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DESIGN AND CONSTRUCTION OF AN AUTOMATIC VOLTAGE REGULATOR FOR A SYNCHRONOUS ALTERNATOR

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***Abstract.** The Automatic Voltage Regulator (AVR) is necessary to keep the terminal voltage of a loaded alternator constant. It is widely used to increase the regulation and stability of synchronous alternators especially in bulk power plants where efficiency and stability is of paramount importance. The AVR is a feedback controller that varies the excitation of the alternator to support a constant output voltage by increasing or decreasing the excitation level of the alternator as the load varies. In this research, the transfer functions of the various stages of the AVR are decided for the purpose of the design of the Voltage Regulator. The performance of the AVR is decided by the basic no load and load test on the alternator. The results show that there was tremendous improvement in the terminal voltage of the alternator with the AVR and a significant drop in the terminal voltage of the alternator without the AVR.*

Keywords: automatic voltage regulator, synchronous alternator, voltage regulator

1. INTRODUCTION

The synchronous alternator has remained the only equipment for generation of bulk electricity to drive industries on which modern economies of nations depend. Today synchronous alternators that can generate up to 500MW are available in the market. Consequently, the Automatic Voltage Regulator, which is one of the peripheral equipment for stable and effective operation of the modern alternators needs to be well understood in developing economies. In Nigeria where efforts have been ongoing to overcome the woes of severe dearth of generating capacity and reduce the cost of getting the technology for bulk power generation, the need to develop the technology for alternator peripheral equipment such as the AVR cannot be overemphasized.

Early controllers which applied the use of bank of resistors, motor generator sets (ward-Leonard system) were bulky, slow in response and most times generated losses to their disadvantage. Also, their efficiencies were compromised and not amenable to the closed loop control system and had to be checked closely. The disadvantages said above made them occupy space, with high cost and uneconomical. Due to the invention of semiconductor controllers and other peripheral control equipment's, precise speed and power control of machines were developed. The semiconductor controllers which is more compact, amenable to the feedback control, having less losses and increased efficiencies dropped the disadvantages met by the conventional controllers mentioned above. The foremost recognized control system was the Hero's device built in the 17th century [1].

In recent times, different control schemes and programs are being developed for easy control and to give high performance output of electrical machines. The necessity for the automatic voltage regulator arose with the high drop of terminal voltage with load in electric power alternators. An alternator voltage regulator can be defined as a device for varying at will the output voltage of the alternator or for automatically supporting it at or near a prescribed value. With an automatic voltage regulator, the voltage of an alternator can be supported constant even under rapid fluctuation of load. The automatic voltage regulator AVR usually run through the field of the alternator or the field of an exciter to vary the field current with the changes in line voltage. In the case of system disturbance, the automatic voltage regulator will respond to prevent the voltage from falling enough for the synchronous machine to lose synchronism thereby causing instability to the system. Modern day AVR consists of thyristor and transistor-controlled systems. The thyristor is a semiconductor switch which is used for a wide variety of application. The thyristor is controlled to force excitation downwards as well as upwards as needed to vary the output voltage of the alternator.

The aim of this project is to design, construct and analyse the performance of a synchronous alternator with the peripheral AVR equipment control. The need for the project cannot be over emphasized since at the centre of any power generating plant is an alternator. The performance of the alternator and by extension its efficiency should be of utmost importance to a power engineer. This will be done by examining the synchronous alternator, analyse the various control equipment's and obtain its operating limits.

A study of the performance characteristics of all circuit devices and systems to be used in the AVR is to be done. The transfer function of the AVR for the alternator, the exciter and the thyristor controller in the forward path were obtained using the natural characteristics and parameters of each stage. Also, the transfer function of the voltage sensing circuit in the feedback path was obtained to produce a complete block diagram of the AVR being designed. With the block diagram, the stability of the AVR is investigated using the Routh Hurwitz criteria. This would enable a design for corrective circuits in the feedback path to be introduced. The performance of the AVR and the steady state error are to be obtained as tests results after the design and construction of the peripheral equipment.

2. SECTION 1 – AUTOMATIC VOLTAGE REGULATOR

An automatic voltage regulator for an alternator is a device designed to support a constant voltage level at the terminals of the alternator. As a result of the presence of armature resistance, the terminal voltage of the alternator reduces as the load increases. The automatic voltage regulator increases or reduces the excitation of the synchronous alternator automatically if there is a decrease in the output voltage because of transient disturbance in the system. Active and reactive power demands changes continually and are never steady, therefore the excitation of alternators must be regulated continually to match the reactive power demand with reactive generation otherwise the voltages of various system buses may go beyond the prescribed limits [2]. The feedback system in the automatic voltage regulator makes it automatic. The feedback in the automatic voltage regulator is used to compare the reference excitation signal with the error signal. The difference between them is amplified and used to control the regulation element in such a way as to reduce the voltage error [3]. Various kinds of automatic voltage regulator exist, but for this project, the static continuous type of automatic voltage regulator is investigated. It has the advantage of supplying extremely fast response times, it has no moving parts, small for given power output and the cost is decreased while system reliability is increased [2].

The automatic voltage regulator includes a reference system to give an error signal whose magnitude and sign depends on the deviation of the output signal V_o from the reference signal V_{ref}. The excitation controller then responds to the error voltage V_{er} accordingly [4]. The excitation controller is ideally an amplifier with gain K_o such that:

$$V_{ex}=K_oV_{er} \tag{1}$$

The error voltage is proportional to the deviation of V_o from V_{ref}:

$$V_{er}=V_{ref}-K_1V_o \tag{2}$$

The alternator may also be regarded as an amplifier since its internal voltage is proportional to the excitation voltage:

$$V_o=K_2V_{ex} \tag{3}$$

From equation (1) and (2):

$$V_{ex}=K_o(V_{ref}-K_1V_o) \tag{4}$$

From (3) and (4):

$$V_o=K_2(K_oV_{ref}-K_1V_o) \tag{5}$$

Therefore:

$$\frac{V_o}{V_{ref}} = \frac{K_0K_1K_2}{1+K_0K_1K_2} \tag{6}$$

2.1 Transfer function of the D.C. exciter field

A hypothetical exciter is assumed available as in most power station alternators.

The exciter field current is given using Laplace transformation by (Figure 1):

$$V_f(s) = I_f(s)\,[R_f + sL_f] \tag{7}$$

$$I_f(s) = \frac{V_f(s)}{R_f} \times \frac{1}{1+\tau_f(s)} \tag{8}$$

Were

$\tau_f = L_f/R_f$ - the exciter field time constant

V_f - Exciter field voltage in volts

I_f - field current

R_f - Resistance of the exciter field

L_f - Inductance of the exciter field

The emf of the dc exciter is given by:

$$E_o = K_1\,\omega\,\phi$$

Where:

E_o - emf of the exciter field

ϕ - exciter field flux

ω - speed of rotation of the exciter

K_1 - constant

But $\phi = K_2\,i_f$

$$E_o = K_3\,\omega\,i_f = K_v\,\omega\,i_f \tag{9}$$

Where:

$$K_3 = K_1\,K_2$$

If the exciter voltage regulation is ignored,

$$V_f = K_3\,\omega\,i_f$$

For a constant speed of rotation

$$V_f = K_e\,i_f$$

Where:

$K_e = K_3\, \omega$ - gain of the exciter field (Volt/Amp)
$V_f(s) = K_e\, I_f(s)$

Substituting equation (8) into (9) we have:

$$E_o = K_v\, \omega \frac{V_f}{R_f(1+\tau_f s)}$$

$$\frac{E_o}{V_f} = K_v\, \omega \frac{1}{R_f(1+\tau_f s)}$$

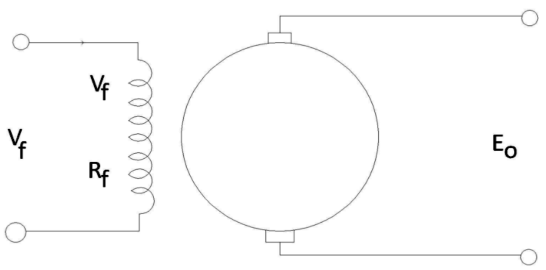

Figure 1. Excited DC Field

2.2 Transfer function of the voltage sensing circuit

The transfer function of the voltage sensing circuit (Figure 2) is given by:

$$\frac{V_L(s)}{V_S(s)} = \frac{1}{1+sR_D C_L} = \frac{1}{1+\tau_s}$$

Where:
R_D - forward resistance of the rectifying diodes
C_L - filter capacitor
$\tau_s = R_D\, C_L$

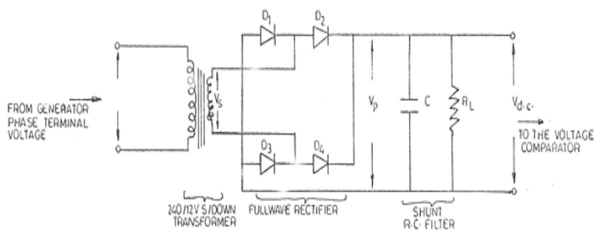

Figure 2. Voltage Sensing Unit

2.3 Transfer function of the automatic voltage regulator

The closed loop transfer function of the automatic voltage regulator is given by:

$$T(s) = \frac{G(s)}{1+G(s)H(s)}$$

Where:
G(s) - forward loop transfer function, $G(s)= G_1(s)\times G_2(s)\times G_3(s)$
H(s) - feedback loop transfer function

Using:
$G_1(s)$ = Amplifier = K_A
$G_2(s)$ = Exciter circuit = $\frac{K_e/R_f}{1+\tau_f s}$
$G_3(s)$ = Alternator = $\frac{Kg/R_g}{1+\tau_g s}$
H(s) = Voltage sensing circuit = $\frac{1}{1+\tau s}$

Therefore, the transfer function of the automatic voltage regulator becomes:

$$T(s) = \frac{G_1(s)G_2(s)G_3(s)}{1+\, G_1(s)G_2(s)G_3(s)H(s)}$$

Substituting the above equations, the transfer function becomes:

$$T(s) = \frac{K_A\left(\frac{K_e/R_f}{1+\,\tau_f s}\right)\left(\frac{K_g/R_g}{1+\,\tau_g s}\right)}{1+\,K_A\left(\frac{K_e/R_f}{1+\,\tau_f s}\right)\left(\frac{K_g/R_g}{1+\,\tau_g s}\right)\left(\frac{1}{1+\,\tau s}\right)}$$

2.4 Transfer function of the comparator

The comparator circuit is used to compare the output voltage (feedback voltage) of the alternator with the dc reference voltage of the AVR. An error voltage is the difference between the feedback dc voltage of the alternator and the reference voltage of the AVR which is sent to the amplifier circuit for amplification. The 741 IC was used as the comparator circuit for this AVR as shown in Figure 3. The output waveform of the comparator is a dc wave since a feedback voltage from the alternator stepped down, rectified and filtered is compared to a reference dc voltage to give a dc waveform.

Mathematically,

$$V_e = V_{o\,(dc)} - V_{Ref\,(dc)}$$

$$V_o = V_e$$

The Amplification of the comparator is $\frac{R_f}{R}$, therefore the output voltage is:

$$V_o = \frac{R_f}{R} \cdot V_e$$

A 741 IC with $R_1 = R_2 = R_3 = 10\text{k}\Omega$ was used for the design.

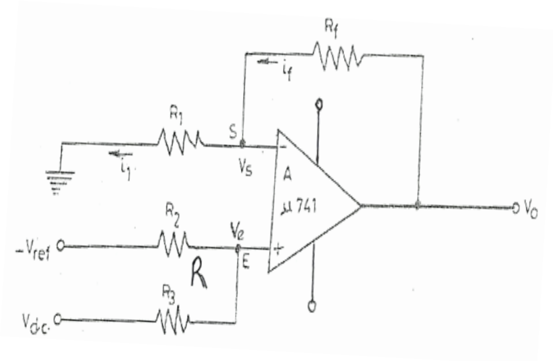

Figure 3. Voltage comparator

2.5 Transfer function of the voltage amplifier

The amplifier circuit receives as its input the output of the comparator circuit. (Figure 4) This input to the amplifier which is the error voltage from the comparator could be so small and insensitive when compared to the voltage required to fire the thyristor firing circuit hence the need for the amplifier circuit. The amplifier circuit which is a 741 IC amplifies the error voltage from the comparator and then fed to the firing circuit in the forward loop as the control voltage to the firing pulses. The control voltage controls the point at which the thyristor is fired to support the required operating conditions and in so doing controls the excitation of the field of the alternator. The output waveform of the amplifier is a dc waveform since a dc waveform was received from the comparator.

Output voltage of Amplifier = V_o
Input voltage of Amplifier = V_e = Error voltage
Transfer function = $\frac{V_o}{V_e}$
Amplification = - $\frac{R_f}{R_1}$

$$\frac{V_o}{V_e} = -\frac{R_f}{R_1}$$

$$V_o = -\frac{R_f}{R_1} \cdot V_e$$

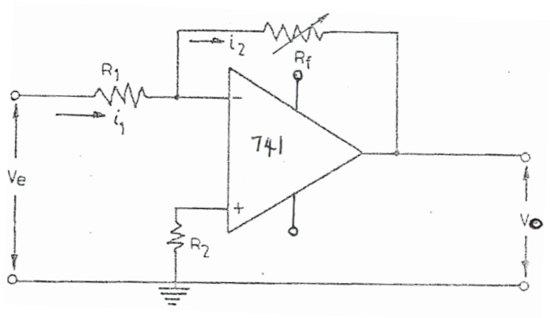

Figure 4. Voltage amplifier

2.6 Transfer function of the asymmetrical single-phase bridge

The bridge rectifier is two diodes and two thyristors in the asymmetrical configuration used for the control of armature current of the dc motor. Half wave rectification is achieved through the diodes. The thyristor which is a semiconductor switch regenerates the power back into the supply system. Consequently, they force excitation downwards as well as upwards. They are controlled by signals in the form of firing pulses from the firing circuit (UJT) (Figure 5). The error signal from the automatic voltage regulator is amplified and applied to the firing circuit which regulate the output of the asymmetrical single-phase bridge by varying the point in the supply cycle at which the thyristors fire i.e., their firing angles [5]. The controlled output is then supplied to the field of the generator.

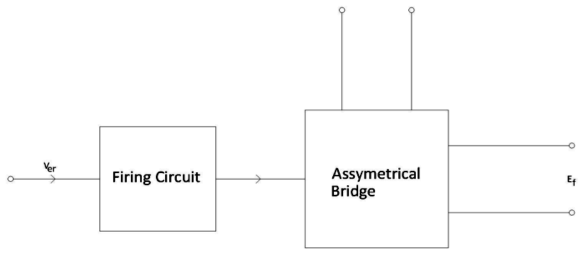

Figure 5. Asymmetrical single-phase bridge

E_f - Exciter field = 220V
V_{er} - Error voltage
K_A - DC Open loop gain
V_{Ref} - Reference voltage = 6V

During the laboratory test of the project. Range of Error voltage:

$$V_{er} = 0.1V \text{ to } 0.7V$$

$$\text{Gain } K_A = \frac{E_f}{V_{er}}$$

3. SECTION 2 – DESIGN AND ANALYSIS OF THE AVR

Alternators are one of the sources of reactive power. The alternators reactive power is controlled by the excitation of the field. A change in the real power demand of an alternator affects the frequency while a change in the reactive power demand affects the voltage magnitude. The basic way to control the reactive power of an alternator is to control the alternators excitation field using an automatic voltage regulator (AVR) to hold the terminal voltage magnitude of the alternator at a specified level. When there is an increase in the reactive power load of an alternator, it will be followed by a drop in the terminal voltage magnitude. This drop in terminal voltage will now be sensed by the feedback loop of the AVR.

3.1 The AVR in open loop

The transfer function block diagram for the AVR was given as (Figure 6):

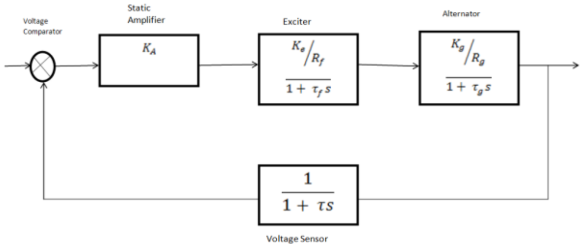

Figure 6. Block diagram of an AVR

Tests on the AVR circuit. The AVR was tested using an alternator in the laboratory. The input voltage to the AVR of 240VAC supplies controlled excitation to the alternator. With the AVR in open loop, the alternator was driven up to synchronous speed using the DC motor and the weakening of its field to raise the speed. The output of the asymmetrical bridge was varied to excite the alternator to produce output voltage above rated voltage. The excitation voltage was varied using the variable resistor R of the firing circuit (Figure 7).

By displaying the output voltage of the bridge on the oscilloscope and varying the resistor R of the firing, it was confirmed that the excitation voltage and hence the output voltage of the alternator can be phased backwards or forwards.

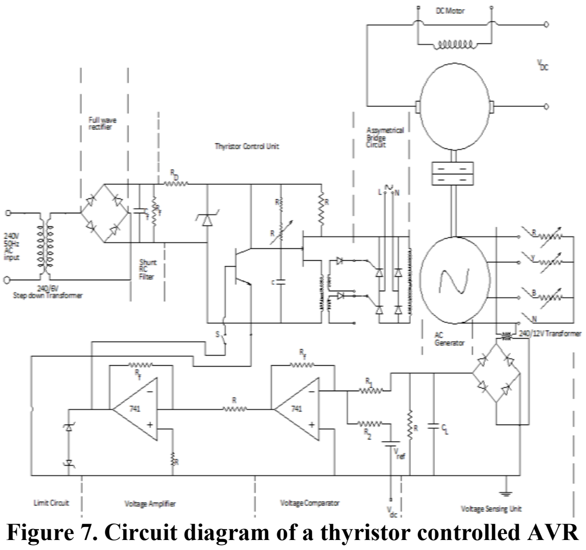

Figure 7. Circuit diagram of a thyristor controlled AVR with an alternator

Testing the firing circuit. The firing circuit of the asymmetrical single-phase bridge as shown in Figure 5 above used for the AVR was a UJT oscillator that generated pulses used to turn on the thyristor through a pulse transformer. The UJT is biased to feed and control the excitation circuit of the alternator through the pulse transformer to the asymmetrical single-phase bridge.

The waveforms as displayed below are the output waveforms of the different stages of the circuit in the oscilloscope in the laboratory (Figure 8).

Figure 8. Output waveform of the pulse transformer

Testing of the comparator. The 741 IC was used as the comparator circuit. It compares the reference dc voltage with the alternator terminal voltage to give a comparator dc output voltage. Whenever there is an occurrence of an error voltage V_e in the comparator, it is amplified with an amplification factor of $\frac{R_f}{R}$ to give a comparator output voltage of V_o. If the comparator output voltage is equal to the error voltage multiplied by the amplification factor i.e.:

$$V_o = \frac{R_f}{R} . V_e$$

then the comparator is in perfect condition. For the tests carried out in the laboratory, the comparator output voltage was always equal to the amplification factor multiplied by the error voltage. The output wave as seen in the oscilloscope in the laboratory is as shown below (Figure 9).

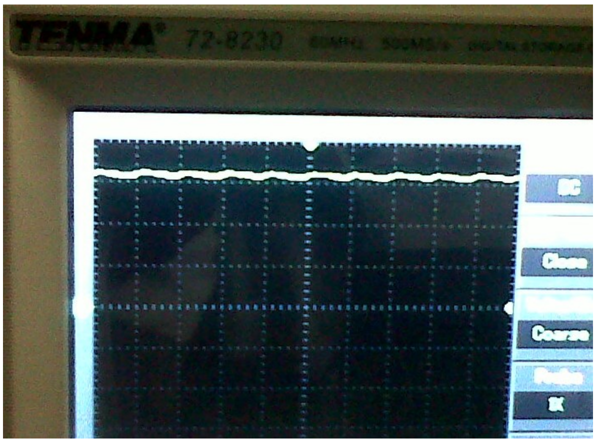

Figure 9. Output waveform of the comparator

Testing of the amplifier. The amplifier receives as input the output of the comparator circuit with the sole aim of amplification to produce its own output. The amplifier amplifies a less sensitive error voltage from the comparator that will be fed to the firing circuit in the forward loop as the control voltage to the firing pulses. When the amplifier receives the error voltage V_e, it amplifies at a constant amplification factor of $\frac{-R_f}{R}$ to give an amplified output voltage V_o. If the output voltage of the amplifier is equal to the error voltage multiplied by the amplification factor i.e.:

$$V_o = \frac{-R_f}{R} \cdot V_e$$

then the amplifier is in perfect condition. If not, it is not in good condition.

For the tests carried out on the amplifier in the laboratory, the amplified output voltage is equal to the error voltage multiplied by the amplification factor. The output of the amplifier as seen in the oscilloscope in the laboratory is as shown below (Figure 10).

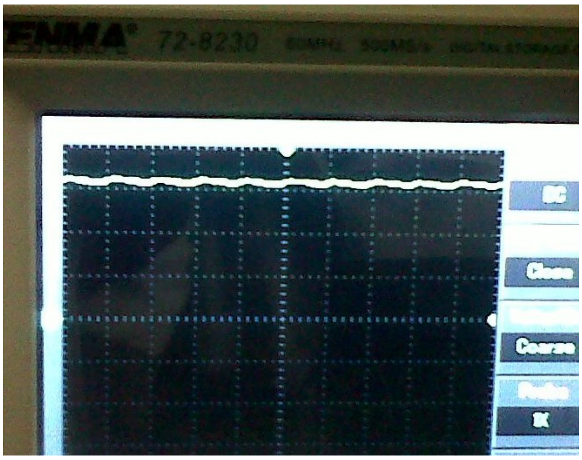

Figure 10. Output waveform of the amplifier

Load test on the alternator. The loading frame was connected to the alternator. The alternator was run up to synchronous speed and its output voltage was varied up to its rated voltage. The loading frame related to the AVR on open loop. The load was varied and a record of the variation of the terminal voltage with load was taken. The AVR switch S was then closed, and the load varied to obtain the variation of the terminal voltage with load. The variation of the terminal voltage with load, with and without the AVR is shown in Figure 11. The terminal voltage without the AVR is seen to drop to about 50% of its no load value at a load current of 8 Amps. With the AVR in place, the drop in terminal voltage is reduced to about 10% for the same load current. This shows the efficiency of the AVR in reducing the drop in terminal voltage. Steady state errors of 1-2% are achievable in modern AVR design. The use of the AVR achieved a constant terminal voltage up to a load current of about 3.5 Amps before the voltage drop started.

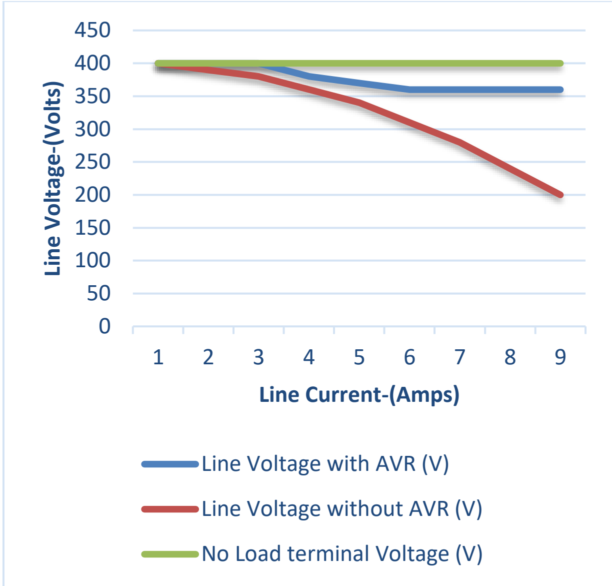

Figure 11. Alternator Load Test Graph

The table below (Table 1) gives the relationship between the line current in Amperes and the variation of the terminal voltage of the AVR in Volts on no load, load with and without the AVR.

Table 1. Alternator test results

Line Current (A)	No Load terminal Voltage (V)	Line Voltage without AVR (V)	Line Voltage with AVR (V)
0	400	400	400
1	400	390	400
2	400	380	400
3	400	360	380
4	400	340	370
5	400	310	360
6	400	280	360
7	400	240	360
8	400	200	360

4. CONCLUSION

A thyristor based Automatic Voltage Regulator was designed and constructed for a 5KVA synchronous alternator driven by a D.C motor. The peripheral equipment was tested on the alternator to obtain its efficiency in preventing a drop in terminal voltage when the alternator is on load.

The voltage regulation was achieved by using an asymmetrical single-phase bridge controlled by a UJT oscillator to feed the excitation circuit of the alternator. Feedback control was achieved by using the error voltage to turn a transistor that increases or reduces the rate of charging of the oscillator capacitor. The parameters of the experimental machine were measured and the transfer function of each section of the controller obtained. The block diagram of the AVR was thus derived enabling one to investigate its ability to control and regulate the alternator terminal voltage, its stability, stages of output waveforms and its speed of response.

The various sections of the AVR were tested separately for design performance. The alternator was tested on no load and on load with and without the AVR. The terminal voltage without the AVR was seen to drop immediately for a line current of 1Amps to about 50% of the initial line voltage at a line current of 8 Amps while the terminal voltage was seen to experience a gradual drop for a line current of 3.5 Amps to 6 Amps to maintain a constant terminal voltage even as the line current was increased with a total drop of about 10% of the initial line voltage. For the no load test on the alternator, no drop in line voltage was experienced. Also, an oscilloscope was used to test the output waveform of the various stages of the AVR, it was seen that the output voltage of the comparator was a dc waveform which conform to theoretical standards of comparing a dc reference voltage with a feedback dc rectified and filtered voltage. The output of the amplifier voltage was a dc waveform since a dc waveform was received from the comparator.

The results from this research confirm that the AVR increases the performance and stability of the alternator on load to keep a constant terminal voltage even as the load increases.

In conclusion, it is recommended that every power generating plant should have an AVR due to its high importance as found in this project work. In the future research work of a similar project, it is necessary to add a controller that will act as a stabilizer to the AVR to improve its performance.

5. REFERENCES

[1] D'azzo J. and Houpis C. Linear control systems analysis and design. International Federation of Automatic Control 1983; 19(5): 587.
[2] Htay M. and San Win K. Design and construction automatic voltage regulator for diesel engine type stand-alone synchronous generator World Academy of Science, Engineering and Technology 2008; 42: 652-658.
[3] Alam MR, Roy R B., Jahangir S.M. and Rahman D.J. Single phase automatic voltage regulator design for synchronous generator. International Journal of Electrical and Computer Sciences IJECS-IJENS 2011; 11(05) 37-42.
[4] Okoro C.C., Design criteria for an automatic voltage regulator for alternators. The Nigerian Engineer 1983; 18(3): 131-137.
[5] Rajput R.K. Electrical Machines. books.google.com., 2002.