Experimental Study of the Effect of Excitation Current on the Output Voltage of a Self-excited Synchronous Generator

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Abstract: Energy needs continue to increase. Currently, the demand for electrical energy is growing at a higher rate than other energies. Based on Energy Outlook 2019, coal-fired power generation still dominates. However, if no new coal reserves are found, then medium to high-quality coal reserves are projected to be exhausted in 2038. To meet the need for electrical energy, it is necessary to utilize the energy available in nature optimally and stable with changes in electrical load. The potential for hydro energy that can be utilized to generate electricity is 75,901 MW. Generators in a power plant have an important role as a converter of mechanical energy into electrical energy to be utilized. However, to be able to use the stability of the electrical energy produced needs to be considered. One way to stabilize the output voltage of a generator can be done by adjusting the excitation current value. Therefore, the purpose of this study is to determine the effect of the self-amplifying excitation system on a synchronous generator on the output voltage produced when there is no electrical load and an electrical load. The test results show that the excitation current greatly affects the output voltage of the synchronous generator. The hope of this research can be applied to the prototype of the vortex turbine pico hydropower plant which is currently being researched as well.

1 INTRODUCTION

Energy has an important role in supporting human life. Along with the times, energy needs continue to increase (Baskoro & Adiwibowo, 2017). Currently, the demand for electrical energy is growing at a higher rate compared to other energies (Team Secretary-General of the National Energy Council, 2019). Based on Energy Outlook 2019, coal-fired power generation still dominates. However, if no new coal reserves are found, then medium to high-quality coal reserves are projected to be depleted in 2038 (Agency for the Assessment and Application of Energy, 2018). To meet the needs of electrical energy, it is necessary to utilize the energy available in nature optimally and stable with changes in electrical loads.

Indonesia is very rich in its renewable energy potential. One of the renewable energy that can be used as electrical energy is hydro energy. Based on Indonesia's clean energy status report, the potential for hydro energy that can be utilized to generate electricity is 75,091 MW (Tampubolon & Adiatama, 2019). The utilization of hydro energy into electrical energy in a simple form is mostly obtained from the application of hydropower plants with pico and micro scales.

In a previous study conducted by Pambudi (2020), he has designed a laboratory-scale micro-hydro power generation system by utilizing an induction generator and a permanent magnet generator (synchronous generator) to compare the output of electrical power generated. The results of this study indicate that a permanent magnet generator (synchronous generator) has an optimal efficiency and power output of 195.3 watts with an efficiency of 89%. However, power plants can be utilized, if the output of electrical energy is stable due to changes in electrical load.

In another study conducted by (Syahputra, 2012), examined the effect of a synchronous generator voltage stabilizer system using a separate amplifier excitation system. The test results show that the synchronous generator output voltage is greatly affected by the size of the excitation current.

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However, the application of an excitation system with a separate amplifier is not possible if it is applied to a prototype of a pico hydropower plant that utilizes hydro energy directly in the river because the excitation system is easy to implement, namely utilizing a rectified generator output voltage for an excitation source for the synchronous generator itself.

Therefore, in this study, we will utilize a self-amplifying excitation system resulting from rectifying the AC power output from the synchronous generator into DC electricity, then stored in the battery as an excitation supply to the synchronous generator. The purpose of this study is to determine the effect of the self-amplifying excitation system on a synchronous generator on the output voltage produced when there is no electrical load and an electrical load. The hope of this research can be applied to the prototype of the vortex turbine pico hydropower plant which is currently being researched as well.

2 MATERIALS AND METHODS

2.1 Excitation System

The excitation system is a system of flowing direct current electricity supply as a reinforcement to the electric generator so that it produces electric power and the output voltage depends on the amount of excitation current (Nurdin et al., 2018). The generator excitation system is an important element to form a stable generator terminal voltage profile. The operating system of this generator excitation unit functions to keep the generator voltage constant (Fahmi & Irwanto, 2020). One of the excitation systems in an electric generator is an excitation system using a brush.

The excitation system uses a brush (brush excitation), the source of electric power comes from a power source that comes from a direct current (DC) generator or an alternating current (AC) generator which is rectified first using a rectifier. If you use a power source that comes from an AC generator or permanent magnet generator (PMG), the magnetic field is a permanent magnet. In the rectifier cabinet, alternating current is converted or rectified into direct current voltage to control the main exciter field coil. To drain the excitation current from the main exciter to the generator rotor using slip rings and charcoal brushes (Nurdin et al., 2018).

The use of slip rings and brushes, usually used in small-capacity generators. This spring is made of metal which is usually attached to the engine shaft but is isolated from the shaft. Where the two ends of the field winding on the rotor are connected to the slip ring. By connecting the positive and negative terminals of the direct current source to the slip ring through the brush, the field winding will get a supply of direct current electrical energy from an external source (Fahmi & Irwanto, 2020).

2.2 Synchronous Generator

An alternating current (AC) generator or also known as an alternator is a device that functions to convert mechanical energy (motion) into electrical energy (electrical) by means of magnetic field induction. This energy change occurs due to a change in the magnetic field in the armature coil (where the voltage is generated in the generator). It is said to be synchronous generator because the number of rotations of the rotor is equal to the number of rotations of the magnetic field on the stator (Nurdin et al., 2018). This synchronous speed results from the rotational speed of the rotor with the magnetic poles rotating at the same speed as the rotating field on the stator. The field coil in a synchronous generator is located on the rotor while the armature coil is located on the stator (Boldea, 2016).

Synchronous generators convert mechanical energy into alternating electrical energy electromagnetically. Mechanical energy comes from the prime mover that rotates the rotor, while electrical energy is generated from the electromagnetic induction process that occurs in the stator coils (Nurdin et al., 2018). A simple form of a synchronous generator can be seen in Figure 1. In general, a synchronous generator consists of a stator, a rotor, and a rotating part of the air gap. The air gap is the space between the stator and the rotor.

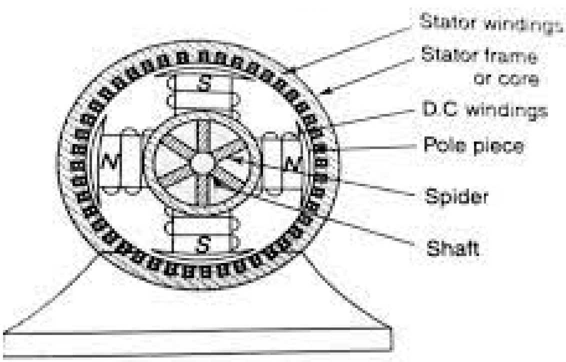

Figure 1: Synchronous Generator.

2.3 Synchronous Generator Working Principle

Nurdin (2018) in his book describes the working principle of a synchronous generator in general as follows:

1. The field coil contained in the rotor is connected to a certain excitation source that will supply direct current to the field coil. With the direct current flowing through the field-coil it will cause a flux whose magnitude with time is constant.
2. The prime mover which is coupled to the rotor is immediately operated so that the rotor will rotate at its nominal speed.
3. The rotation of the rotor will simultaneously rotate the magnetic field generated by the field coil. The rotating field generated in the rotor will be induced in the armature coil so that the armature coil located in the stator will produce a magnetic flux that varies in magnitude with time. A change in the magnetic flux surrounding a coil will cause an induced emf at the ends of the coil.

2.4 System Design

The overall system is depicted in Figure 2. The prime mover used to rotate the synchronous generator in this study was obtained from an electric drill set at a rotational speed of 1000 rpm – 1300 rpm.

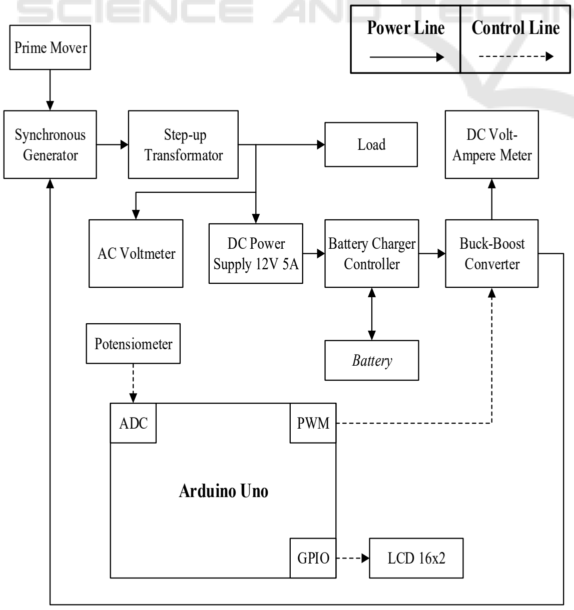

Figure 2: The Experimental Setup and The Design Diagram Block.

The rotational speed of this prime mover is made stable so that the research discussion does not get out of topic. The stable AC output voltage in this study was generated from a step-up transformer with the aim of getting a working voltage value of 110V AC. Meanwhile, the synchronous generator used is a car alternator that has a working voltage of 12V AC.

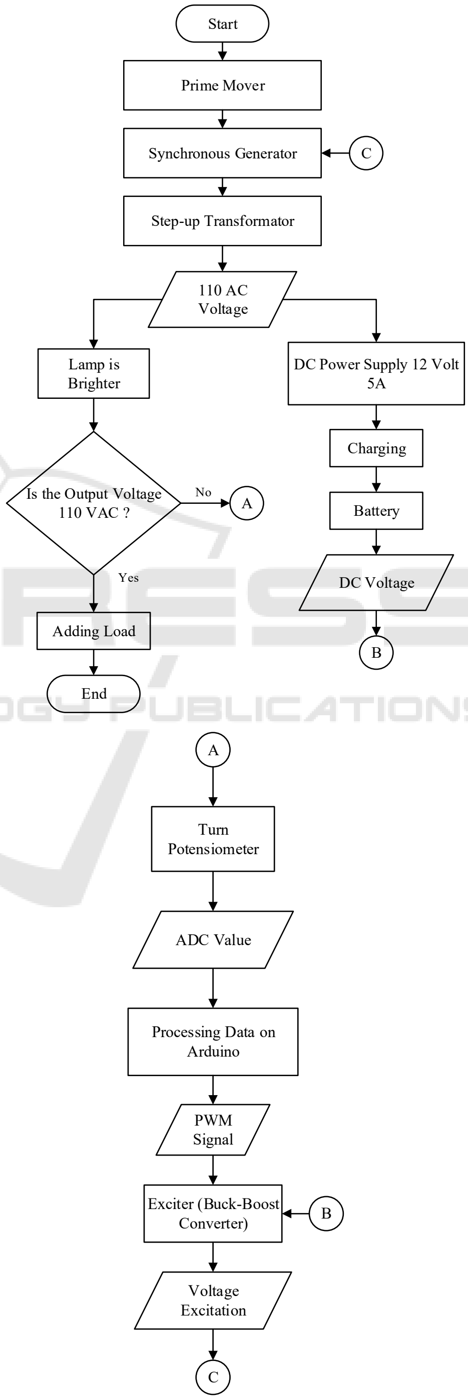

Figure 3: Flow Chart Excitation System.

The output voltage of this transformer will then be used as a supply for the excitation and loading system. The electrical load used for testing the stability of the output voltage is a 5-watt incandescent lamp. In accordance with the block diagram in Figure 2, the excitation system used is a self-excited excitation system. The self-excited system in this study was designed by changing the AC voltage output to a stable DC voltage with the aim of supplying the battery storage system which is used as an excitation supply. The use of the battery here is done with the aim of making the supply input voltage to the exciter, namely the buck-boost converter, stable. The buck-boost converter exciter is controlled by a microcontroller with ADC input from a potentiometer to adjust the duty cycle of the exciter. This stability setting is seen from the results of the AC voltmeter reading which then by looking at the voltmeter it can be done by setting the excitation by turning the potentiometer. 16 x 2 LCD is used to display the duty cycle value. The workflow of the tool in this study can be seen in Figure 3 below.

2.5 Wiring Diagram

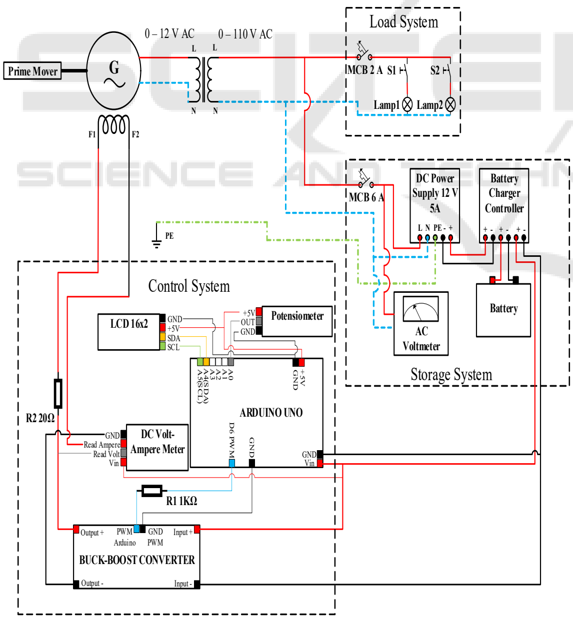

Figure 4: Wiring Diagram of the Voltage Stabilizer.

The wiring diagram of the excitation system in this study is shown in Figure 4. The excitation system made has 2 systems with their respective functions connected to each other. The two systems are storage systems and control systems. The storage system is used for charging the battery as an exciter supply in the control system. The DC voltage output from the battery will be connected to the supply with the exciter (buck-boost converter) and at the same time supply to the microcontroller (Arduino Uno).

The control system in the plan made uses Arduino Uno as a regulator of the exciter output voltage value (buck-boost converter). The excitation DC output voltage on the exciter is controlled by setting the duty cycle by the microcontroller with the ADC input by the potentiometer. The DAC output value from the microcontroller in the form of PWM is obtained from the conversion of the potentiometer ADC value to the duty cycle value.

3 RESULTS

In accordance with the purpose of this study, the tests carried out were testing the synchronous generator excitation system with no load and electrical load. Figure 5 shows the testing of the excitation system circuit in this study.

Figure 5: Excitation System Circuit Testing.

Excitation system testing is carried out by keeping the AC output voltage value reaching a working voltage of 110V AC. Table 1 contains test data on the effect of excitation current on AC output voltage without loading.

Table 1: Zero Load Test with *If* Setting.

RPM	Vf (V)	If (A)	V Out (V)	K (%)
1159	0,00	0,00	11,76	No Excitation
1194	2,00	0,04	21,14	99
1120	2,20	0,05	23,17	90
1297	2,40	0,06	25,60	80
1280	2,80	0,08	25,84	70
1196	3,50	0,12	28,82	60
1059	12,00	0,48	23,48	50
1005	13,10	0,53	23,83	40
1130	13,60	0,54	25,41	30
1114	13,90	0,56	25,40	20
1113	14,20	0,58	26,18	10
1110	14,50	0,58	25,82	0
1275	15,30	0,61	105,20	52
1268	15,70	0,62	107,80	51
1233	15,80	0,63	107,10	50
1291	16,20	0,65	111,10	49

This no-load test was carried out at Alwy's house which aims to see how the effect of the excitation current on the AC output voltage. In this no-load test, the rpm value is maintained in the range between 1000 - 1300 rpm, because the prime mover used is an electric drill with rpm depending on the stability of the electric voltage at home. Based on the data in Table 1, the output voltage will be strongly influenced by the presence of excitation current according to the graph in Figure 6 below.

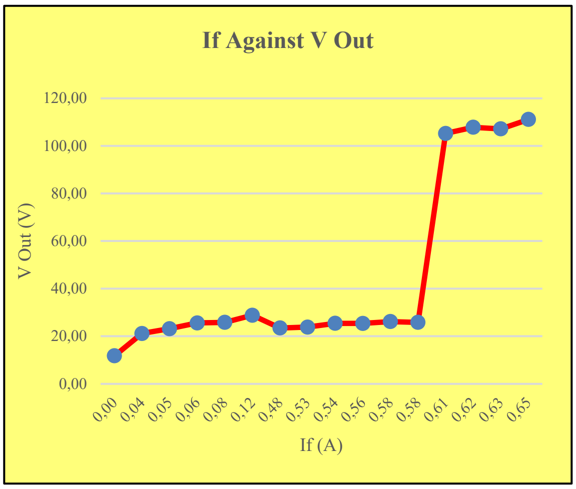

Figure 6: Characteristics of Excitation Current Change to The Zero Load Generator Output Voltage.

The graph in Figure 6 shows that the output voltage will increase with an increase in excitation current. The increase in excitation current will cause the rotating magnetic field to increase in the rotor. The rotating field generated by this rotor will then be induced in the armature coil in the stator which results in greater magnetic flux. The greater the magnetic flux changes, the greater the induced emf at the ends of the coil.

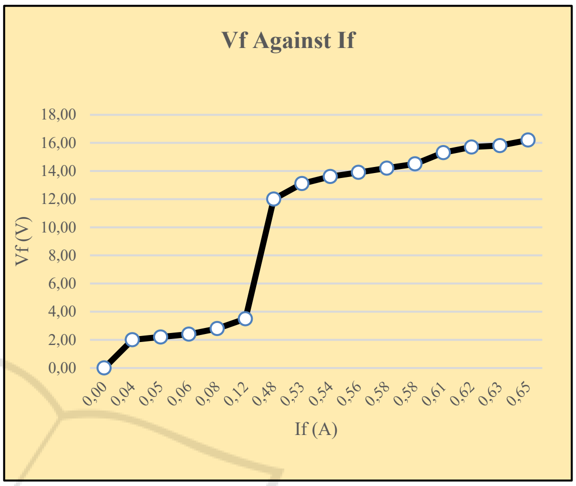

Figure 7: Graph Effect of The Excitation Voltage on The Excitation Current.

Figure 7 shows an increase in excitation current caused by an increase in excitation voltage in the exciter with the duty cycle setting as switching on the buck-boost converter MOSFET which is regulated by the microcontroller (Permana & Dewira, n.d.). The buck-boost converter which acts as an exciter will provide a DC voltage to generate an excitation current which makes the field coil on the generator rotor create a magnetic field. So that in this study attempts to adjust the value of the excitation current by setting the excitation voltage because the value of the excitation resistance is fixed.

The reliability of the generator in producing electrical energy is also seen from testing the stability of the output voltage against loading. Figure 8 is a photo of the excitation system testing with a load using a 5watt incandescent lamp.

The following table 2 contains the test data for the excitation system under loading if the excitation current value is kept constant. The electrical load used is a 5watt incandescent lamp. This incandescent lamp is used as an electrical load because it has a good cos phi compared to other electrical loads.

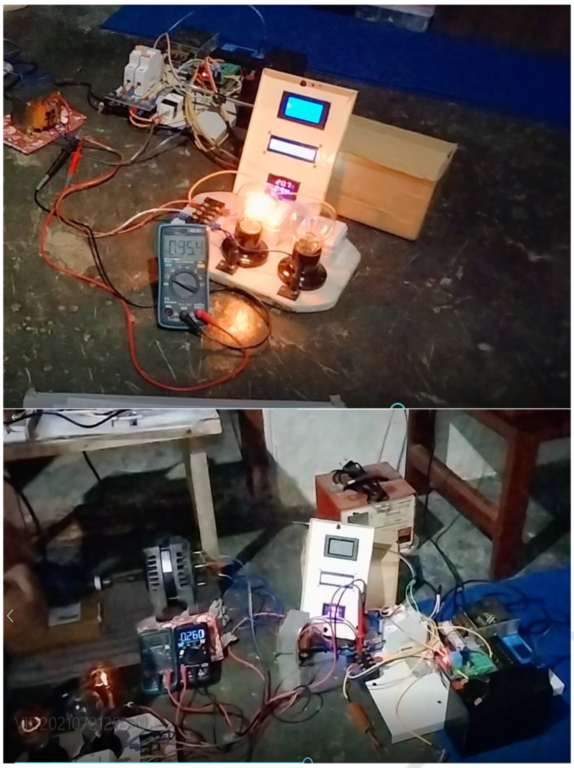

Figure 8: Excitation System Circuit Testing with Lamp.

Table 2: Loaded Test with Constant *If*.

RPM	Vf (V)	If (A)	K (%)	Ia (A)	V Out (V)	Load (Watt)
1142,00	14,30	0,59	0	0	90,17	0
832,90	14,30	0,59	0	0,124	38,65	1 x 5
710,40	14,30	0,59	0	0,191	16,71	2 x 5
687,50	14,30	0,59	0	0,224	7,86	3 x 5

The value of the excitation current is kept constant in order to see the effect of increasing the value of the load current (Ia) on the value of the resulting output voltage. The graph in Figure 9 describes the characteristics of the change in load current (Ia) to the output voltage.

Characteristics of changes in the value of the load current (Ia) which is increasing will cause the value of the output voltage to decrease. In addition, the increasing value of the load current will cause the value of the RPM to decrease. The graph in Figure 10 shows a decrease in RPM caused by an increase in load current.

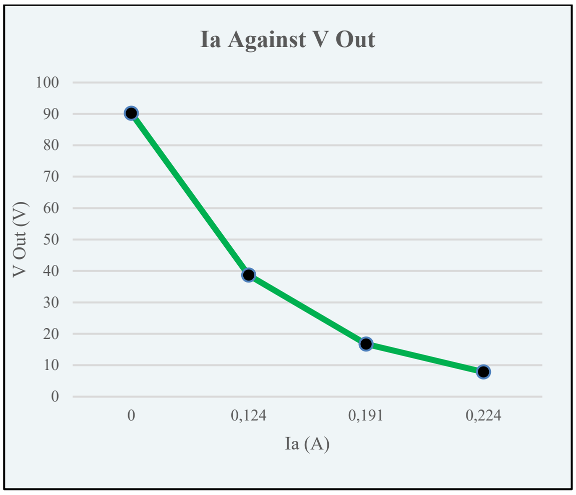

Figure 9: Load Change Characteristics (*Ia*) to The Generator Output Voltage with Constant *If*.

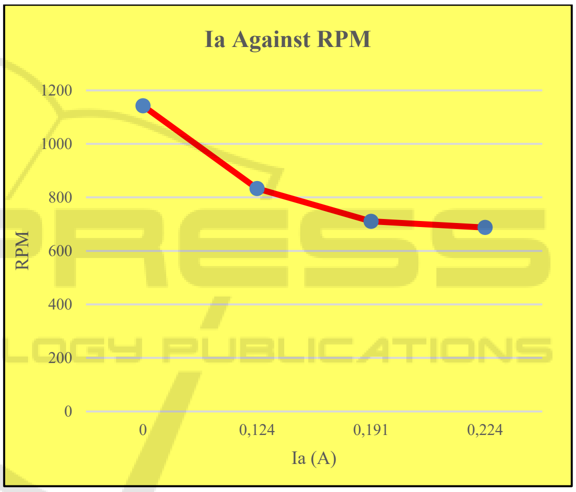

Figure 10: The Effect of Increasing Load Current on RPM.

Table 3 below contains data from the experimental results of the excitation system under load conditions by setting the excitation current value. This experiment was conducted with the aim of knowing the effect of increasing the excitation current under load conditions on the resulting output voltage.

Table 3: Loaded Test with *If* Setting.

RPM	Vf (V)	If (A)	K (%)	Ia (A)	V Out (V)	Load (Watt)
1175	16,3	0,66	50	0,000	110,40	0
1172	20,6	0,84	46	0,146	95,40	1 x 5
1178	24,7	1,06	36	0,250	90,90	2 x 5
1172	28,9	1,30	0	0,318	89,80	3 x 5

The graph in Figure 11 shows the effect of the excitation current (If) on the output voltage under load conditions.

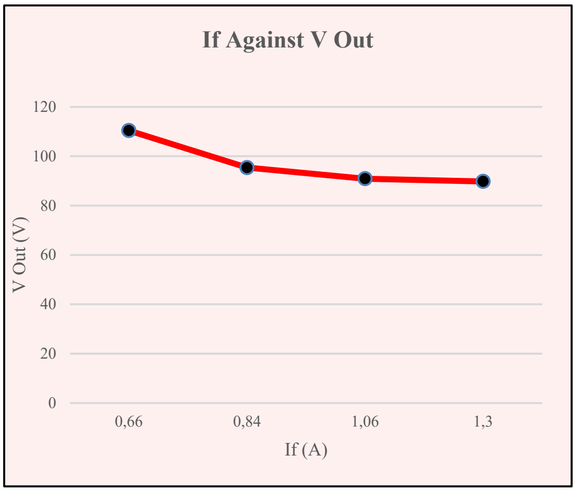

Figure 11: Effect of The Excitation Current on The Output Voltage in Loaded Condition.

From the graph, the value of the output voltage will be relatively stable at the condition of the output voltage value of 80 – 110 V AC when the load current value increases. This stable output voltage is because the value of the excitation current is increased according to the condition of adding a load that causes the output voltage to drop.

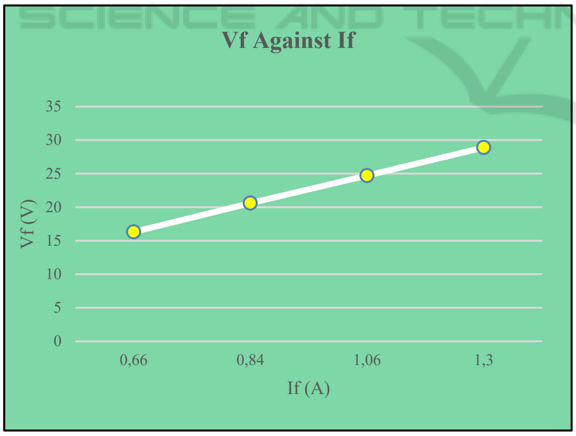

Figure 12: Graph Effect of The Excitation Voltage on The Excitation Current with Load Changing Condition.

Under loaded conditions, the excitation current value will give a stable output voltage value. An increase in the excitation current in this study is caused by an increase in the value of the excitation voltage at the exciter. The graph in Figure 12 shows the condition of an increase in excitation current caused by an increase in excitation voltage.

4 DISCUSSIONS

Each test performed, the rotation of the synchronous generator is treated constant ranging from 1000 - 1300 rpm, and it is seen that the increase in the value of the excitation current in the field winding greatly affects the generator output voltage. The greater the excitation is given, the greater the generator output will be (Boldea, 2016). Excitation current test results are in line with the following equation:

$$Eff = n \times c \times \emptyset \quad (1)$$

Where:
Eff = ggl effective induced (Volt)
c = constant
n = rotor rotation (rpm)
∅ = magnetic flux (Weber)

If the excitation current value (If) is constant when the load test is carried out, the voltage value will be inversely proportional to the addition of the load current (Ia) (Li, 2019). The higher the load current value, the lower the output voltage value. The value of the voltage can be stabilized by increasing the excitation current in the field coil in the rotor of the synchronous generator.

5 CONCLUSIONS

Based on the tests and analyzes that have been carried out, it can be concluded that the output voltage of the synchronous generator is strongly influenced by the adjustment of the excitation current given. The output voltage value of 110 VAC in the zero-load test occurs when the excitation current is 0.65A while if an excitation current of 0.04 the output voltage is still at a value of 21.14 VAC. The generator output voltage will be directly proportional to the excitation current value. The addition of the load causes the generator output voltage to decrease, this shows an inverse relationship between the addition of the load current (Ia) and the synchronous generator output voltage.

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