JEES JOURNAL OF ENGINEERING AND EARTH SCIENCES

JEES ISSN: 1897-8680
JEES 2023
VOLUME 16 ISSUE NO 1
PAGE 11 - 20

EXPERIMENTAL INVESTIGATION OF EXCITATION VOLTAGE IMPACTS ON THE SYNCHRONOUS GENERATOR OUTPUT VOLTAGE

*,[1]Ogunlowo, M., [2] Ojo, A. J., & [3]Ejiko, S. O.
[1,2]Department of Electrical & Electronic Engineering, Federal Polytechnic, Ado Ekiti
[3]Department of Mechanical Engineering, Federal Polytechnic, Ado Ekiti
Corresponding author: jide4tees@gmail.com

ABSTRACT

This study is aimed at conducting an experimental investigation of excitation voltage impacts on synchronous generator voltage output. One of the major concerns in the operation of a generator is the means of exciting the field windings which determines the magnitude and stability of the output voltage. During this process, excitation has to be provided for the generator windings since generators require excitation systems to remain synchronized; the basic function of excitation systems is therefore to provide the energy required for the magnetic field keeping the generator in synchronism. There are two methods of coupling usually adopted for generators, these are direct and indirect coupling (rigid and flexible coupling). In this research work, the direct coupling method is used to have maximum mechanical energy transfer between the prime mover and the alternator. Measurements of relevant electrical quantities such as current, speed, a.c, and d.c voltage were taken using an ammeter, tachometer, and voltmeter respectively while the readings were tabulated analysis. It is obvious from this work that, if the excitation voltage is not regulated to give the acceptable output voltage of 220V ± 5% at a corresponding induced voltage, it could cause damage to electrical loads connected across the output terminals of the synchronous generator. It is envisaged that research effort would be subsequently channeled towards achieving the design and development of an automatic voltage regulator (AVR) with 85% local content to address this problem and examine its effects on the output voltage as an improvement to this research.

KEYWORDS: Analysis; AVR; Coupling; Excitation; Measurement; Turbine

INTRODUCTION

Electric energy (power) is produced by coupling a prime mover that produces the mechanical energy to an alternator through which electrical energy is being produced. There are two methods of coupling usually adopted for generators, these are direct and indirect coupling (rigid and flexible coupling). In this research work, the method used for coupling is a direct coupling method. The basic block diagram is shown in Figure 1.

This research effort exploits the experimental approach to investigate the effect of varying the excitation voltage on the output voltage of a synchronous generator. This when achieved, would assist in the design and development of an automatic voltage regulator locally, using 85% local content materials. Ngema (2016) stated in his work that generators require excitation systems to remain synchronized. The basic function of excitation systems is therefore to provide the energy required for the magnetic field keeping the generator in synchronism. Boldea (2015) submitted that energy is defined as the capacity of a body system to do mechanical work. Intelligent harnessing and control of energy determines essentially the productivity and, subsequently, the lifestyle of, and advancement of a society. Energy is stored in nature in quite a few forms such as fossil fuels (coal, petroleum, and natural gas); solar radiation; and in tidal, hydro, wind, geothermal, and nuclear forms while Energy is not stored in nature in electrical form. However, electric energy is easy to transmit over very long distances and complies with customer's needs through adequate planning and control.

Generator Control and Excitation

The control principle of the synchronous generators with electrically excited winding is well known, considering the frequency and voltage control by means of the active and reactive power adjustment. The active power comes from the mechanical prime mover while the reactive power is commanded and controlled with the DC excitation winding and voltage regulator. In most cases, the two control loops operate separately from each other with the use of the speed's (revolution/min) governor and voltage regulator. This kind of operation may be considered a scalar control procedure, which disregards some phenomena, i.e. the coupling effect between the electrical axis of the synchronous generator (Kozak, 2018).

The synchronous generator excitation system is a key part of the power system. The excitation system of a synchronous generator makes it possible to supply the energy generated by an engine (turbine) to the power grid. As a result, high priority is assigned to the reliability and availability of excitation equipment when choosing systems. Ngema (2016) stated in his work that generators require excitation systems to remain synchronized. The basic function of excitation systems is therefore to provide the energy required for the magnetic field keeping the generator in synchronism. The excitation system itself is divided into two types, excitation systems with brush and without brushes (brushless excitation).

i. Excitation system with a brush: In this, the excitation system can use a DC generator or an AC generator but is first rectified by a rectifier because the current used in the excitation system is a direct current. The flow will be channeled to the slip ring and then channeled to the second generator amplifier field.

ii. Static excitation system: The static excitation system also is described as a self-excitation because this excitation system is supplied from the synchronous generator itself but needs to be rectified by the rectifier first. On the rotor, there is little left and the magnetic field will induce a voltage in the stator. The voltage will then be put back into the rotor which previously had been rectified by the rectifier, consequently, the resulting magnetic field is getting bigger and makes the existing terminal voltage go up (Catur Pamungkas et al., 2017).

Zaleskis (2013) affirmed that the basic components of static excitation systems are thyristor rectifiers, controlled with excitation regulators using thyristor ignition impulse circuits. This can be performed in two ways via the transformer, namely either from an independent source (so-called independent excitation) or directly from the generator (so-called dependent excitation). The main benefit of static excitation systems is the speed with which the excitation voltage responds to the change of regulator voltage. A closed-loop system based on PID control (Proportional integral derivative).

Control of Excitation

Single-ended primary inductor converter (SEPIC) is a type of dc/dc converter that allows the electrical potential at its output to be greater than, less than, or, equal to that at its input. The output of the SEPIC is controlled by the duty cycle of the control switch; a controlled excitation system for a synchronous type generator is utilized in the application of Aircraft. To adjust the excitation of small and medium-capacity synchronous generators the most widely used system is a staticself-excitation system. The use of these systems in semiconductor converters provides high-speed operation of generator excitation control. However, this system has a disadvantage, a limited possibility of forcing the excitation in emergency operation in the case of a significant voltage slump at the generator output and a consequent fall in the input voltage of the thyristor converter (Kutsyk & Tutka, 2014).

The excitation system of a synchronous generator helps both the generator and the system to provide stable voltage and controlled reactive power. When the excitation system fails due to the short or open circuit of the circuit breaker, the reactive power of the generator will be negative and will be reduced. The reduction of reactive power converts the synchronous generator to an asynchronous generator, and the negative amount shows that the generator absorbs the reactive power from the system. The absorbing reactive power from the weak system can cause a voltage collapse in the power system. During loss of excitation (LOE), the generator generates the active power the same as before but at a lower value (Moravej et al., 2019; Murali Krishna et al., 2023)**.**

The excitation of synchronous generators is one of the main challenges in the power system. The field windings are energized through an Automatic Voltage Regulator (AVR) with control and measuring units which provides satisfactory operation with little disturbances like power swing (Chandrasekaran et al., 2016).

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Implication of loss of excitation

When a synchronous generator loses excitation, the rotor field magnetomotive force (mmf) decays suddenly while the prime mover is still delivering power to the generator. Therefore, the generator loses synchronism and runs asynchronously at a speed higher than the power system, absorbing reactive power for its excitation from the power system and supplying some active power to the power system at the same time. The adverse effects of a synchronous generator running asynchronously are high stator currents, end core heating, torque pulsations, and disturbance to the system because of its drawing reactive power from the system and the following voltage drop (Tarnapowicz et al., 2021). Usta et al., (2007) in their article emphasized that loss of excitation results in:

i. Heavy over-loading of the armature windings of the generator.
ii. Induced eddy current in the rotor surface and rotor windings at a slip frequency resulting in heavy thermal heating in the rotor body.
iii. Large voltage drop in the transmission lines with the possible drop-out of these lines, and loss of system stability.
iv. Loss of the magnetic coupling between the rotor and the stator sides, immediately

following the decrease in the magnetic coupling between them.

For these reasons, the loss of the excitation field of a generator should be detected as fast as possible, corrected if possible or tripping of the affected generator should be done fast enough to prevent any damage to that generator or the power system as a whole. The DC power supply is not only to provide exciting current but also to meet the controlling requirements of the operation of the power grid and those of the response of short circuits. At the same time, the efficiency of the long-term operation of the grid should also be considered. The relay protection of the power grid requires the grid to reclose within 1 second after short-circuit and requires that the DC excitation process be completed before reclosing. Because the purpose of the dc excitation is to saturate the core as quickly as possible (Li, 2017; Wang et al., 2021).

Pajuelo et al., (2013) proposed a support vector machine (SVM)-based technique for identifying loss-of-excitation (LOE) conditions in synchronous generators from other disturbances such as external faults and power-swing conditions. It was stated that the approach requires only one zone of LOE and the time coordination is reduced significantly. The proposed method is compared with the traditional two-zone impedance method. Several operating conditions within the generator capability are used to verify the generality of the SVM-based classifier. The proposed classifier identifies an LOE condition in all cases before the impedance enters the larger mho impedance zone. Faults and power-swing conditions are identified correctly, thereby preventing incorrect operation of the LOE impedance zone. The reviews suggest that there is no end to efforts put to addressing excitation issues considering its importance in power generation.

MATERIALS AND METHOD

The method adopted for this research work is that of experimental approach which involves the use of laboratory equipment and measuring instruments. A d.c motor of voltage 220V, 3A rating was used as a prime mover while a three-phase synchronous machine was used as an alternator. A power supply module comprising both fixed and variable d.c and a.c voltage supply was used as the workbench for the connection. The measuring instruments such as an ammeter, voltmeter, and tachometer were used for the measurement of current, voltages, and speed (rpm) respectively. The circuit diagram used for the experimental set-up is shown in Figure 2 while the practical implementation using connecting probes is displayed in Plate 1. The DC motor M2 is connected to a fixed 220V DC supply to serve as a prime mover while the three-phase synchronous motor is directly coupled to the shaft of the prime mover with its windings connected in star. The field windings of the synchronous motor are connected to a 0-80 V d.c source through a variable resistance box to enable variations of the excitation voltage between 0-60 V in 5 V steps while the field current is being monitored through the connected ammeter. The readings were collated, tabulated, and analyzed to establish the relationship between the excitation voltage and output parameters of the synchronous generator.

RESULTS AND DISCUSSION

The excitation voltage was varied in steps of 5 V considering 0 – 60 V while the measurement of the generator field current, the line voltage, and the system speed were taken per step and the readings obtained were recorded in Table 1.

Result

Table 1 shows the major output parameters of a synchronous generator concerning the variation of the excitation voltage. The characteristic behaviors of the generator include (a) the field current of the generator in response to the varied excitation voltage, (b) the line Voltage (Induced Voltage) of the synchronous generator as the excitation voltage increases, and (c) the measured speed of the system concerning variation in the excitation voltage. Figure 3, figure 4, and Figure 5 respectively show the effects of Excitation voltage variations on Field current, Induced voltage, and Speed of Generators

Discussion

In Figure 3, the generator field current increases with the increase in the excitation voltage with a value of 0.24 A for an excitation value of 60 V. It shows the current changes in proportion to the changes in the excitation voltage.

Similarly, in Figure 5, the induced voltage (Line Voltage) increases with the rise in the excitation voltage. Using Equation 1 to determine the induced voltage of the generator, it depicts that if the excitation voltage is not controlled, the value of the output voltage would go beyond the 380V expected from the line voltage of the generator.

$$E_O = \left(\sqrt{3} \left(\frac{V1 + V2 + V3}{3} \right) \right). \qquad \text{(i)}$$

However, the speed of the system remains approximately constant with respect to the excitation voltage throughout the range of variation which proves the characteristics of synchronous machines as shown in Figure 5. The figure also shows that excitation voltage is highly effective between 5-30V and drops as it increases to 40V. meanwhile, the speed of the generator is expected to be constant but due to another factor such as voltage fluctuation, it gives between 2700 -2800rpm.

CONCLUSIONS AND RECOMMENDATIONS

It is obvious from this work that the excitation voltage plays a vital role in the operations of synchronous generators and it is expected to be regulated to prevent abnormal rise in the induced voltage which could be enormous and cause damage to electrical loads connected across the output terminals of the synchronous generator. It is expected that research effort should be conscientiously channeled towards achieving the design and development of an automatic voltage regulator (AVR) with 85 % local content capable of regulating the excitation voltage and by implication the induced voltage of synchronous generator at a given rated capacity.

REFERENCES

Boldea, I. (2015). *Synchronous generators* (2nd ed.). Boca Raton, USA: CRC Press

Catur Pamungkas, R., Yusvin Mustar, M., & Syahputra, R. (2017). Analytical studies of the excitation system of synchronous generator in steam power plant unit 3 and 4 at PJB UP Gresik. *Journal of Electrical Technology UMY*, *1*(3), 148 – 156.

Chandrasekaran, V., Nagarajan, D., & Nagaraj, B. (2016). New development in the performance improvement synchronous motor. *Circuits and Systems*, *07*(10), 2865 - 2874. https://doi.org/10.4236/CS.2016.710245

Kozak, M. (2018). Initial excitation issues of synchronous generator with VSI inverter in varying rotational speed operation. *Multidisciplinary Aspects of Production Engineering*, *1*(1), 377 - 383. https://doi.org/10.2478/MAPE-2018-0048

Kutsyk, & And Tutka, A. S. (2014). The Semiconductor self-excitation system of synchronous generator with fuzzy voltage controller. *Science and Innovation*, *10* (3), 5 – 15.

Li, H. (2017). Design and study of DC excitation power controller of superconductor fault current limiter. *Vibroengineering Procedia*, *14*, 265 - 270. https://doi.org/10.21595/VP.2017.19173

Moravej, Z., Rasooli, H., & Pazoki, M. (2019). Analysis of loss of excitation protection schemes of synchronous generators in a compensated transmission line with UPFC. *International Journal on Electrical Engineering and Informatics*, *11*(3), 485 - 505. https://doi.org/10.15676/IJEEI.2019.11.3.3

Murali Krishna, V. B., Sandeep, V., Narendra, B. K., & Prasad, K. R. K. V. (2023). Experimental study on self-excited induction generator for small-scale isolated rural electricity applications. *Results in Engineering*, *18*, 1 - 8.

Ngema, D. N. (2016). *Generator Excitation Control and Coordination for Protection*. Unpublished M.Sc. thesis. University of Kwazulu-Natal

Pajuelo, E., Gokaraju, R., & Sachdev, M. S. (2013). Identification of generator loss-of-excitation from power-swing conditions using a fast pattern classification method. *IET Generation, Transmission and Distribution*, *7*(1), 24 - 36. https://doi.org/10.1049/IET-GTD.2012.0340

Tarnapowicz, D., German-Galkin, S., & Staude, M. (2021). Investigation concerning the excitation loss of synchronous generators in a stand-alone ship power plant. *Energies*, *14*(2828), 1 - 17.

Usta, O., Musa, M. H., Bayrak, M., & Redfern, M. A. (2007). A new relaying algorithm to detect loss of excitation of synchronous generators. *Turkish Journal of Electrical Engineering and Computer Sciences*, *15*(3), 339 – 349.

Wang, R., Liu, X., & Huang, Y. (2021). Synchronous Generator Excitation System for a Ship Based on Active Disturbance Rejection Control. *Mathematical Problems in Engineering*, *2021*, 1 – 17. https://doi.org/10.1155/2021/6638370

Zaleskis, G. (2013). *Self-excitation system for synchronous generator*. https://doi.org/10.2478/ecce-2013-0019

Table 1: The Measured parameters during the experiment

Excitation Voltage V_E (V)	**Field Current I_f (A)**	**Induced Voltage E_o (V)**	**Speed (RPM)**	**V_1 (V)**	**V_2 (V)**	**V_3 (V)**
0	0	3.464	2700	02	02	02
5	0.01	25.98	2800	15	15	15
10	0.03	55.424	2800	32	32	32
15	0.06	81.404	2800	47	47	47
20	0.07	107.384	2800	62	62	62
25	0.10	142.024	2800	82	82	82
30	0.10	180.128	2800	104	104	104
35	0.12	211.304	2700	122	122	122
40	0.14	244.212	2700	141	141	141
45	0.18	277.12	2700	160	160	160
50	0.20	301.368	2700	174	174	174
55	0.22	332.544	2700	192	192	192
60	0.24	356.792	2700	206	206	206

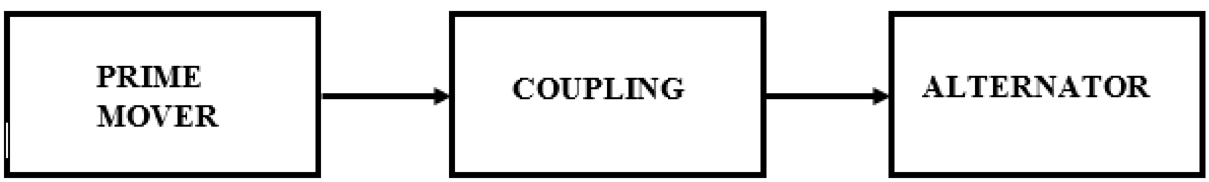

Figure 1. The block diagram of a typical generator set

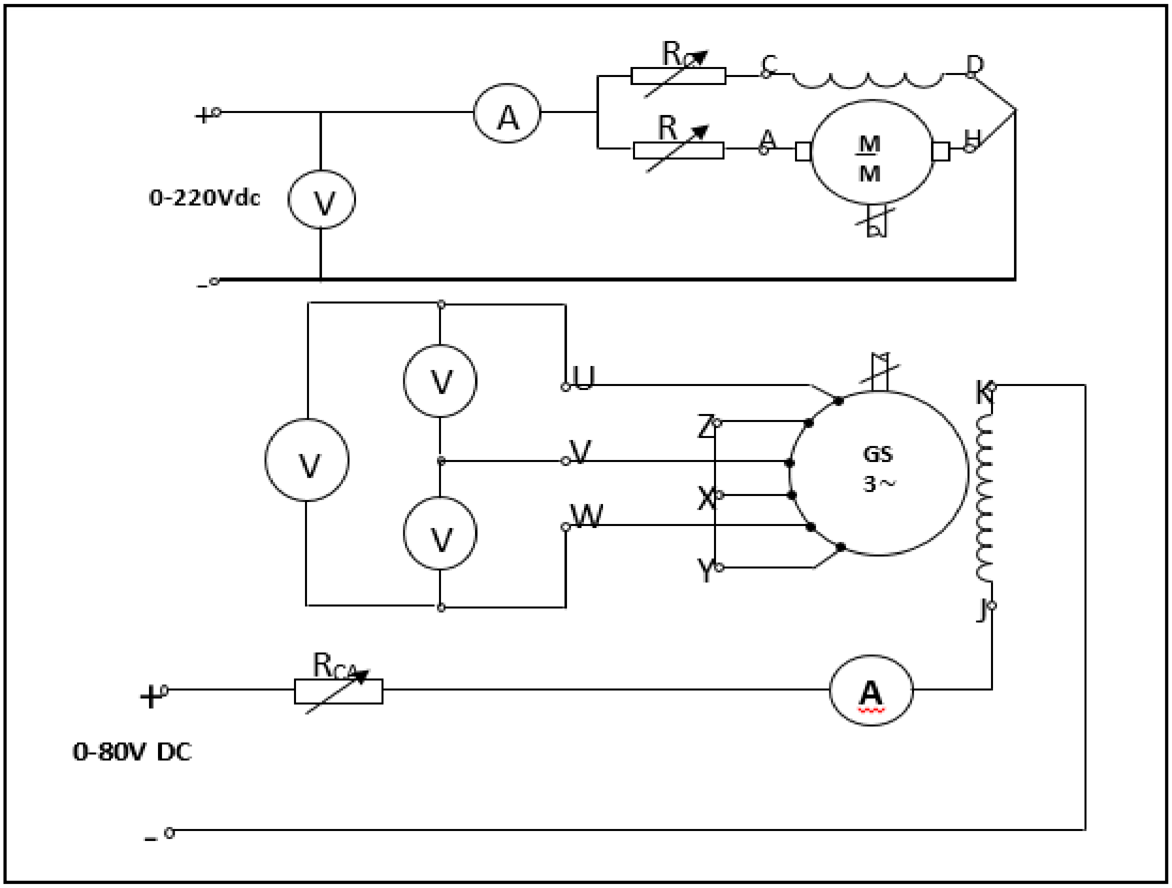

Figure 2. The circuit diagram of the synchronous machine for the experimental set - up

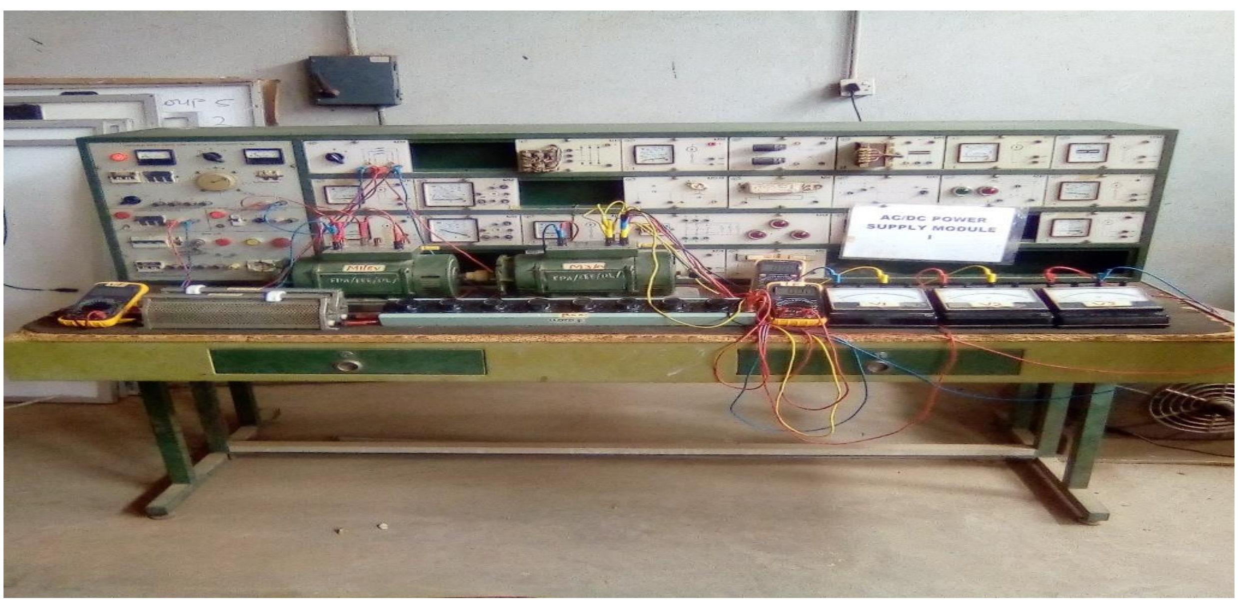

Plate 1. The experimental implementation of the circuit diagram

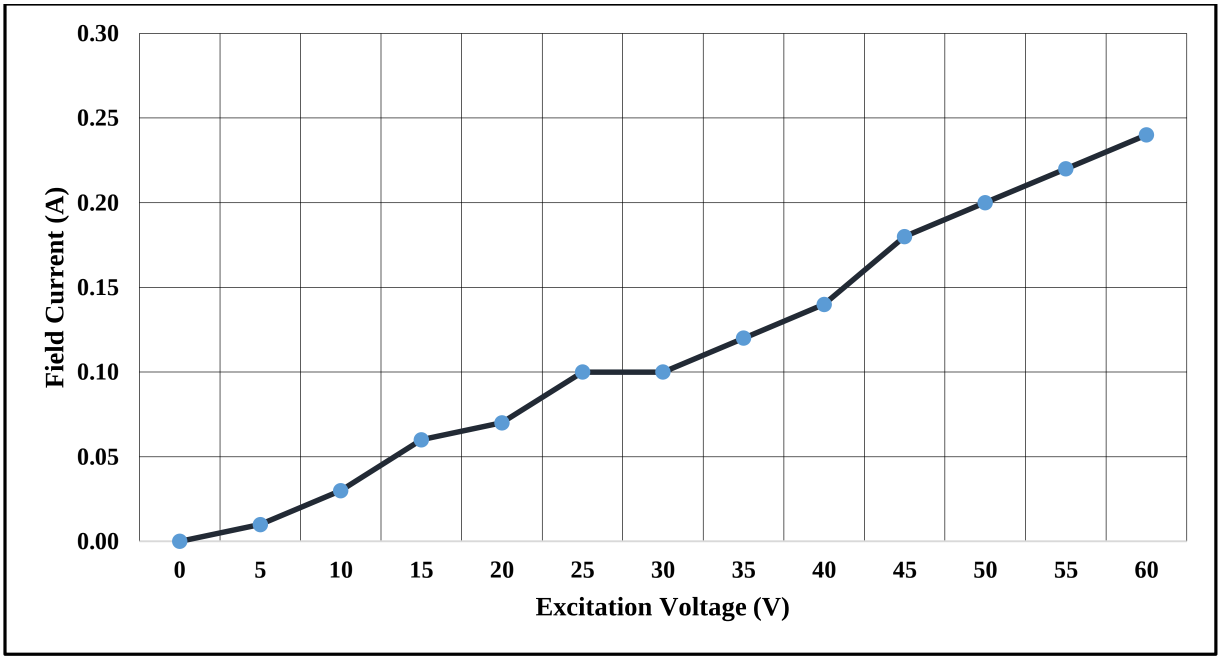

Figure 3. Graph showing the effect of excitation voltage on the generator field current

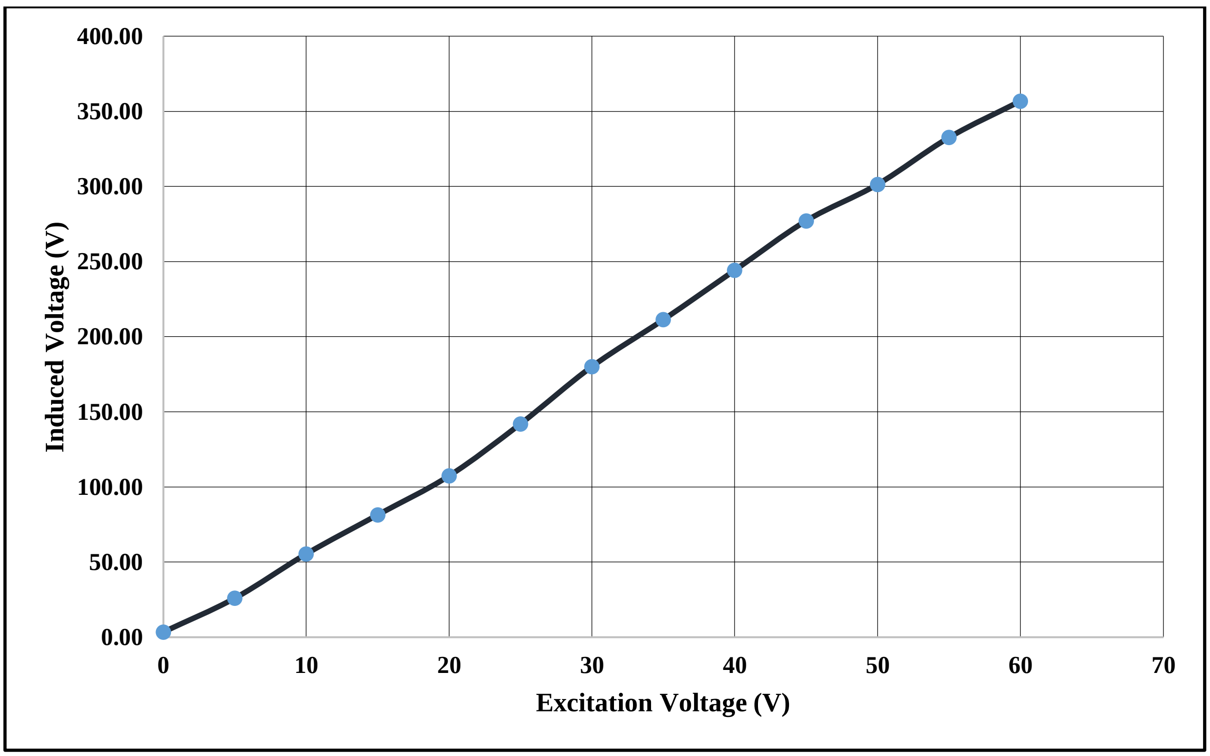

Figure 4. Graph showing the effect of excitation voltage on the output voltage of the generator

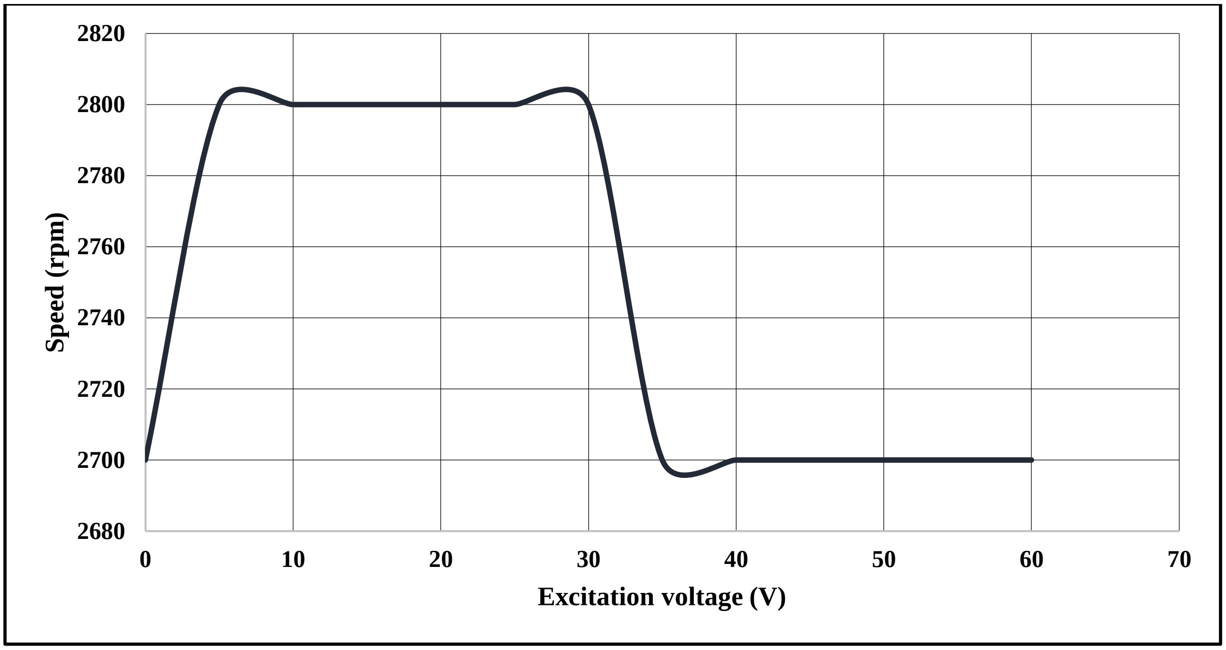

Figure 5. Graph showing the effect of excitation voltage on the no-load speed of the generator