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The effect of power factor on the performance of hydro power three-phase synchronous generator under inductive load

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Abstract

Three-phase synchronous generators have numerous advantages for power generation applications. One of their strengths is the ability to operate at varying speeds. Voltage generation in synchronous generators relies on an excitation system, which greatly influences voltage and frequency stability. This paper examines the loading of three-phase synchronous generators with inductive loads. The research includes simulation results and laboratory testing. To support the analysis with simulations, testing was conducted in the laboratory. To represent the prime mover, a DC motor was used as the initial driver, along with the excitation system. The test results indicate that adding resistive loads yields better outcomes in output voltage waveform formation. Resistive loads significantly impact the generator's speed and terminal voltage, thus requiring the precise operation for stability of a three-phase synchronous generator. Based on the outcomes of processing simulation data, doing laboratory tests, and analyzing processes from a hydropower plant it is found that a three-phase synchronous generator with resistive-inductive load produces better output voltage waveforms. The resistive load affects the formation of the synchronous generator's terminal voltage waveform, while the inductive load causes the current waveform to lag behind the terminal voltage. Additionally, the resistive load affects the decrease in generator speed, requiring adjustment of the armature current in the DC motor as the prime mover.

Keywords: Sinusoidal; Excitation; Voltage; Current; Power; Inductive

1. Introduction

Many conventional power stations employ synchronous generators. Their proper operation greatly influences the safe functioning of these generators in the power system, and the opposite is also true: any disruptions in their operation may have disastrous effects on the power system [1]. Synchronous generators have several parameters such as armature current, field current, and excitation current. For the synchronous generator's field winding, the excitation system seeks to deliver direct current. The reactive power, field current, and terminal voltage of the synchronous generator are all controlled by the excitation system [2]. Three-phase synchronous generators must operate stably to maintain a constant voltage and frequency output. Instability in synchronous generators can adversely affect the loads, especially electronic devices. The more loads that need to be operated by the synchronous generator and the more diverse the types of loads, the need for proper operational control to maintain stability becomes crucial [3], [4].

One of the factors of fluctuation is load impedance. At any given time, the amount of load to be operated will vary, thus affecting the total impedance of all the loads. Impedance also affects the power factor of each load, which in turn impacts the load current [5]. Since voltage needs to remain stable, load current fluctuations can cause terminal voltage instability. To address this issue, adjustments to the generator's excitation current need to be made to keep it in line with the requirements [6], [7]. By making operational adjustments, synchronous generators can maintain the stability of their voltage and frequency optimally.

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This paper explains the influence of speed, frequency, and terminal voltage on a hydropower three-phase synchronous generator in response to variations in inductive loading. This research aims to analyze the impact of inductive loading on the performance of a hydropower three-phase synchronous generator. Through simulation, laboratory testing, and analysis of the hydropower plant differences in the generator's response to variations in inductive loading were observed.

2. Material and methods

2.1. Characteristic Three-Phase Synchronous Generator

A three-phase synchronous generator can convert mechanical energy into electrical energy. The equivalent circuit of a three-phase synchronous generator is depicted in Figure 1.

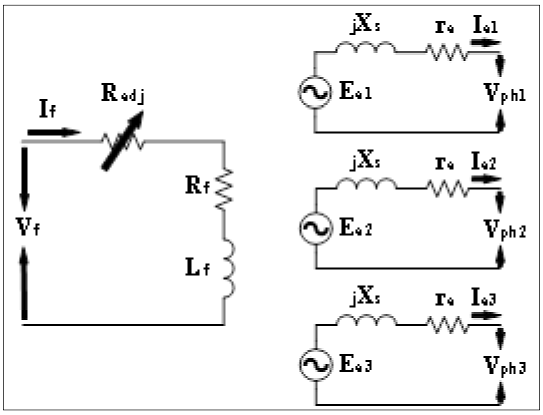

Figure 1 Equivalent Circuit of a Three-Phase Synchronous Generator

A three-phase synchronous generator consists of a laminated iron rotor with salient poles, while its stator has a simple winding. On the rotor and the stator, respectively, are a field coil and an armature winding. The electrical energy produced is a three-phase voltage with a 120° difference between each phase [8], [9]. A three-phase synchronous generator operates on the basis that the field coil on the rotor generates a direct current that induces a magnetic flux in the other field coils [10], [11]. The generator's speed is defined by Equation (1):

$$n_s = \frac{120\ x\ f}{P} \qquad (1)$$

Where ns is the rotor's spinning speed in rpm, P is the number of rotor poles, and f is the frequency in Hz. The magnetic field created by the field coil will revolve as the rotor does. This rotating field is then induced in the armature winding, causing a continuous change in the magnetic flux around the winding [11], [12].

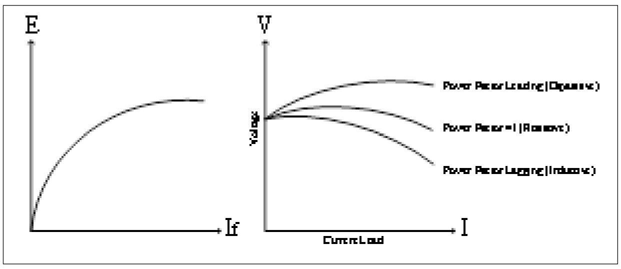

Figure 2 Characteristic Synchronous Generator without Load (Left) and with Load (Right)

Three types of loads can be connected to the generator, namely resistive, inductive, and capacitive loads. This loading will affect the terminal voltage, frequency, and speed of the generator. In Figure 2, the curve of a three-phase synchronous generator is shown without load and with different types of loading.

When a resistive load is connected, there will be a relatively small voltage drop with a power factor of one. However, if the generator is loaded with an inductive load, there will be a significant voltage drop, resulting in a lagging terminal voltage concerning the terminal current. Conversely, if the generator is loaded with a capacitive load, there will be a significant voltage rise, causing the terminal voltage to lead to the terminal current [13].

A generator's output voltage is influenced by the size of the excitation current and the rate of rotation of the rotor [12], [14]. The larger the excitation current and the speed, the greater the voltage produced by the generator as shown in Figure 3.

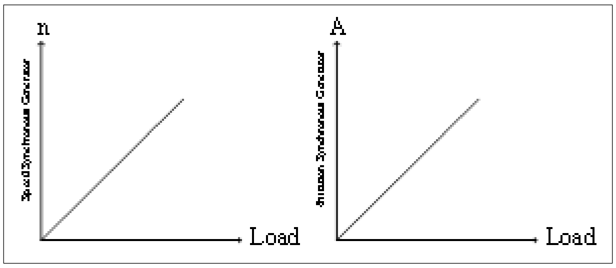

Figure 3 The Curve of Synchronous Generator Speed versus Load (Left) and the Curve of Excitation Current versus Load for Synchronous Generator (Right)

2.2. Power Factor and Phasor Diagram of Synchronous Generator

In AC or Alternating Current electrical systems, there are three types of power known, especially for loads with impedance (Z). As shown in Figure 4, the power factor of an AC electrical system may be calculated theoretically as the cosine of the angle between the voltage phase and the current phase. The letter S stands for seeming power. P is used to signify active power. The reactive power symbol is Q.

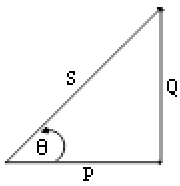

Figure 4 Power Triangle

Here are some equations for active power, reactive power, and apparent power of a three-phase synchronous generator as stated in Equation (2), Equation (3), and Equation (4).

$$P = V\ x\ I\ x\ Cos\ \theta \quad (2)$$

$$Q = V\ x\ I\ x\ Sin\ \theta\ x\ \sqrt{3} \quad (3)$$

$$S = V\ x\ I \quad (4)$$

A higher phase angle between active power and visible power brought on by high reactive power will result in a lower power factor. There is never a power factor value greater than one. The value of the power factor represents the phase angle between active power and apparent power in an electrical system. When the power factor is low, it can have a negative impact by causing high load currents [15], [16].

When the apparent power and active power values are known, the power factor's value may be calculated. The acceptable power factor is defined as having a value up to 0.85 by IEEE Standard 1547. Equation (5) illustrates the power factor.

$$Cos = \frac{P}{S} \quad (5)$$

Cos θ is used to express the power factor. P is used to signify active power. The letter S stands for seeming power [17].

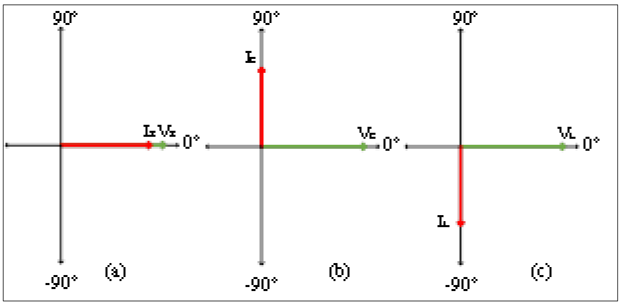

Figure 5 (a) Phasor Diagram of Resistive Load (b) Phasor Diagram of Capacitive Load (c) Phasor Diagram of Inductive Load

3. Results and discussion

To support the analysis with simulations, testing was conducted in the laboratory and analysis from a hydropower plant. To represent the prime mover, a DC motor was used as the initial driver, along with the excitation system shown in Figure 10, and the specifications of the synchronous generator and DC motor are provided in Table 1 and Table 2. The simulation circuit in this research is shown in Figure 6 and Figure 7.

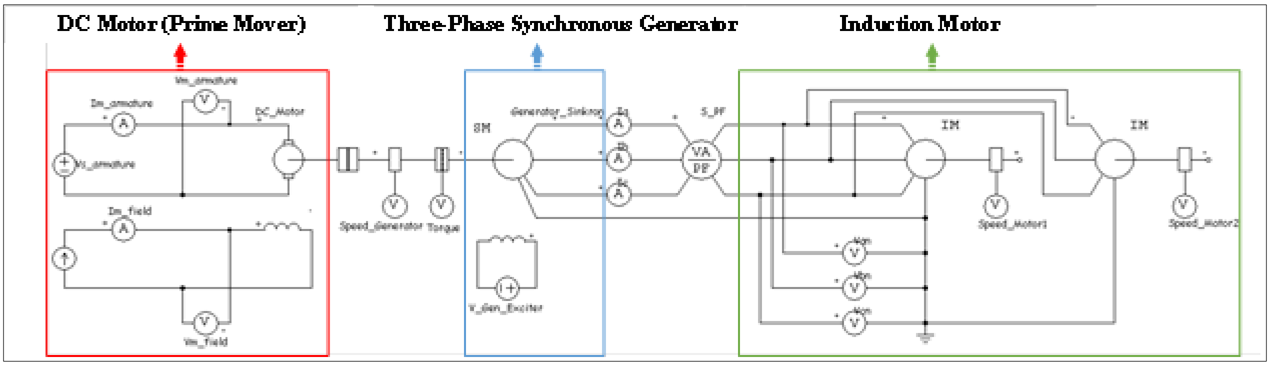

Figure 6 Simulation of Three-Phase Generator Circuit with Inductive Load Variation

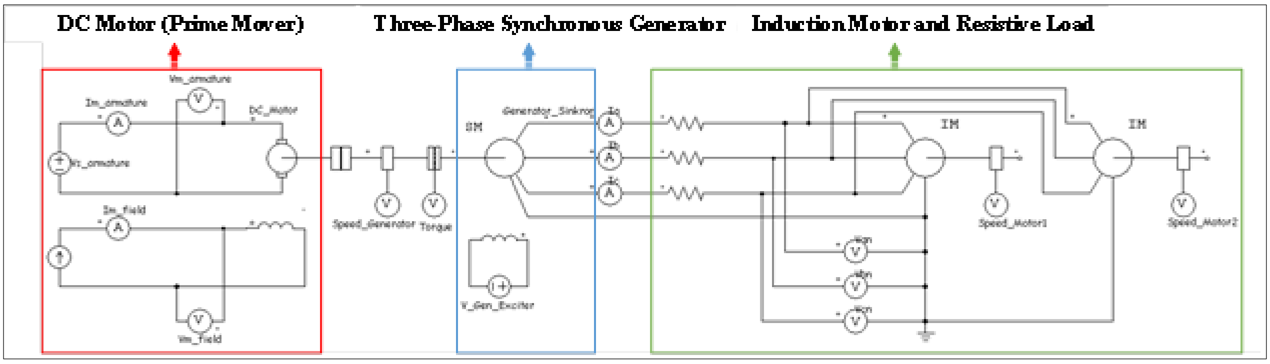

Figure 7 Simulation of Three-Phase Generator Circuit with Resistive-Inductive Load Variation

Figure 8 Analysis Process from Hydropower Plant with Induction Load

Figure 9 Dashboard Hydropower Plant

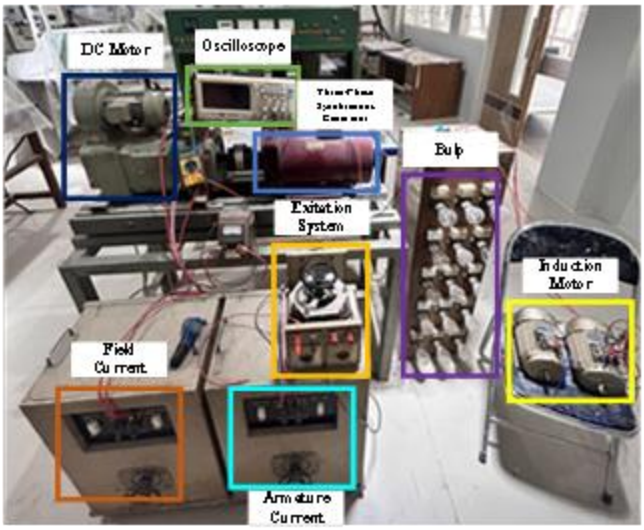

Figure 10 Three-Phase Generator Circuit with Inductive Load Variation

Table 1 Specification of Three-Phase Synchronous Generator

No.	Model	Value	Unit
1	Max Speed	1.500	RPM
2	Rated Current	10	Ampere
3	Rated Voltage	220/380	Voltage
4	Rated Power	5	kW
5	Number Pole	4	Pole

Table 2 Specification of DC Motor

No.	Model	Value	Unit
1	Max Speed	1.500	RPM
2	Rated Current	10	Ampere
3	Rated Voltage	220/380	Voltage
4	Rated Power	5	kW
5	Number Pole	4	Pole

3.1. Three-Phase Generator Circuit with Inductive Load

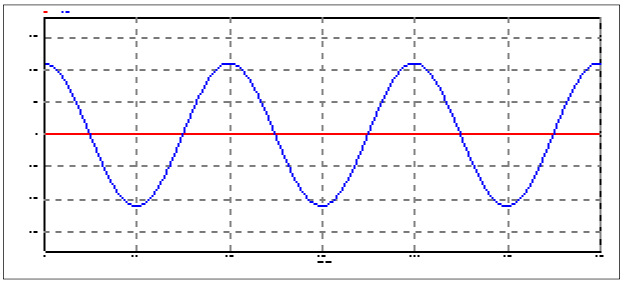

Figure 11 Voltage and Current in a Load-Free Synchronous Generator (Blue represents Voltage and Red represents Current)

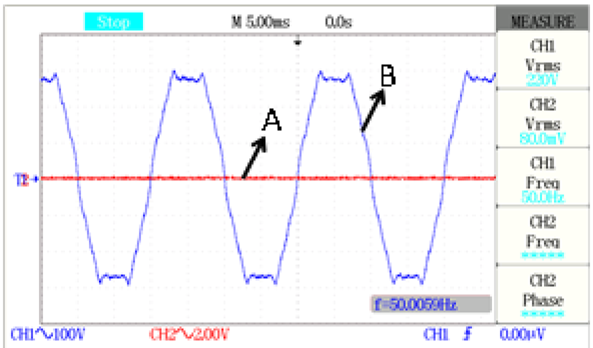

Figure 12 Current (A) and Voltage (B) in a Three-Phase Synchronous Generator Before Connecting with Load

The first simulation and testing of a three-phase synchronous generator without load, as shown in Figure 11 and Figure 12. Results from simulation and testing without load show no current from the generator, speed of 1.500 rpm, frequency of 50 Hz, with an excitation current of 1.65 Amperes and an armature current of 1.6 Amperes on the prime mover. In this research, measurements were conducted on one phase, namely phase R with Neutral, and the current measurement was performed on phase R.

Next, it will be loaded by an induction motor as an inductive load, resulting in a change in the terminal voltage from 220 Volts to 210.4 Volts, with a terminal current in the generator of 0.56 Amperes. The speed of the generator, which was originally 1500 rpm, becomes 1505 rpm with a frequency of 49.5 Hz, as seen in Figure 13 and Figure 14.

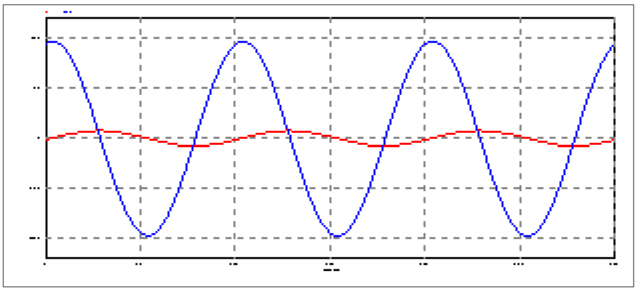

Figure 13 Voltage and Current in a Synchronous Generator During Inductive Load

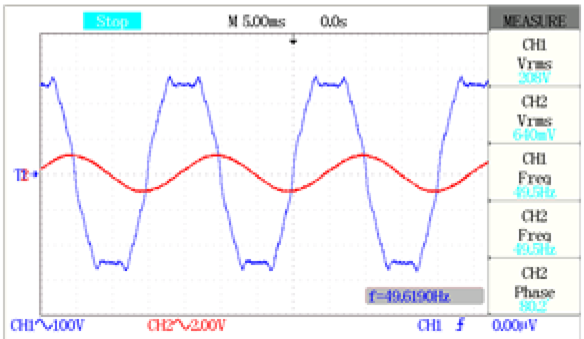

Figure 14 Voltage and Current of the Synchronous Generator During Inductive Load (with 1 Induction Motor)

The next step is to make improvements to the excitation current from 1.65 Amperes to 1.9 Amperes and the armature current to 1.75 Amperes to achieve a voltage of 220 Volts and a speed of 1500 rpm, with the increasing output current from 0.56 Amperes to 0.64 Amperes, as shown in Figure 15 and Figure 16.

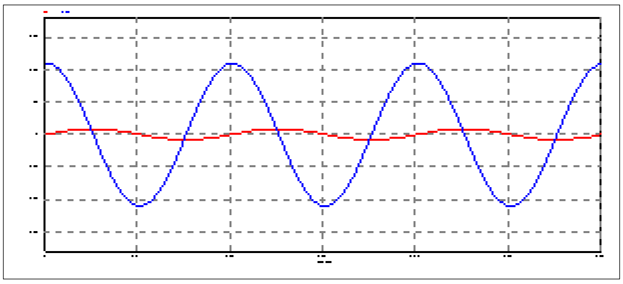

Figure 15 Improvement of Voltage and Current in the Synchronous Generator with Inductive Load

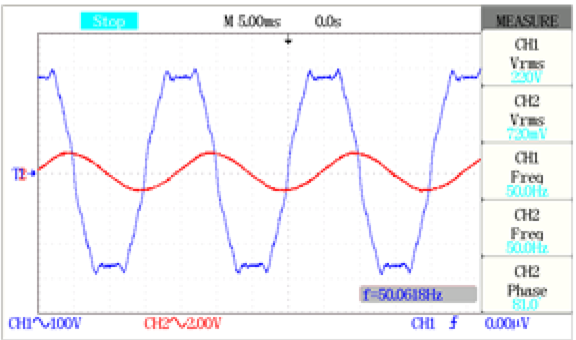

Figure 16 Voltage and Current of the Synchronous Generator During Improvement of Inductive Load

Two induction motors are used to power the subsequent load. Figures 17 and 18 depict the synchronous generator's voltage and terminal current under the load of two induction motors.

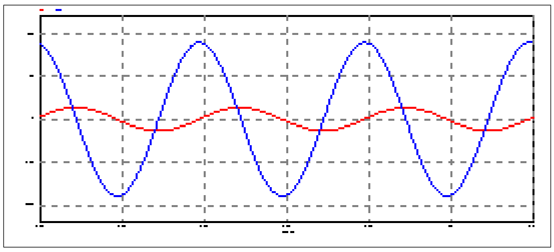

Figure 17 Voltage and Current in a Synchronous Generator During Inductive Load

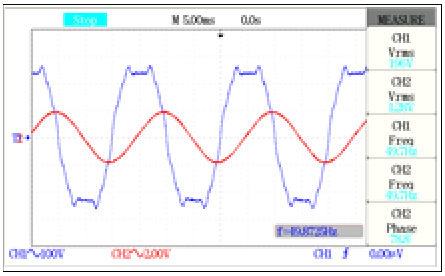

Figure 18 Voltage and Current of Synchronous Generator During Inductive Load (with 2 Induction Motors)

The inductive load with two induction motors causes a decrease in the terminal voltage of the generator. The initial voltage of 220 Volts becomes 198.3 Volts, and the synchronous generator's speed increases to 1503 rpm with a frequency of 49.7 Hz. Therefore, it is necessary to make improvements to the excitation current, increasing it from 1.65 Amperes to 2.16 Amperes, to restore the voltage to 220 Volts and the speed to 1500 rpm. The output current also increases from 1.06 Amperes to 1.3 Amperes, as shown in Figure 19 and Figure 20.

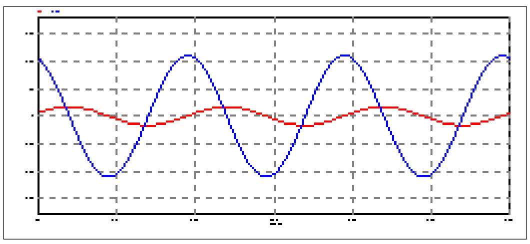

Figure 19 Improvement of Voltage and Current in the Synchronous Generator with Inductive Load

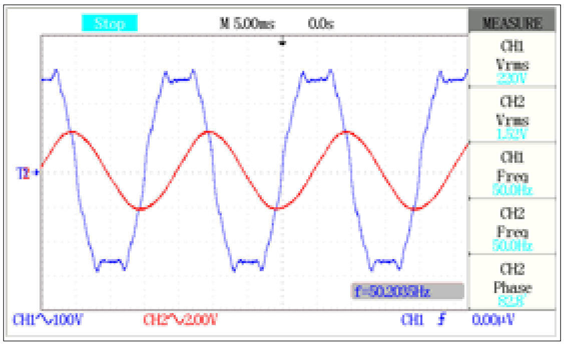

Figure 20 Voltage and Current of the Synchronous Generator During Improvement of Inductive Load

3.2. Three-Phase Generator Circuit with Resistive-Inductive Load

In the simulation and testing of a three-phase synchronous generator with a resistive-inductive load, the concept remains the same as before. It starts with an output voltage of 220 Volts, a speed of 1500 rpm, and a frequency of 50 Hz. In the simulation and testing, the first load consists of one induction motor in parallel with five incandescent lamps, representing resistive loads in each phase. This can be seen in Figure 21 and Figure 22 for the output voltage and output current.

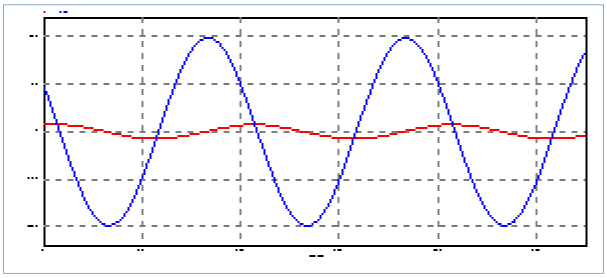

Figure 21 Voltage and Current in a Synchronous Generator During Resistive-Inductive Load

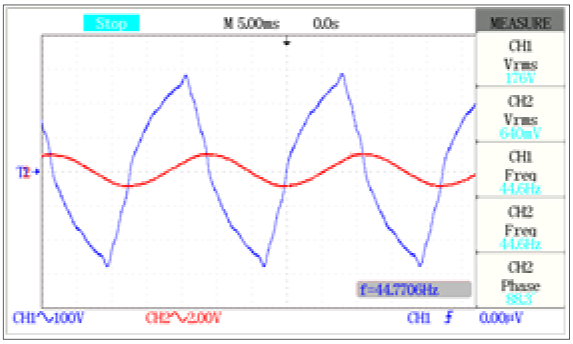

Figure 22 Voltage and Current of the Synchronous Generator During Resistive-Inductive Load (with 1 Induction Motor and 5 Incandescent Lamps)

The data obtained from Figure 21 and Figure 22 shows a decrease in the output voltage to 178.3 Volts, a synchronous generator speed of 1344 rpm, and a power factor of -0.3 at a frequency of 44.6 Hz. The output current obtained is 0.5 Amperes. To stabilize the voltage and speed of the generator, parameter adjustments are needed, resulting in the values shown in Figure 23 and Figure 24.

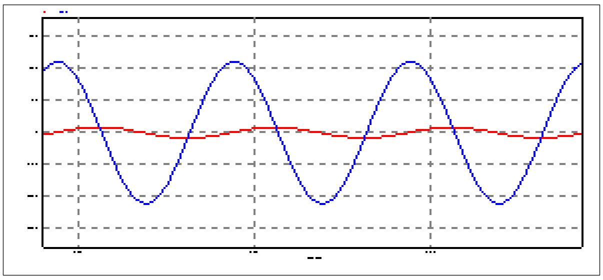

Figure 23 Improvement of Voltage and Current in the Synchronous Generator with Resistive-Inductive Load

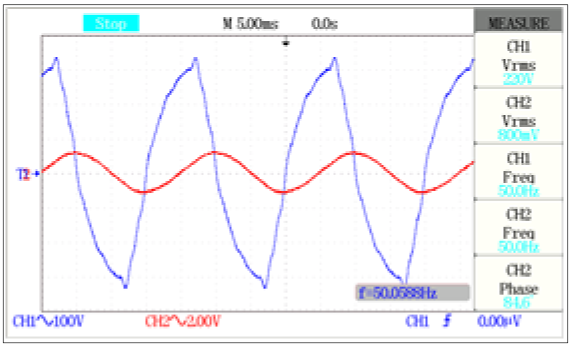

Figure 24 Voltage and Current of the Synchronous Generator After Improvement on Resistive-Inductive Load (with 1 Induction Motor and 5 Incandescent Lamps)

The improvement is made by adjusting the excitation current to restore it to 2.12 Amperes, from its previous value of 1.65 Amperes, to return the voltage to 220 Volts. As the terminal voltage increases to 220 Volts, there is a change in the output current from 0.5 Amperes to 0.6 Amperes, and the power factor has a value of -0.29. The armature current is adjusted to 8.99 Amperes from 1.6 Amperes to achieve a speed of 1500 rpm and a frequency of 50 Hz once again.

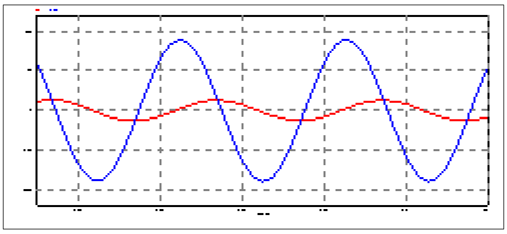

Figure 25 Voltage and Current in a Synchronous Generator During Resistive-Inductive Load

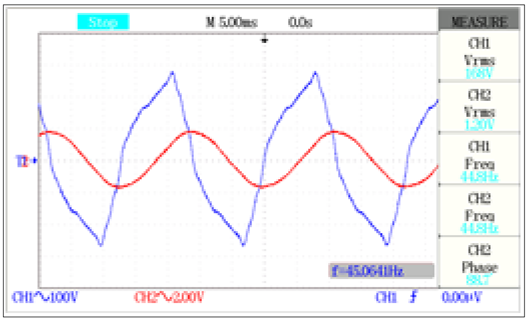

Figure 26 Voltage and Current of the Synchronous Generator During Resistive-Inductive Load (with 2 Induction Motors and 5 Incandescent Lamps)

To further analyze the performance of the three-phase synchronous generator, simulation, and laboratory testing are conducted using 2 induction motors and 5 resistive loads, similar to before. The synchronous generator's terminal voltage and current are displayed in Figure 25 and Figure 26.

The decrease in output voltage, with a value of 171 Volts, is accompanied by a decrease in speed to 1358 rpm and a power factor of 0.2, with a frequency of 44.8 Hz. Additionally, the output current has a value of 2.79 Amperes. As seen in Figure 27 and Figure 28, the output voltage has stabilized again.

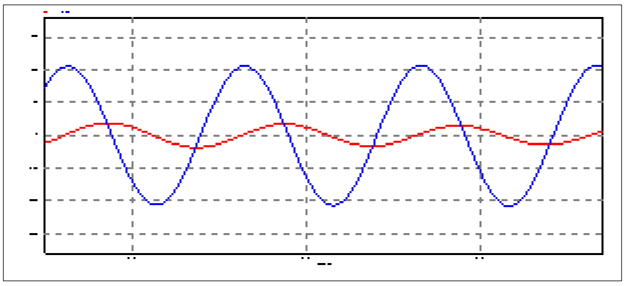

Figure 27 Improvement of Voltage and Current in the Synchronous Generator with Resistive-Inductive Load

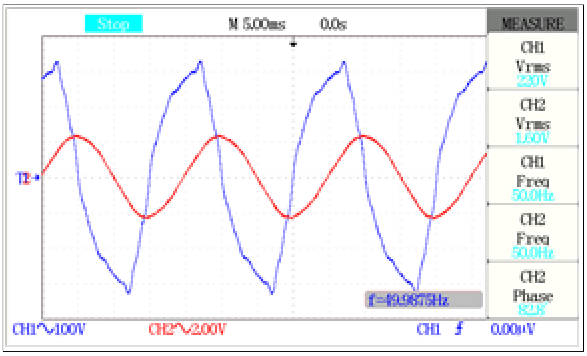

Figure 28 Voltage and Current of the Synchronous Generator After Improvement on Resistive-Inductive Load (with 2 Induction Motors and 5 Incandescent Lamps)

The measurement results obtained after the repair on the resistive-inductive load with 2 induction motors show that the excitation current has increased to 2.45 Amperes, the armature current is 9.3 Amperes to achieve a voltage of 220 Volts, a speed of 1500 rpm with a frequency of 50 Hz, and the output current is 1.34 Amperes. The power factor has a value of -0.12.

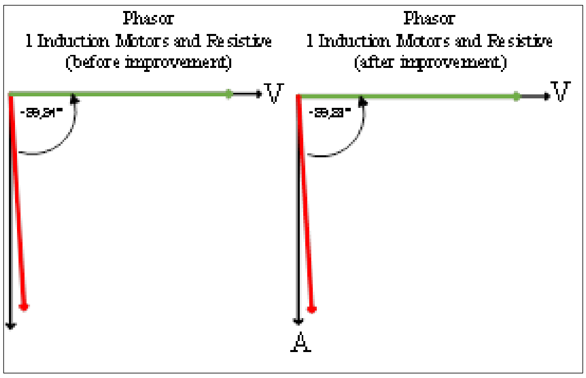

Figure 29 Phasor of the Synchronous Generator During Inductive Load (with 1 Induction Motor and 5 Incandescent Lamps)

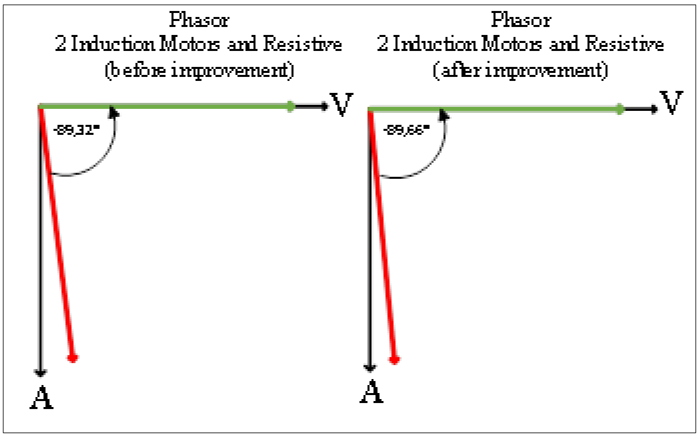

Figure 30 Phasor of the Synchronous Generator During Inductive Load (with 2 Induction Motors and 5 Incandescent Lamps)

4. Conclusion

Based on the outcomes of processing simulation data, doing laboratory tests, and analysis from a hydropower plant it is found that a three-phase synchronous generator with resistive-inductive load produces better output voltage waveforms. The resistive load affects the formation of the synchronous generator's terminal voltage waveform, while the inductive load causes the current waveform to lag behind the terminal voltage. Additionally, the resistive load affects the decrease in generator speed, requiring adjustment of the armature current in the DC motor as the prime mover. Before the addition of the resistive load, the terminal voltage drop for the inductive load was 210.4 Volts and 198.3 Volts from 220 Volts. After adding the resistive load, the terminal voltage changed to 178.3 Volts and 171 Volts from 220 Volts. The best value of cos θ, with a value of 0.2, was obtained when one induction motor was loaded with 5 incandescent lamps.

Compliance with ethical standards

Acknowledgements

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References

[1] Institute of Electrical and Electronics Engineers, 2019 IEEE/IAS 55th Industrial and Commercial Power Systems Technical Conference (I & CPS) : May 5-8, 2019, Fairmont Palliser, Calgary, Alberta, Canada.

[2] S. Schmuelling, C. Kreischer, and M. Gołębiowski, "Maszyny Elektryczne-Zeszyty Problemowe Nr 3/2015 (107) 89 COMPARISON OF DIFFERENT METHODS FOR EXCITATION OF SYNCHRONOUS MACHINES."

[3] O. V. Gazizova, G. P. Kornilov, and A. P. Sokolov, "Development of a System for Regulating the Excitation of Synchronous Generators of Factory Power Plants Connected to a Powerful Energy System," in Proceedings - International Ural Conference on Measurements, UralCon, Institute of Electrical and Electronics Engineers Inc., 2022, pp. 229–233. doi: 10.1109/UralCon54942.2022.9906730.

[4] R. Hongtao, "Analysis of the Short Circuit at the Outlet of Self-excited Synchronous Generator," in 2020 5th International Conference on Power and Renewable Energy, ICPRE 2020, Institute of Electrical and Electronics Engineers Inc., Sep. 2020, pp. 221–224. doi: 10.1109/ICPRE51194.2020.9233222.

[5] S. Sesnic, A. Soldo, and D. Poljak, "Transient Impedance of the Synchronous Generator Grounding Electrode due to Short Circuit Current," in Proceedings of the 2020 International Symposium on Electromagnetic Compatibility - EMC EUROPE, EMC EUROPE 2020, Institute of Electrical and Electronics Engineers Inc., Sep. 2020. doi: 10.1109/EMCEUROPE48519.2020.9245753.

[6] R. E. Pivetta, I. L. Dal Forno, L. G. Scherer, R. F. De Camargo, and F. B. Grigoletto, “Self-Excited Induction Generator Based Generation System Regulation Using Synchronous Generator as Reactive Power Compensator,” in 2022 14th Seminar on Power Electronics and Control, SEPOC 2022, Institute of Electrical and Electronics Engineers Inc., 2022. doi: 10.1109/SEPOC54972.2022.9976454.

[7] L. Tom, R. Ramanathan, G. Vakil, C. Gerada, and A. McQueen, “Analysis of Integration Options for A Two-Stage Synchronous Generator,” in 2021 International Conference on Sustainable Energy and Future Electric Transportation, SeFet 2021, Institute of Electrical and Electronics Engineers Inc., Jan. 2021. doi: 10.1109/SeFet48154.2021.9375652.

[8] A. A. Reddy and S. S. Bhat, “Modeling of Dual Excited Synchronous Generator with slip frequency excitation,” in Proceedings of 2020 IEEE 1st International Conference on Smart Technologies for Power, Energy and Control, STPEC 2020, Institute of Electrical and Electronics Engineers Inc., Sep. 2020. doi: 10.1109/STPEC49749.2020.9297716.

[9] S. Tsegaye and K. A. Fante, “Analysis of Synchronous Machine Excitation Systems: Comparative Study.”

[10] S. M. Toufighian, J. Faiz, and A. Erfani-Nik, “Static Eccentricity Fault Detection in Salient and Non-Salient Synchronous Generators Using Harmonic Components,” in 2021 12th Power Electronics, Drive Systems, and Technologies Conference, PEDSTC 2021, Institute of Electrical and Electronics Engineers Inc., Feb. 2021. doi: 10.1109/PEDSTC52094.2021.9405971.

[11] P. Popovski, G. Veljanovski, B. Arapinovski, and M. Atanasovski, “Electomagnetic Analysis of Synchronous Generator,” in 2021 56th International Scientific Conference on Information, Communication and Energy Systems and Technologies, ICEST 2021 - Proceedings, Institute of Electrical and Electronics Engineers Inc., Jun. 2021, pp. 189–192. doi: 10.1109/ICEST52640.2021.9483490.

[12] S. Yahia, A. Mohamed, and X. Yan, “Comparison of Virtual Synchronous Generators Dynamic Responses.”

[13] M. U. Naseer, B. Asad, P. S. Ghahfarokhi, A. Kallaste, T. Vaimann, and A. Rassolkin, “Experimental Determination of Equivalent Circuit Parameters for a Synchronous Generator,” in 2021 IEEE Open Conference of Electrical, Electronic and Information Sciences, eStream 2021 - Proceedings, Institute of Electrical and Electronics Engineers Inc., Apr. 2021. doi: 10.1109/eStream53087.2021.9431442.

[14] A. G. Baayeh, “Application of hilbert-huang transform to protect synchronous generator against loss of excitation,” in 2020 15th International Conference on Protection and Automation of Power Systems, IPAPS 2020, Institute of Electrical and Electronics Engineers Inc., Dec. 2020, pp. 84–88. doi: 10.1109/IPAPS52181.2020.9375596.

[15] Y. A. Ahmed, Y. I. M. Al-Mashhadany, and M. A. Nayyef, “High performance of excitation system for synchronous generator based on modeling analysis,” Bulletin of Electrical Engineering and Informatics, vol. 9, no. 6, pp. 2235–2243, Dec. 2020, doi: 10.11591/eei.v9i6.2627.

[16] R. Kumar and A. Kumar, “Reactive Power Cost Characteristics for Synchronous Generator in Deregulated Electricity Markets.”

[17] A. Kutsyk, M. Semeniuk, M. Khai, and T. Galantyi, “An Experimental Study of a Voltage Control Quality of a Diesel-Engine Synchronous Generator with a Phase-Compounding Excitation System,” in Proceedings of the 25th IEEE International Conference on Problems of Automated Electric Drive. Theory and Practice, PAEP 2020, Institute of Electrical and Electronics Engineers Inc., Sep. 2020. doi: 10.1109/PAEP49887.2020.9240899.