}{V_p} \cdot N_p \tag{3}$$

By entering the primary winding value (Np=1) and the desired secondary stress, the value of Ns=0.192926 was obtained. Based on this configuration, the simulation results show that the transformer output voltage is at a value of 30 VAC, as visualized in Figure 3. In addition, the actual measurements show consistency with theoretical calculations, which is an indicator of the accuracy of the transformer design in lowering the voltage.

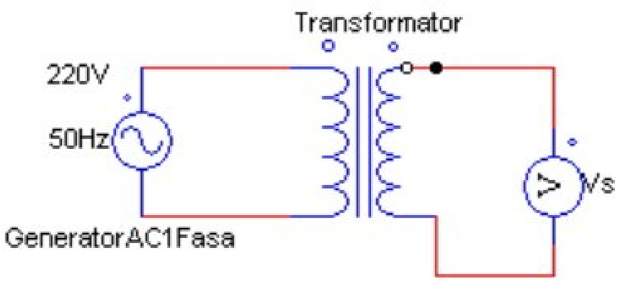

Figure 3. Voltage Lowering System Design

3.2. Uncontrolled Half-Wave Rectifier Network Design

The uncontrolled half-wave rectifier circuit is designed using key components such as a diode as the rectifier, a resistor with a load of 243.3 Ohm, and an electrolyte capacitor (C=2200μF) as a filter. This circuit is assembled together with a pre-designed transformer system. To measure voltage as well as input and output current, voltmeters and ammetermeters are used. Figure 4 shows a circuit configuration without filters, while Figure 5 shows a circuit configuration equipped with filters.

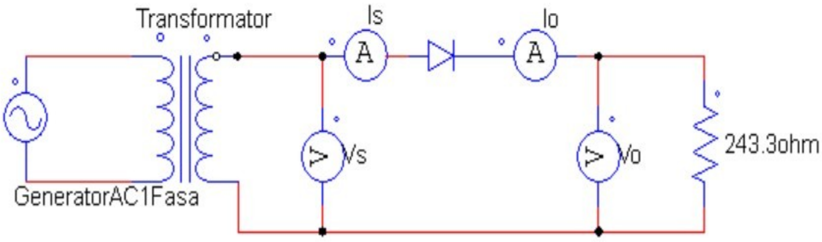

Figure 4. Unfiltered One-Phase Half Wave Uncontrolled Rectifier Circuit

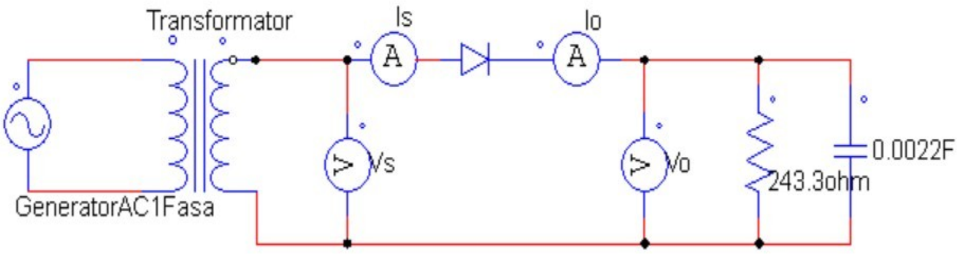

Figure 5. One Phase and Half Wave Uncontrolled Rectifier Circuit with filter

3.3. Unfiltered Circuit Simulation Results

The simulation results show that at an input voltage of 30 VAC (Vrms), the peak voltage (Vm) can be calculated as follows:.

$$V_m = V_{rms} \cdot \sqrt{2} = 30 \cdot \sqrt{2} = 42,43\,\text{V} \tag{4}$$

The average output voltage (Vdc) and average output current (Idc) are then calculated using the standard formula of the half-wave rectifier. The unfiltered output wave is visualized in Figure 21, which shows a half-wave pattern with unstable amplitude.

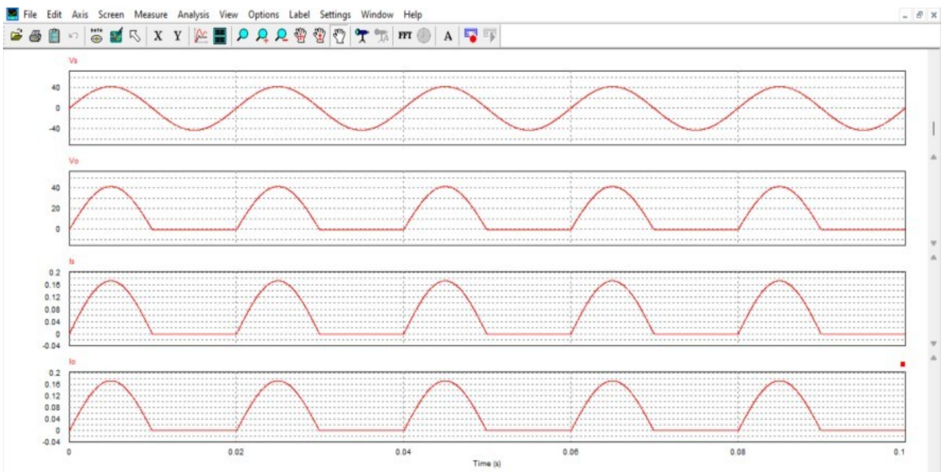

Figure 6. Unfiltered Rectifier Input and Output Waves

The simulation results data are summarized in Table 1, while the percentage of error between the simulation results and the theoretical calculations is shown in Table 2.

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Table 1. Unfiltered Rectifier Simulation Results

Shell(rms)	I s(rms)	V o(DC)prak	V o(DC)theory	I o(DC)prak	V o(rms)theory	V o(rms)prak	I o(rms)prak
30	0,085	13,15	13,51	0,054	21,21	20,76	0,085
45	0,133	21,21	20,26	0,087	31,36	32,57	0,133
60	0,17	26,65	27,01	0,109	42,42	41,97	0,17

Table 2. Error Percentage of Calculation and Simulation Results

Shell(rms)	V o(DC)prak	V o(DC)theory	Error %	V o(rms)theory	V o(rms)prak	Error %
30	13,15	13,51	2,66	21,21	20,76	2,12
45	21,21	20,26	4,68	31,36	32,57	3,85
60	26,65	27,01	1,33	42,42	41,97	1,06

3.4. Circuit Simulation Results with Filters

When a filter capacitor is added, the output voltage (V dc) becomes more stable with a wave pattern close to pure DC (Figure 7). The smaller ripple voltage indicates that the filter capacitor successfully improves the quality of the output voltage.

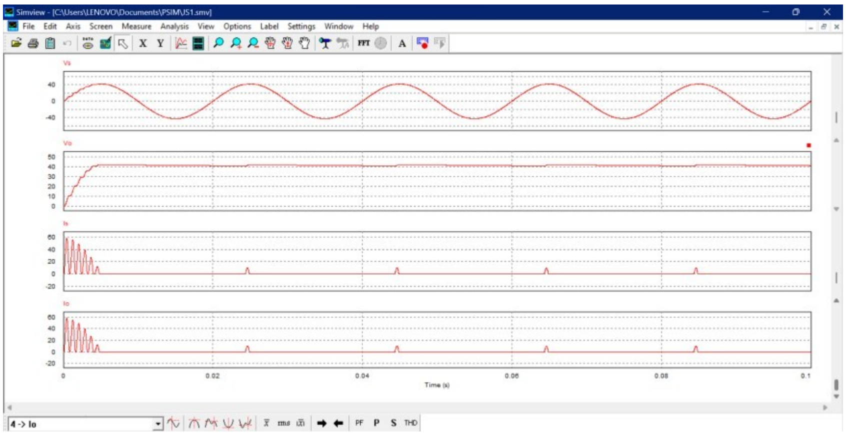

Figure 7. Rectifier Input and Output Waves with Filters

The measurement and simulation results are summarized in Table 3, while the percentage error between the simulation results and the theoretical calculations is shown in Table 4.

Table 3. Rectifier Simulation Results with Filters

Shell(rms)	I s(rms)	V o(DC)prak	V o(DC)theory	I o(DC)prak	V o(rms)theory	V o(rms)prak	I o(rms)prak
30	5,85	40,66	41,63	1,06	41,63	40,9	5,85

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45	8,87	61,68	62,45	1,62	62,45	62,05	8,87
60	12	82,67	83,26	2,17	83,26	83,17	12

Table 4. Error Percentage of Calculation and Simulation Results

Shell(rms)	$V_{o(DC)prak}$	$V_{o(DC)theory}$	Error %	$V_{o(rms)theory}$	$V_{o(rms)prak}$	Error %
30	40,66	41,63	2,33	41,63	40,9	1,11
45	61,68	62,45	1,23	62,45	62,05	0,64
60	82,67	83,26	0,708	83,26	83,17	0,108

4. Conclusion

This experiment concluded that the greater the value of the filter capacitor used, the smaller the value of the ripple voltage produced, thus approaching the characteristics of pure DC voltage. In an uncontrolled half-wave rectifier circuit, the output at the resistive load shows a value equivalent to the transformer output peak voltage, minus a voltage drop of 0.7 V due to the forward bias of the silicon diode. This analysis shows that the integration of transformer and rectifier is able to optimize the energy conversion from AC to DC with a low error rate between the simulation results and theoretical calculations.

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