Faculty of Engineering & Technology
Electrical & Computer Engineering Department

Electrical Machines Laboratory (ENEE3101)

Report 3

"Three Phase Synchronous Generator"

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for being late.

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1. Abstract

This experiment is a comprehensive exploration of generator behavior under various conditions. It starts by examining no-load voltage and short-circuit characteristics, then moves on to analyzing voltage and current responses for different resistive, inductive, and capacitive loads. The study also investigates circuit synchronization for multiple generators and the four-quadrant operation of a synchronous machine in both isolated and non-isolated setups, emphasizing efficiency measurements. Each aspect's findings will be summarized to gain a deeper understanding of generator characteristics and behavior across diverse scenarios.

2. Method used

1 multi-function machine 0.3	**732 28**
1 machine test system	**731989**
1 Extremely low DC power supply	**725 352 D**
1resistive load	**732 40**
1 capacitive load	**732 41**
1 inductive load	**732 42**
2 RMS meters	**727 10**
1 multifunction meter	**727230**
1 power factor meter	**727 12**

Table 1: The method of used in experiment

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3. Theory

- **Synchronous Generators**

Synchronous Generators or Alternators are Synchronous Machines used to convert mechanical power to AC electric power. Synchronous generators are essential components in power generation systems, and their construction involves a stator and a rotor as key components.

- **Stator**

The stator is the stationary part of the synchronous generator and typically consists of a laminated iron core with three-phase windings. The stator winding, also known as the armature winding, is responsible for generating the main output voltages. It is connected to the electrical grid or the load. As the rotor rotates, it induces a rotating magnetic field in the stator windings due to electromagnetic induction.

- **Rotor**

The rotor is the rotating part of the generator and is mounted on a shaft. A DC current is applied to the rotor winding, also known as the field winding, to create a magnetic field in the rotor. This magnetic field interacts with the stator's rotating magnetic field, inducing voltage in the stator windings .The rotor is turned by a prime mover, which could be a steam turbine, gas turbine, or other mechanical sources of energy.

- **Working Principle:**

The DC current supplied to the rotor winding creates a fixed magnetic field in the rotor. As the rotor turns, it carries this magnetic field with it, producing a rotating magnetic field in the machine. The rotating magnetic field cuts across the stationary stator windings, inducing a three-phase AC voltage according to Faraday's law of electromagnetic induction. The frequency of the induced voltage is determined by the speed of rotation and the number of poles in the generator.

- **Windings:**

1. Field Winding (Rotor Winding):

This winding is located on the rotor and is connected to a DC power source. It produces the main magnetic field in the generator when a DC current flows through tithe strength of the magnetic field generated by the field winding is crucial in determining the generator's output voltage.

2. Armature Winding (Stator Winding)

This winding is located on the stator and is connected to the electrical load. It is responsible for generating the main output voltages of the generator through electromagnetic induction. The induced voltage in the armature winding is three-phase AC, and it is the primary power output of the synchronous generator. [1]

In summary, the synchronous generator's construction involves a stationary stator with armature windings and a rotating rotor with a field winding. The interaction between the rotating magnetic field produced by the rotor and the stationary armature windings generates three-phase AC voltages, which can then be used to supply electrical power to the grid or a specific load

$$.n_s = \frac{120 f_e}{P}$$

Equation 1:speed calculation formula

Where P is the number of poles and fe is the frequency

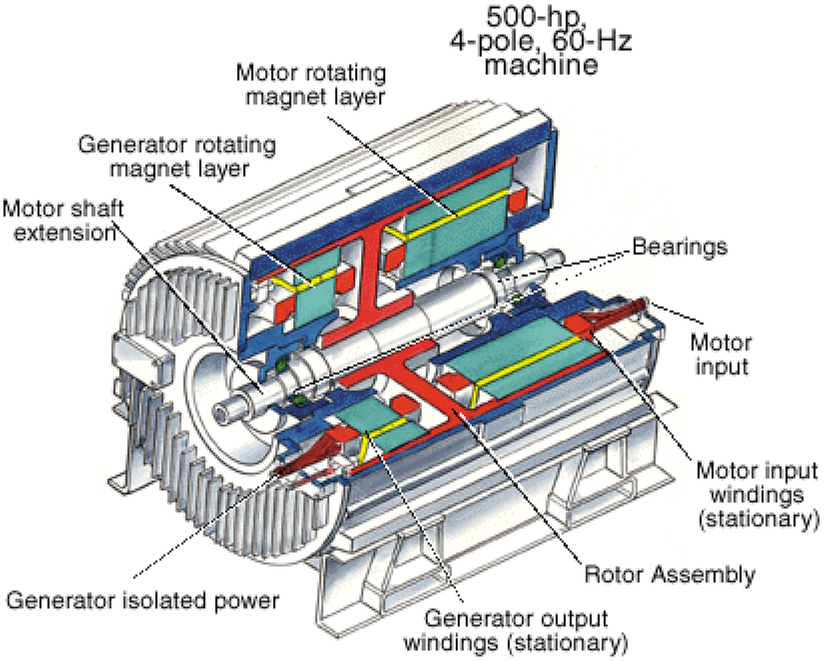


Figure 1: synchronous generator [2]

Synchronous generators require a direct current (DC) to be supplied to the rotor windings to create a magnetic field. There are several methods for supplying this DC current, each with its advantages and considerations.

- External DC Power Supply by means of Slip Rings and Brushes
- Brushless Exciter

- Brushless Exciter with a Pilot Exciter

- **Power Losses and Power-Flow Diagram**

A synchronous generator operates by converting mechanical power input from a prime mover into electrical power output. The prime mover drives the rotor, and a DC applied to the rotor windings produces a magnetic field. This rotating magnetic field induces a voltage in the stator windings, generating three-phase AC power. The power-flow diagram involves the conversion of mechanical power to rotor electrical power, the creation of a magnetic field, and the subsequent generation of electrical power in the stator. However, the process is not without losses, including copper losses, iron losses, mechanical losses, and stray load losses. Minimizing these losses is crucial for optimizing the generator's efficiency. The resulting electrical power is then either supplied to a local load or transmitted to the electrical grid, illustrating the overall energy conversion in a synchronous generator.

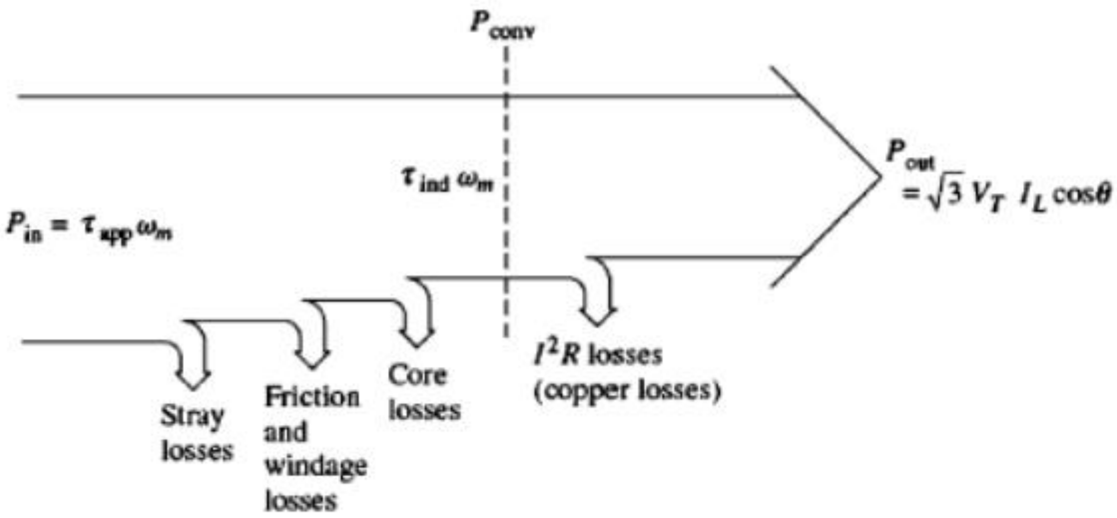


Figure 2:Power-Flow Diagram

$$P_{in} = \tau_{apply} * \omega_m$$

Equation 2:power input

$$P_{out} = \sqrt{3} \times V_T \times I_L \times \cos\theta$$

Equation 3:Power Output

- **Determining the parameters of the synchronous generator model.**
- Open Circuit Test

The open-circuit test for a three-phase generator is performed at its rated speed under no-load conditions. Initially, the field current (If) is set to zero, and then it is gradually increased in steps. The terminal voltage ($V\varphi$), equivalent to EA (electromotive force) at no-load, is measured at each step. The Open-Circuit Characteristic (OCC) of the generator is obtained by plotting EA (or $V\varphi$ or VT) against If. The resulting curve provides valuable insights into the generator's behavior under open-circuit conditions. This test helps analyze the generator's performance and establish its open-circuit characteristics. The Figure 4 below illustrates the Open-Circuit Characteristic obtained from this test. [3]

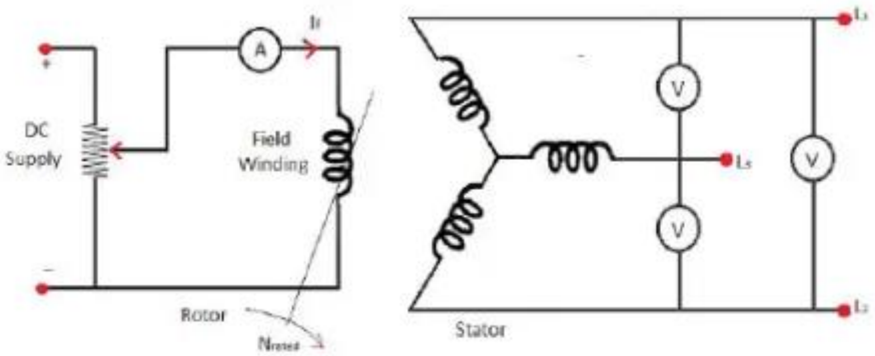


Figure 3: Open Circuit Test [3]

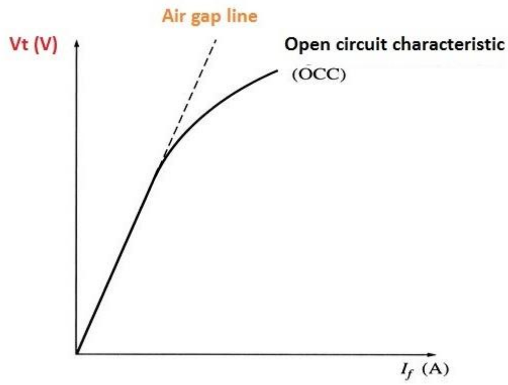


Figure 4: The Open–Circuit Characteristic (OCC) [4]

- Short Circuit Test

To initiate the short-circuit test for a three-phase synchronous generator, start by setting the field current (If) to zero. Proceed by short-circuiting the generator terminals through ammeters. When the terminals are shorted, the armature current (IA) is measured. As the field current (If) is gradually increased, the armature current is recorded at each step. Subsequently, plot the armature current (IA) against the field current (If) to obtain the Short Circuit Characteristic (SCC) of the generator. The SCC provides a representation of the generator's behavior under short-circuit conditions, offering valuable insights into its performance in such scenarios

The diagram below illustrates the Short Circuit Characteristic obtained from this test, highlighting the relationship between the field current and armature current during short-circuit conditions. This test is crucial for understanding the generator's behavior and ensuring its reliability under varying operational conditions.

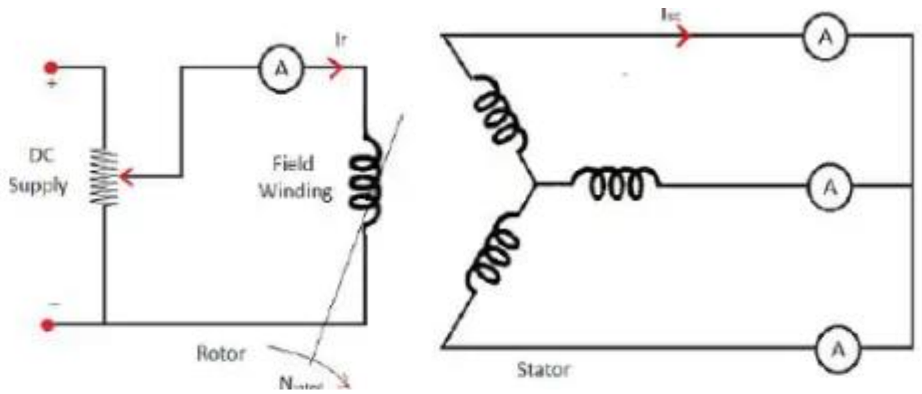


Figure 5: Short Circuit Test

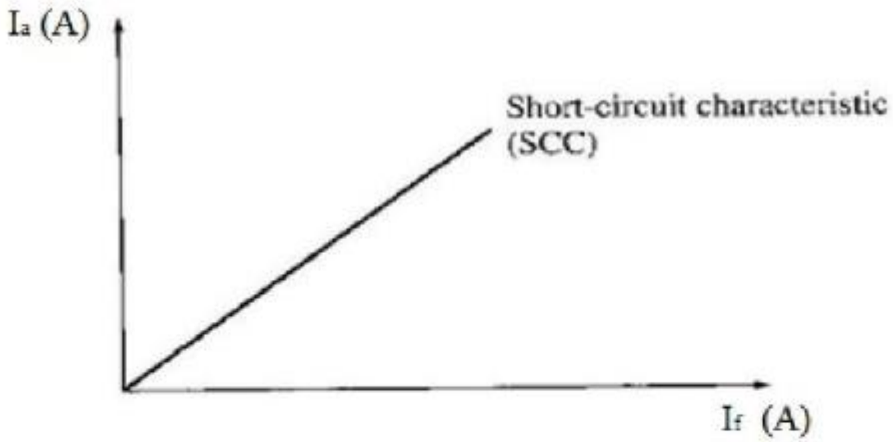


Figure 6: Short Circuit Characteristics (SCC) [5]

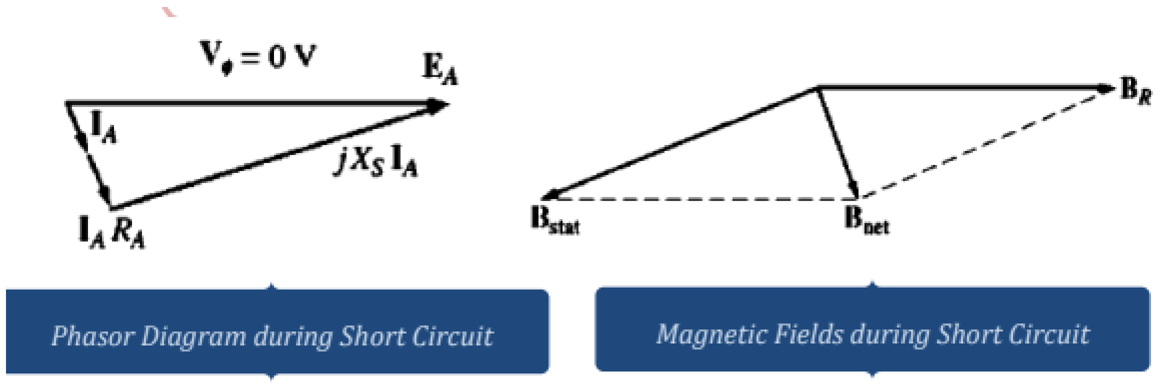


Figure 7: pharos and magnetic during short circuit

$$I_A = \frac{E_A}{\sqrt{R_A^2 + X_S^2}}$$

Equation 4: The armurture current

$$Z_S = \sqrt{R_A^2 + X_S^2} = \frac{E_A}{I_A}$$

Equation 5: The internal impedance

When $Xc >> \ RA$ then,

$$X_S \approx \frac{E_A}{I_A} = \frac{V_{\emptyset,OC}}{I_A}$$

Equation 6: The synchronous reactance

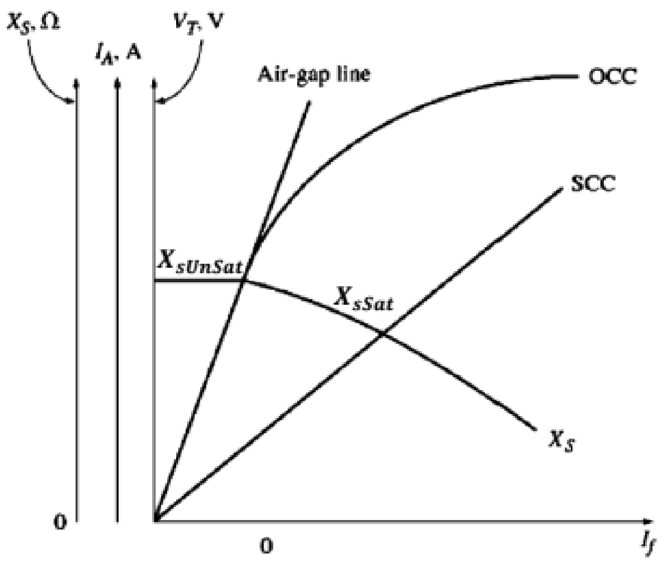


Figure 8: Open-circuit saturation curve

- **Conditions Required for Paralleling Generators**

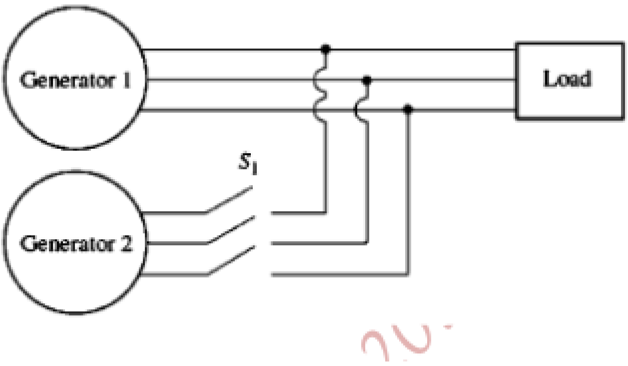


Figure 9: Paralleling Generators

The timing of closing a switch (S1) to connect two generators is a critical factor that cannot be chosen arbitrarily. Inappropriately timed closure can lead to severe consequences, including damage to the generators due to excessive currents and power transients. To mitigate this risk, stringent conditions must be met to ensure the safe and effective connection of the generators. Achieving synchronization between the generators involves ensuring that each of the three phases has precisely the same voltage magnitude and phase angle as the conductor to which it will be linked. This synchronization necessitates adherence to the following conditions:

1. Equal RMS Line Voltages:

The root mean square (rms) line voltages of both generators must be identical to ensure a balanced connection.

2. Phase Angle Equality:

Specifically, the phase angles of the two "a"-phases must be precisely equal, ensuring seamless integration and avoiding voltage differentials.

3. Consistent Phase Sequence:

The two generators must share the same phase sequence, whether it be 'abc' or 'acb' sequence, to maintain coherence in the electrical system.

4. Frequency Adjustment

Before connection, the frequency of the new generator (referred to as the Oncoming Generator, Generator 2) should be marginally higher than the frequency of the running system or generator. This frequency adjustment is crucial for a smooth and controlled transition. These stringent conditions collectively ensure that the generators are synchronized before the switch is closed. Synchronization prevents sudden mismatches in voltage, phase, and frequency, which could otherwise result in damaging currents and power transients. Adhering to these prerequisites guarantees a secure and harmonious connection between generators, minimizing the risk of equipment damage and ensuring the reliability of the overall power system. [6]

- **Example for application three phase generator**

Three-phase generators, also known as three-phase alternators, are widely used in various applications to provide electrical power. Here are some common applications for three-phase generators:

1. Industrial Power Generation:

Three-phase generators are frequently employed in industrial settings to supply power to machinery, manufacturing processes, and other industrial equipment. Their ability to deliver a balanced and efficient power supply makes them suitable for diverse industrial applications.

2. Construction Sites:

Three-phase generators are often used on construction sites to power heavy-duty equipment, tools, and temporary lighting. They provide a reliable source of electrical power for construction activities.

3. Emergency Backup Power:

Three-phase generators serve as reliable backup power sources for critical facilities such as hospitals, data centers, and emergency services. In the event of a power outage, these generators can ensure a continuous and stable power supply.

4. Mining Operations:

Mining sites rely on three-phase generators to power large machinery, conveyors, and other equipment essential for mining operations. Their robust performance and ability to handle heavy loads make them suitable for the demanding conditions of mining environments.

5. Oil and Gas Industry:

In the oil and gas sector, three-phase generators are utilized to power drilling rigs, pumps, and other equipment. They provide a consistent power supply in remote locations where grid power may not be available.

6. Agricultural Applications:

Farms and agricultural operations use three-phase generators to power irrigation systems, grain drying equipment, and other machinery essential for modern farming practices.

7. Events and Entertainment:

Three-phase generators are commonly employed in outdoor events, concerts, and film productions to provide power for stage lighting, sound systems, and other event equipment.

These applications highlight the versatility and reliability of three-phase generators in providing electrical power across a wide range of industries and settings. Their ability to deliver balanced and efficient power makes them essential for diverse applications in today's technological landscape.

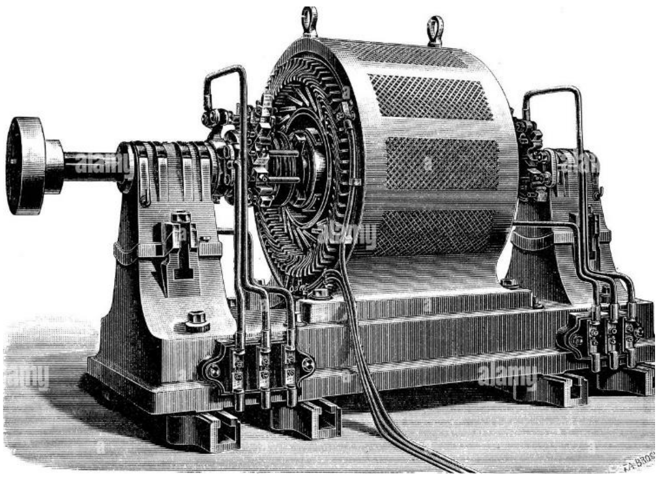


Figure 10: Three-phase generator

- **Types of load connected to the generator**

Three-phase generators are versatile and can accommodate various types of loads, each with its own characteristics. The types of loads connected to a three-phase generator can be broadly categorized into resistive, inductive, and capacitive loads. Each load type affects the generator in different ways:

1. Resistive Loads:

Resistive loads, such as heating elements and incandescent lighting, primarily consume active power (real power) without introducing reactive power. These loads have a power factor close to 1. Connecting resistive loads to a three-phase generator primarily impacts the active power output and does not significantly affect the power factor.

2. Inductive Loads:

Inductive loads, including electric motors, transformers, and solenoids, introduce both active and reactive power components. These loads have a power factor less than 1, and the reactive power demand leads to a lagging power factor. Connecting inductive loads to a three-phase generator can result in a reduction in the overall power factor of the system. To compensate for this, power factor correction devices such as capacitors may be employed to improve the power factor and reduce reactive power demand.

3. Capacitive Loads:

Capacitive loads, although less common, can include equipment like power factor correction capacitors. These loads introduce reactive power with a leading power factor. Connecting capacitive loads to a three-phase generator tends to improve the power factor of the system, reducing the overall reactive power demand.

4. Mixed Loads:

Many practical systems have a combination of resistive, inductive, and capacitive loads. The overall impact on the three-phase generator depends on the mix and the power factor characteristics of each load. Proper load balancing and power factor correction techniques may be employed to optimize the generator's performance.

5. Unbalanced Loads:

Unbalanced loads occur when the three phases of the load draw unequal currents. This situation can lead to phase imbalances and affect the generator's efficiency. It's important to ensure balanced loads to prevent overheating and uneven wear on the generator. The type of load connected to a three-phase generator influences the following aspects:

Active Power (Real Power): The real power drawn by the load affects the generator's capacity and fuel consumption. Reactive Power: Inductive or capacitive loads contribute to the reactive power demand, influencing the power factor and potentially requiring power factor correction measures.

Voltage Regulation: Fluctuations in load characteristics can affect the voltage regulation of the generator. Voltage regulators may be employed to maintain stable voltage levels.

Generator Efficiency: The efficiency of a generator is influenced by the type of load connected, as different loads have varying power factor characteristics. The types of loads connected to a three-phase generator is crucial for optimizing its performance, ensuring stability, and implementing necessary corrective measures to address power factor concerns and maintain efficient operation.

Delta (Δ) and Wye (Y or Δ) are two common configurations for connecting loads to three-phase generators. Each configuration has its advantages and is suitable for different applications. Here's an overview of Delta and Wye connections and how various types of loads can be connected in each:

Delta (Δ) Connection:

In a delta connection, the three phases are connected in the shape of a triangle (Δ). The load is connected between the phases, and the line voltage is equal to the phase voltage multiplied by the square root of 3 (√3). The current flowing through each load is the line current.

Load Connection:

1. Resistive Load (R):

Connect the resistive load between any two phases.

2. Inductive Load (L):

Connect the inductive load between any two phases.

3. Capacitive Load (C):

Connect the capacitive load between any two phases.

4. Mixed Load:

Combination of resistive, inductive, and capacitive loads can be connected between any two phases.

Wye (Y) Connection:

In a wye connection, the three phases are connected at a common point, forming a Y shape. The load is connected between one phase and the common point, and the line voltage is equal to the phase voltage. The line current is equal to the phase current multiplied by the square root of 3 (√3).

Load Connection:

1. Resistive Load (R):

Connect the resistive load between one phase and the neutral point.

2. Inductive Load (L):

Connect the inductive load between one phase and the neutral point.

3. Capacitive Load (C):

Connect the capacitive load between one phase and the neutral point.

4. Mixed Load:

Combination of resistive, inductive, and capacitive loads can be connected between one phase and the neutral point.

Connecting All Load Types:

Delta Connection:

For a delta-connected generator, each load type (resistive, inductive, capacitive, or mixed) can be connected between any two phases.

Wye Connection:

For a wye-connected generator, each load type can be connected between one phase and the neutral point.

The choice between delta and wye connections depends on factors such as the specific application, voltage requirements, and the characteristics of the connected loads. Delta connections are often preferred in industrial settings, while wye connections are common in commercial and residential applications. Additionally, the selection may be influenced by considerations like system stability, fault tolerance, and ease of connecting single-phase loads.

1.5

4. Procedure, Data and Calculations

A. Behavior as a Generator in isolated Operation

Table 2 is to be completed with the data available on the nameplate of the machine. The circuit depicted in Figure 11 is to be utilized for the examination of the Generator's no-load characteristic. For the study of this characteristic, the generator terminals are to be left unconnected to any external load, maintaining an open circuit configuration. A voltmeter is to be connected between any two terminal lines, as indicated in Figure 11.

Nominal Voltage V_N when connected in star:	**400**
Nominal Voltage V_N when connected in delta:	**230**
Nominal Current I_N when connected in star:	**0.83**
Nominal Current I_N when connected in delta:	**1.44**
Nominal Power Factor, $\cos(\theta_N)$:	**0.7-1**
Nominal Power P_N :	**0.27**
Nominal excitation voltage V_{EN}:	**20**
Nominal excitation current I_{EN}:	**4**
Nominal speed n_N:	**1300/1500**

Table 2: Nominal data for machine under test

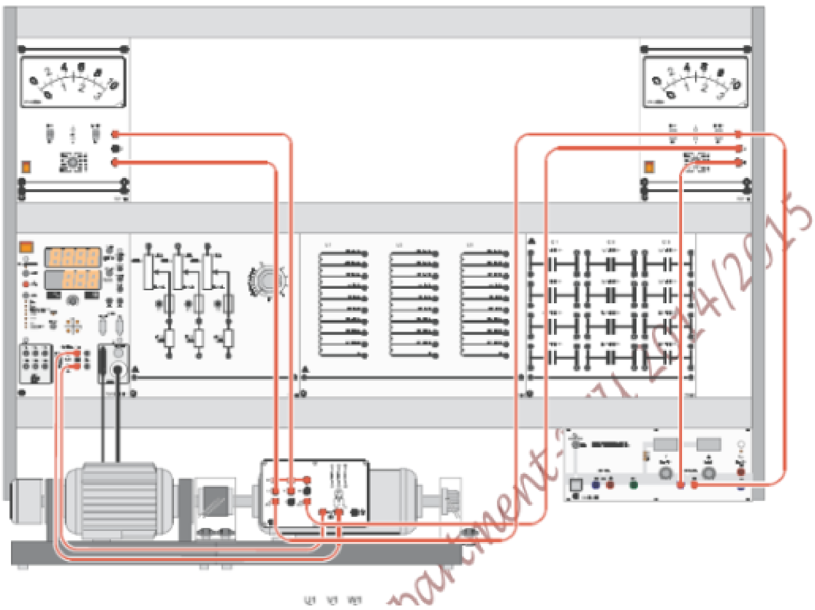


Figure 11: Connection Circuit

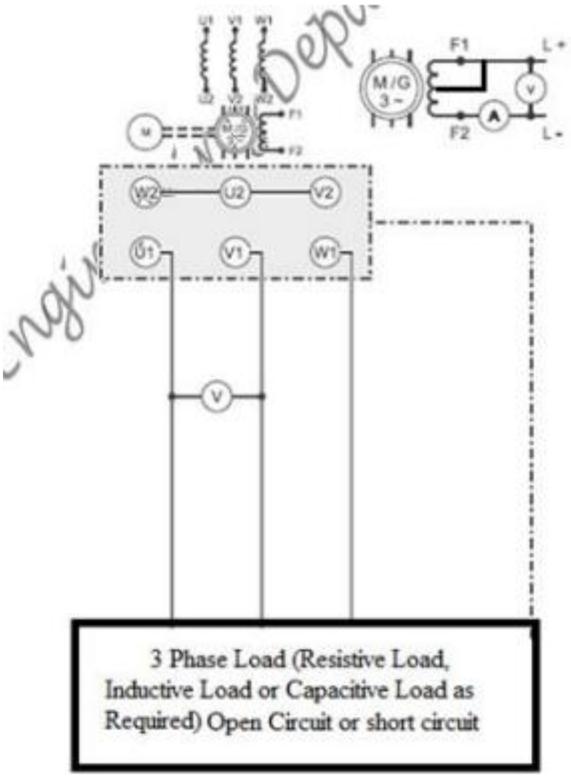


Figure 12:Circuit for studying synchronous Generator

1. Generator NO-LOAD Characteristics

The RED button on the machine test system is to be pressed to activate the system. Once the machine test system is activated, and the operational mode "Load Characteristics" (first mode) is selected, the Generator is to be driven at a constant speed of 1500 rpm. Utilizing the nominal values from Table 2 for excitation current (IE) and output voltage, calculations for IE values corresponding to the given IE/IEN values in Table 3 are to be performed. Following the calculations, the external DC power supply is to be turned on to excite the generator with the required IE for each specified value. During this process, measurements of the voltage V0 (the line-to-line open-circuit voltage) are to be taken, and the obtained values are to be recorded in Table 3. It may be necessary to employ both DC power supplies to achieve the desired IE. Upon completing the measurements and data recording, the DC power supply is to be turned off. The machine test system is then deactivated by pressing the RED button.

$$I_E = I_{NE} * (I_E/I_{EN}) = \ 4 * 0.1 = 0.4\ A$$

Equation 7: The current excitation dpend on nominal vlaues

I_E/I_{EN}	***0.0***	***0.2***	***0.4***	***0.6***	***0.8***	***1.0***	***1.2***
$I_E/[A]$	**0.0**XI_{EN}	0.8	1.6	2.4	3.2	4	4.8
Vo	0	190	300	360	390	410	420
V_0/V_N	0	0.475	0.75	0.9	0.975	1.025	1.05

Table 3: Recording of the No-Load Generator Characteristics

$$\frac{V_O}{V_N} = \frac{V_O}{400} = \frac{190}{400} = 0.475$$

Equation 8:The normalized open-circuit voltage

The provided data represents the analysis of a 3-phase synchronous generator under no-load conditions, with variations in excitation current (IE) and the resulting open-circuit voltage (V0), the table includes different excitation current values (IE) normalized to the nominal value (I_{EN}) and the corresponding absolute values of IE. These values indicate the level of excitation applied to the generator during the no-load test .The table displays the open-circuit voltage (V0) measured at various excitation current levels. The values are both absolute and normalized to the nominal voltage (VN). This provides insights into how changes in excitation current affect the generator's output voltage under no-load conditions. As excitation current increases, there is a corresponding rise in the open-circuit voltage. This relationship indicates the sensitivity of the generator's output to changes in excitation. The normalized values (V0/VN) help gauge the relative magnitude of the open-circuit voltage concerning the nominal voltage. The trend suggests a nearly linear correlation between excitation current and open-circuit voltage. This relationship is typical for the no-load characteristics of synchronous generators. The data provides valuable information for understanding the generator's behavior under varying excitation conditions, offering insights into the generator's capability to produce voltage at different levels of excitation when no external load is connected.

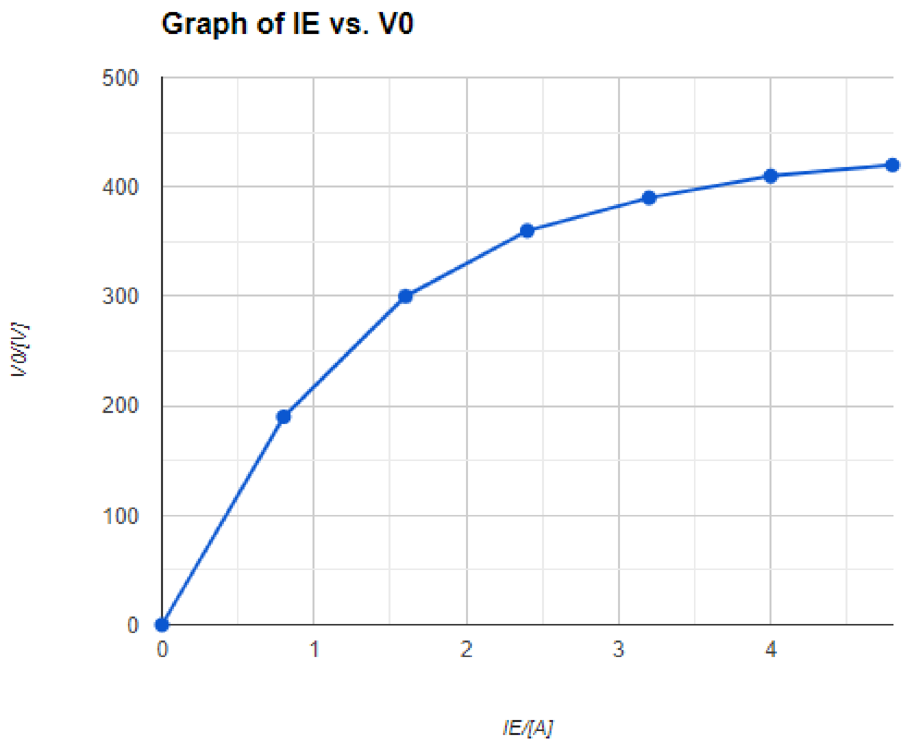


Figure 13: The Relationship between the current extiotion and the output voltage

The observed linearity in the graph implies a straightforward behavior of the cell without significant complicating factors influencing the relationship between voltage (V) and current (I). The well-spaced and evenly distributed data points indicate a careful and reliable execution of the experiment, contributing to the credibility of the results. However, the absence of error bars in the graph prevents a precise assessment of the uncertainty associated with each data point, limiting the ability to quantify the level of confidence in the measurements. Including error bars would provide a clearer understanding of the data's reliability and the potential variation associated with each data point.

2. Generator Short Circuit Characteristic

At a constant speed of 1500 rpm, the generator was operated, and the "Only Motor Operation Button" was pressed to activate generator functionality, indicated by the deactivation of the "Only Motor Operation" indicator. Subsequently, the machine test system was turned on using the RED button in the selected operational mode, "Load Characteristics" (first mode), while ensuring the generator's speed remained at 1500 rpm. To investigate the short-circuit characteristic, the circuit connection was modified. An RMS meter and an Ammeter were serially connected to one of the Generator Terminals to measure the current in one phase. Following this, all generator terminals were short-circuited. Using the nominal values from Table 2, IE values for the specified IE/IEN values in Table 3 were calculated. The generator was then excited with the required IE by activating the external DC power supply. For each IE value, the voltage V0 (line-to-line open circuit voltage) was measured, and the corresponding values were recorded in Table 3. It's worth noting that both DC power supplies might have been utilized to achieve the desired IE. However, in this context, Table 4 was completed by documenting ISC instead of V0.

I_E/I_{EN}	**0.0**	**0.2**	**0.4**	**0.6**	**0.8**	**1.0**	**1.2**
I_E/[A]	0	0.8	1.6	2.4	3.2	4	4.8
I_{SC}/[A]	0	0.16	0.33	0.51	0.68	0.83	0.98
I_{SC}/I_N	0	0.04	0.082	0.127	0.17	0.207	0.245

Table 4: Recording the Generator Short Circuit Characteristics

The provided data illustrates the Short Circuit Characteristic for a Three-Phase Synchronous Generator. This characteristic is crucial for comprehending how the generator reacts under short-circuit conditions at varying excitation levels. As excitation levels escalate (progressing from left to right in the table), both actual and normalized short-circuit currents (ISC) also demonstrate an increasing trend. The use of normalized values enables a comparison independent of the generator's specific rating, offering a clearer understanding of the generator's behavior across diverse excitation levels. This dataset is indispensable for the analysis of the generator's performance during short-circuit conditions, contributing to the design and operation of the generator within safe and efficient operating parameters.

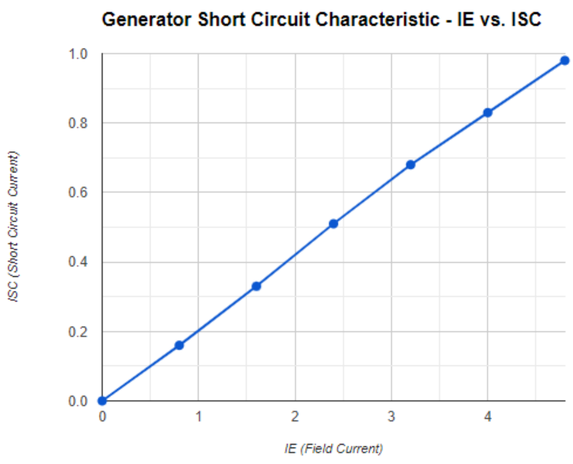


Figure 14: Generator Short Circuit Characteristic

In Figure 14, the observed trend reveals a linear increase in the field current concerning the short-circuit current in a three-phase synchronous generator. Let's delve into an elucidation of the generator's short-circuit characteristic. The graphical representation illustrates the correlation between the field current (IE) and the resulting short-circuit current (ISC). The field current, coursing through the generator's field winding, modulates the magnetic field's strength. Concurrently, the short-circuit current denotes the flow through the generator when its output terminals are abruptly shorted. As the field current intensifies, a commensurate rise in the short-circuit current occurs. This phenomenon arises from a stronger magnetic field inducing a larger electromotive force (EMF) in the generator's armature winding, consequently augmenting the current flow. For power system engineers, the short-circuit characteristic is paramount. It facilitates the design of protective mechanisms to shield the generator from potential damage during short circuits. Given the propensity for high short-circuit currents, swift interruption becomes imperative to prevent overheating of the generator's windings. The specific shape of the short-circuit characteristic can exhibit variation based on generator design. Nevertheless, the overarching trend remains consistent—short-circuit current escalates with an increase in field current. The short-circuit current demonstrates approximate proportionality to the field current, signifying that a doubling of the field current results in a corresponding doubling of the short-circuit current. A nonzero short-circuit current is evident even when the field current is zero, attributable to a minimal current flow termed the leakage current. A peak short-circuit current is reached at a specific field current, representing the maximum attainable value in the context of this characteristic.

I_E/I_{EN}	**0.0**	**0.2**	**0.4**	**0.6**	**0.8**	**1.0**	**1.2**
X_S	0	1187.5	909.09	705.88	573.5	493.97	428.5

Table 5: Recording the Synchronous Reactance for different values of excitation current

From Equation 6

$$X_S \approx \frac{E_A}{I_A} = \frac{V_{\emptyset,OC}}{I_A}$$

Equation 9: The synchronous reactance

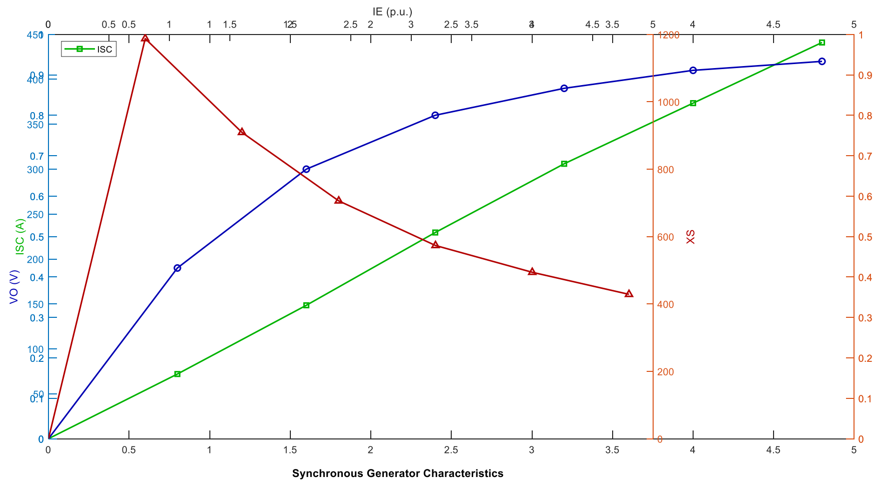


Figure 15: Synchronous Generator Characteristics

The provided graph detailing the Synchronous Generator Characteristics offers a profound insight into the interplay between field current (IE), open-circuit voltage (VO), and short-circuit current (ISC) in a phase synchronous generator. With specified nominal values, including voltage, current, power factor, power, excitation voltage, excitation current, and speed, the graph unravels critical aspects of generator behavior. The Open-Circuit Characteristic (OCC), represented by the blue line, initially adheres to linearity but undergoes deviation owing to iron core saturation at higher field currents. This deviation results in a tapering off of the voltage increase per unit IE, ultimately constraining the generator's voltage-generating capacity. On the other hand, the Short-Circuit Characteristic (SCC), denoted by the green line, manifests as a straight line passing through the origin. This linearity is indicative of the armature current being primarily constrained by the leakage reactance of the stator windings under short-circuit conditions. The slope of the SCC provides a direct insight into the generator's synchronous reactance (XS).While theoretically calculating XS by dividing VO by ISC introduces some error, especially at low field currents influenced by saturation effects, this graph remains an invaluable tool for understanding synchronous generator behavior. It illuminates the OCC and SCC, offering key information on the generator's voltage and current generation capabilities. The calculated XS, despite its limitations, provides crucial insights into the generator's impedance characteristics. Incorporating this graph into the broader understanding of synchronous generators, engineers gain a valuable resource for optimizing operational parameters. The indirect influence of the air gap on XS.

3. Generator Resistive Load Characteristics

The study of the generator's behavior with various resistive load values involves altering the circuit connection, ensuring the load is connected in Y configuration, as depicted in Figure 16. The setting of the resistive load to 100% of its value is carried out, and activation of the machine test system is initiated through the depression of the RED button. The status of the LED indicating "Only Motor Operation" is confirmed to be off. The generator is subsequently operated with a constant speed of 1500 rpm, and external excitation is applied from the DC power supply with the nominal current obtained from Table 1.For each percentage value of the resistive load in Table 6, recording is performed for the load current (I) in one phase and the line-to-line output voltage. The DC power supply is deactivated, and the machine test system is powered down by the depression of the RED button on the machine test system.

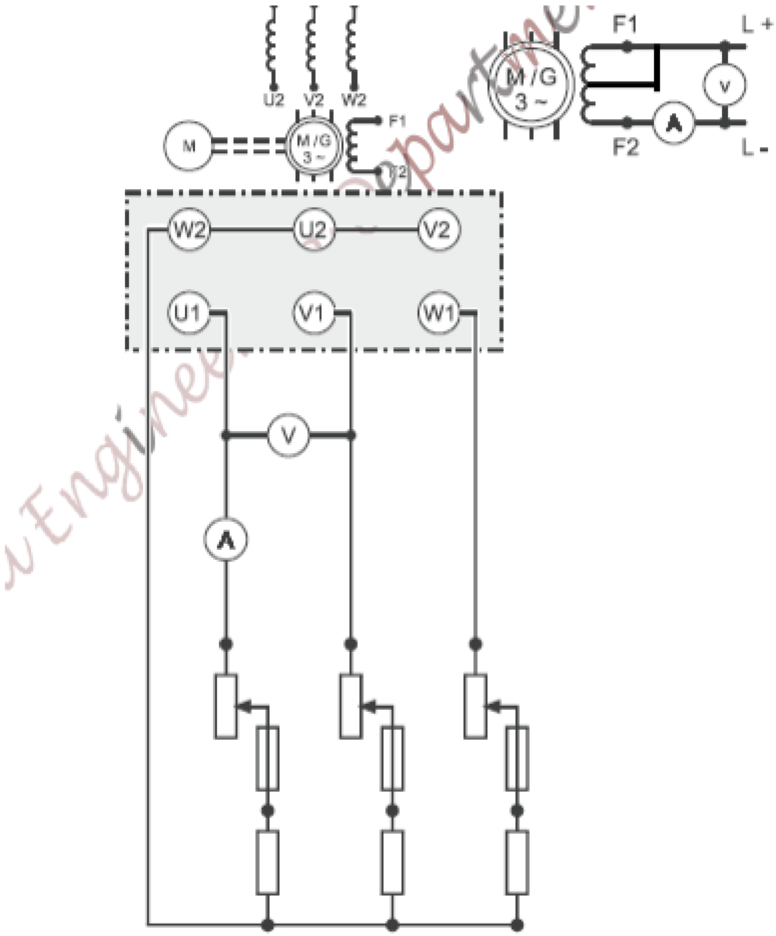


Figure 16: Circuit to study the behavior of the Generator for Resistive Load

R%	**100**	**80**	**60**	**40**	**20**
I/[A]	0.14	0.15	0.2	0.35	0.55
V_{L-L}/[V]	400	400	400	380	350
I/I_N	0.035	0.0375	0.05	0.0875	0.1375
V_{L-L}/V_N	1	1	1	0.95	0.875

Table 6: Generator Resistive Load Characteristic Recording

$$\frac{I}{I_N} = \frac{0.14}{4} = 0.035$$

Equation 10: The Current ratio for Generator Resistive Load

$$\frac{V_{L-L}}{V_N} = \frac{400}{400} = 1$$

Equation 11: The voltage ratio for Generator Resistive Load

As the resistance percentage for the three-phase generator decreases from 100% to 20%, there is a corresponding increase in the current (I) from 0.14A to 0.55A. This trend suggests an inverse relationship between the resistance percentage and current, which aligns with Ohm's Law (V=IR).Throughout the variations in resistance, the line-to-line voltage (VL-L) remains constant at 400V for the first three resistance percentages (100%, 80%, 60%). However, as the resistance decreases further (40% and 20%), there is a slight reduction in VL-L, reaching 380V and 350V, respectively. The current as a percentage of the nominal current (I/IN) increases as the resistance percentage decreases. This reinforces the inverse relationship between the resistance percentage and current. The line-to-line voltage as a percentage of the nominal voltage ($VL - L/VN$) remains constant at 1 for the first three resistance percentages. As the resistance percentage decreases, VL-L/VN decreases slightly, indicating a small deviation from the nominal voltage. Overall, the data suggests a consistent pattern in the relationship between the resistance percentage, current, and voltage. As the resistance percentage decreases, the current tends to increase, while the voltage experiences a slight reduction. These observations align with fundamental electrical principles and provide insights into the behavior of the three-phase generator under varying resistive conditions. Current tends to increase, while voltage experiences a slight reduction. The observations align with fundamental electrical principles and provide insights into the behavior of the circuit under varying resistive conditions.

4. Generator inductive Load Characteristics

The circuit of Figure 16 is connected, and the inductive load is now configured in a Y connection. The measurement procedure detailed above is reiterated, this time for the inductive load values outlined in Table 7. It is essential to emphasize that, for each change in the inductive load value, the system needs to be turned off. This involves setting the excitation current to zero and subsequently pressing the RED button on the machine test system. Additionally, it should be noted that measurements for low values of the inductive load need to be taken swiftly.

L/[H]	**6.0**	**2.4**	**1.0**	**0.6**	**0.2**
I/[A]	0.1	0.2	0.4	0.56	0.76
V_{L-L}/[V]	390	360	300	240	110
I/I_N	0.025	0.05	0.1	0.14	0.19
V_{L-L}/V_N	0.975	0.9	0.75	0.6	0.275

Table 7: Generator Inductive Load Characteristic Recording

The provided data represents the inductive load characteristic recording for a generator with a Y-connected inductive load. Here are comments on the observations: As the inductance increases from 0.2 H to 6.0 H, there is a corresponding decrease in the current (I) from 0.76A to 0.1A. This is consistent with the behavior of inductive loads, where higher inductance impedes the flow of current. The inverse relationship between inductance and current aligns with the principles of inductive circuits. As inductance increases, the current tends to decrease, and vice versa. The inverse relationship between inductance and current aligns with the principles of inductive circuits. As inductance increases, the current tends to decrease, and vice versa. The inverse relationship between inductance and current aligns with the principles of inductive circuits. As inductance increases, the current tends to decrease, and vice versa. The current as a percentage of nominal current decreases with increasing inductance. This trend emphasizes that the inductive load reduces the effective current flowing in the circuit. The line-to-line voltage as a percentage of nominal voltage also decreases with higher inductance. This reduction is indicative of the voltage drop across the inductive load. Overall, the data illustrates the impact of inductance on the generator's behavior with a Y-connected inductive load. The observed trends align with the expected behavior of inductive elements in electrical circuits, showcasing a decrease in current and voltage as inductance increases.

5. Generator Capacitive Load Characteristics

The circuit of Figure 16 is to be connected, and the capacitive load is to be configured in a Y connection. The above measurement procedure is to be reiterated, this time for the capacitive load values outlined in Table 8. It is emphasized that, for each change in the capacitive load value, the system is to be turned off. This involves setting the excitation current to zero and subsequently pressing the RED button on the machine test system. Additionally, it is noted that measurements for low values of capacitance need to be taken swiftly. This is crucial, especially for the Capacitive Load connected in Y, utilizing the specified capacitance values from Table 8 (1 μF and 2 μF), ensuring quick measurements.

C/[µF]	1	2
I/[A]	0.1	0.19
$V_{L\text{-}L}$/[V]	415	430
I/I_N	0.025	0.0475
$V_{L\text{-}L}/V_N$	1.0375	1.075

Table 8: Generator Capacitive Load Characteristic Recording

The provided data reflects the characteristics of a capacitive load connected to a 3-phase synchronous generator with a Y connection. Here are observations and comments on the data: As the capacitance increases from 1 µF to 2 µF, there is a corresponding increase in the current (I) from 0.1A to 0.19A. This relationship is typical for capacitive loads, where higher capacitance facilitates a higher flow of current. The positive correlation between capacitance and current is consistent with the behavior of capacitive loads. Increased capacitance allows for a higher current flow in the circuit. The line-to-line voltage increases from 415V to 430V as the capacitance increases. This suggests that higher capacitance contributes to a rise in voltage. The current as a percentage of nominal current increases with higher capacitance. This indicates that the capacitive load allows more current to flow relative to the nominal current. The line-to-line voltage as a percentage of nominal voltage also increases with higher capacitance. This rise in voltage percentage suggests enhanced voltage output with increased capacitance. Overall, the data illustrates the impact of capacitance on the behavior of the 3-phase synchronous generator with a Y-connected capacitive load. The positive correlations observed align with expected behaviors for capacitive elements in electrical circuits.

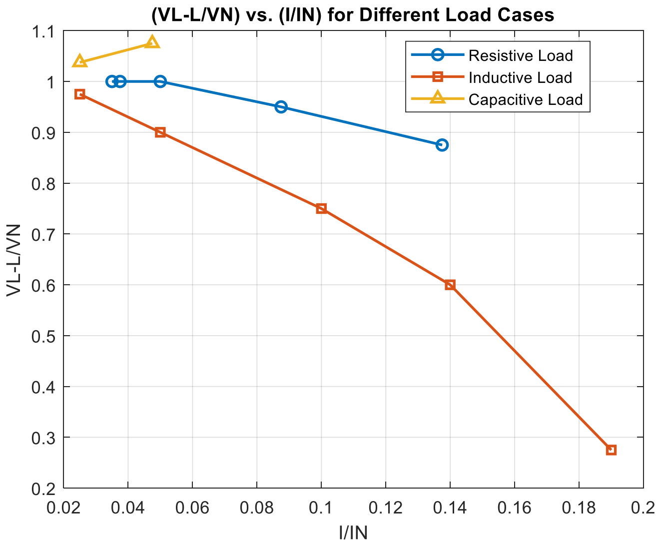


Figure 17: Relative line-to-line voltage versus normalized current characteristic curve for different load cases

The graph shows the relationship between the relative line-to-line voltage (VL-L/VN) and the normalized current (I/IN) for three different load cases: resistive, inductive, and capacitive. The X-axis represents the normalized current, ranging from 0.02 to 0.2, while the Y-axis represents the relative line-to-line voltage, ranging from 0.2 to 1.1.

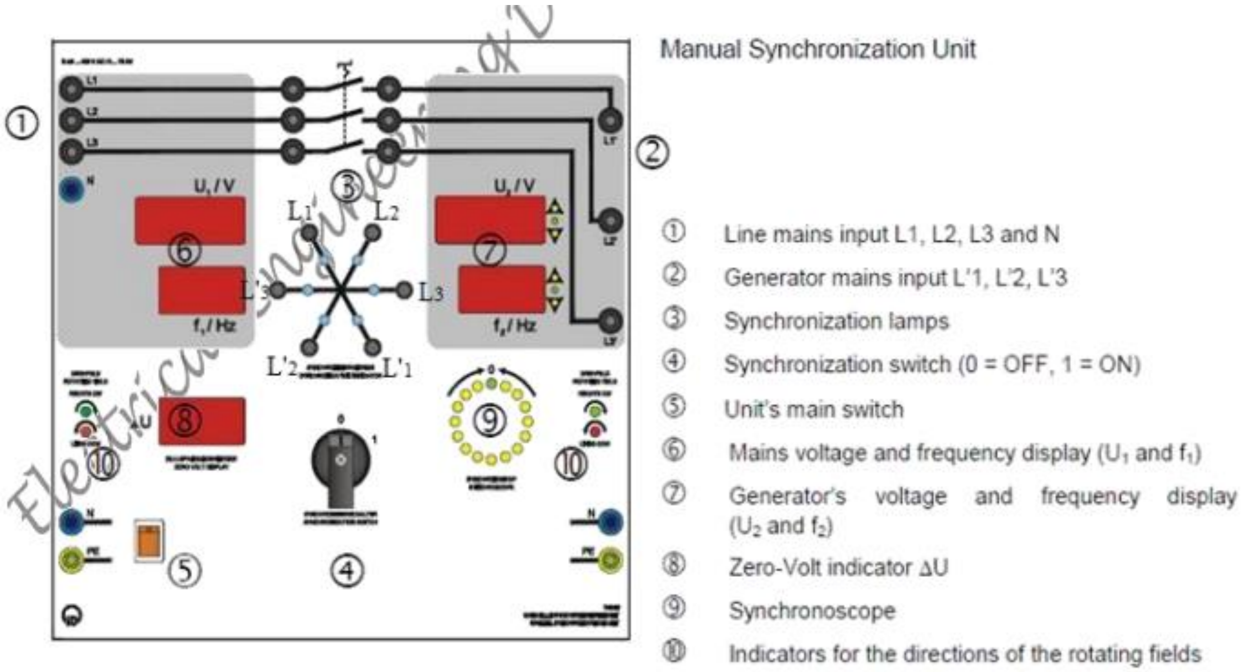
Resistive Load: The voltage and current for the resistive load are in phase, meaning they peak and trough at the same time. This is because resistors only dissipate power, and there is no reactive power involved. As the current increases, the voltage also increases proportionally, resulting in a straight line with a slope of 1.

Inductive Load: The voltage for the inductive load lags behind the current, meaning the voltage peak occurs after the current peak. This is because inductors oppose changes in current, and as the current tries to increase, the inductor induces a voltage in the opposite direction. As the current increases, the voltage decreases, and the curve for the inductive load bends downward.

Capacitive Load: The voltage for the capacitive load leads the current, meaning the voltage peak occurs before the current peak. This is because capacitors oppose changes in voltage, and as the voltage tries to increase, the capacitor stores energy and draws current in advance. As the current increases, the voltage increases, and the curve for the capacitive load bends upward. The graph, located at I/IN = 0.1 and VL-L/VN = 0.75, appears to be the intersection point of the curves for the inductive and capacitive loads. This could be interpreted as the point where the reactive power from the inductor (lagging) and the capacitor (leading) cancel each other out, resulting in a purely resistive load-like behavior. The graph highlights the different ways in which different load types affect the voltage and current in a circuit. This is important for understanding how power systems behave and for designing efficient electrical systems. The power factor, which is a measure of how effectively electrical power is used, can be calculated from the voltage and current waveforms. Resistive loads have a power factor of 1, while inductive and capacitive loads have power factors less than 1.

B. Synchronizing Circuit

In this section, the generator is to be connected in parallel with the main power lines, ensuring that the Synchronization switch is in the 0 (off) position. The Line Mains input L1, L2, L3, and N is connected to the three-phase power supply while ensuring that the 3-phase power supply remains in the OFF state. The oncoming generator terminals, connected through the machine test system unit to measure the output parameters, are linked to the Generator mains input L'1, L'2, and L'3. The generator is driven by the machine test system to a speed of 1507 rpm, resulting in a slightly higher frequency than the main frequency. Subsequently, the machine is excited with the nominal excitation current from Table 4.1 using the external power supply 725 852 D.The 3-phase power supply is then turned on, and the indicators for the directions of the rotating fields (number 10 on the synchronizing unit) are observed. If the indicators show the same direction of rotation on both sides, confirming the same phase sequence, the synchronization process is proceeded with. In case of a discrepancy (indicated by a RED and a Green LED), the main 3-phase power supply is turned off, phases are swapped, and then the power supply is turned back on. After confirming the same phase sequence on both sides and ensuring the RMS line voltage is consistent, attention is given to the slightly higher frequency (~50.1Hz) of the oncoming generator compared to the main supply.Subsequently, the synchroscope indicator is monitored until it reaches 12 O'clock, at which point all synchronization lamps should be off (no light). The synchronization switch is then switched to the ON state (position 1). The mode of operation of the machine test system is directly changed from Load Characteristics mode to Torque Regulation Mode to control the output power fed to the grid.The nominal torque (TN) of the machine under test (AC multifunction machine 732 28) is calculated using the nominal values obtained from Table 2. The actual torque values are calculated using the provided equation for the torque normalized values in Table 9. The torque values are then changed in steps as indicated in Table 9. At each torque value, readings are taken (using the CBM 10 software) for the generator input power, generator output power, output current of the generator, and output power factor of the generator.



$$\tau = \frac{P}{\omega} = \frac{270}{1500 * \frac{2\pi}{60}} = 1.72$$

Equation 12: The power-torque relationship or the mechanical power formula

T/T_N	0.0	0.2	0.4	0.6	0.8
T_{act}	0	0.34	0.68	1.03	1.37
V	379	379	380	380	380
I	0.15	0.17	0.22	0.28	0.36
Cos(θ)	0.35	0.4	0.63	0.72	0.76
P_{in}	11.6	41.7	32	139	185
P_{out}	34.46	44.63	91.22	132.68	180.07

Table 9: studying the behavior of the generator when connected in parallel with the main power grid

From Equation 3

$$P_{out} = \sqrt{3} \times V_T \times I_L \times \cos\theta = \sqrt{3} * 379 * 0.15 * 0.35 = 34.46w$$

As the input torque increases in the Synchronizing Circuit scenario

1. Voltage (V): The voltage remains relatively constant at 380V across different torque levels. This stability in voltage is crucial for maintaining a consistent power supply to the grid. The constant voltage suggests that the generator is effectively synchronized with the main power lines, ensuring a reliable electrical output.

2. Current (I): The current drawn by the generator increases with higher torque levels. This is a direct result of the generator working against an increased mechanical load. As the torque applied to the generator increases, more current is required to produce the additional mechanical power necessary to drive the generator.

3. Power Factor $\cos\theta$: The power factor generally increases with higher torque levels. A higher power factor indicates improved efficiency in converting electrical power. This suggests that the generator is

operating more effectively at higher torque inputs, with a better alignment of real power and apparent power.

4. Input Power (Pin): The input power required to drive the generator increases with higher torque levels. This is expected, as higher torque demands more mechanical power input to maintain generator operation. The increase in input power reflects the additional energy needed to overcome the higher mechanical load.

5. Output Power (Pout): The output power delivered by the generator also increases with higher torque levels. This demonstrates the generator's capacity to deliver more electrical power to the grid as the mechanical input (torque) is elevated. The increase in output power is a positive outcome, indicating the generator's ability to meet higher electrical demand. IN summary, the observed trends in voltage, current, power factor, input power, and output power align with expectations for a synchronized generator operating under increasing torque conditions. The stability in voltage and favorable changes in other parameters suggest that the Synchronizing Circuit effectively manages the generator's connection to the main power lines, providing reliable and efficient electrical power output.

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5. Discussion and Results

For part A:

1.

The presented data from the open-circuit test on the 3-phase synchronous generator is comprehensive and well-executed, providing a thorough exploration of the generator's behavior under no-load conditions. The experiment, which involved varying excitation current (IE) and measuring resulting open-circuit voltage (V0), successfully achieved its objectives. The data reveals a clear relationship between excitation current and open-circuit voltage, showcasing the generator's sensitivity to changes in excitation levels. The inclusion of normalized values (V0/VN) adds a valuable dimension, allowing for a standardized comparison of open-circuit voltage relative to the nominal voltage (VN). The observed nearly linear correlation between excitation current and open-circuit voltage aligns with expectations for the no-load characteristics of synchronous generators. Overall, this part of the experiment is well-executed and yields the desired output, providing valuable insights into the generator's performance under varying excitation conditions during no-load operation.

2.

In conclusion, the Short Circuit Characteristic data for the Three-Phase Synchronous Generator provides valuable insights into the generator's behavior under short-circuit conditions at different excitation levels. The progressive increase in both actual and normalized short-circuit currents (ISC) as excitation levels rise indicates a direct correlation between excitation and short-circuit current. The use of normalized values allows for a consistent and insightful comparison, irrespective of the generator's specific rating, providing a comprehensive understanding of its performance across various excitation levels. This dataset is instrumental in the analysis and design of the generator, particularly in ensuring its safe and efficient operation under short-circuit conditions. The information derived from this Short Circuit Characteristic is crucial for engineers and operators to establish appropriate protective measures and operational parameters for the generator, contributing to the overall reliability and stability of the power system.

3.

The analysis of the Generator Resistive Load Characteristics reveals a consistent pattern in the behavior of the three-phase generator as the resistance percentage varies. The observed increase in current and the slight reduction in voltage align with Ohm's Law, indicating an inverse relationship between resistance percentage and current. The constancy of line-to-line voltage (VL-L) for the initial resistance percentages suggests stable voltage output within certain resistance ranges. However, as resistance decreases beyond 60%, there is a marginal reduction in VL-L, possibly influenced by the changing load conditions. The increase in current as a percentage of nominal current (I/IN) with decreasing resistance further supports the inverse relationship. Despite the variations, the line-to-line voltage as a percentage of nominal voltage (VL-L/VN) remains relatively constant, with a slight deviation at lower resistance percentages. These findings underscore the generator's adaptability to resistive load changes, maintaining stable voltage output for a range of resistances. The observed trends provide valuable insights for optimizing the generator's performance and designing electrical systems that can accommodate varying resistive conditions effectively. Overall, the study enhances our understanding of how resistive loads impact the electrical characteristics of the three-phase generator, contributing to the broader field of electrical engineering.

4.

The analysis of the generator's inductive load characteristics, specifically with a Y-connected inductive load, reveals a consistent and predictable relationship between inductance, current, and voltage. As inductance increases, there is a proportional decrease in current, aligning with fundamental principles of inductive circuits. The inverse correlation observed emphasizes the impedance effect of inductance, hindering the effective flow of current in the circuit. Furthermore, the data illustrates a decline in line-to-line voltage as inductance increases, indicating a voltage drop across the inductive load. These trends showcase the expected behavior of inductive elements and provide valuable insights into the impact of inductance on generator performance. In summary, the study underscores the significance of considering inductive characteristics for optimizing generator behavior. The observed patterns contribute to a comprehensive understanding of how inductive loads influence current and voltage, providing valuable information for designing and operating electrical systems effectively

5.

The analysis of the 3-phase synchronous generator with a Y-connected capacitive load highlights distinct trends in response to changes in capacitance. As the capacitance increases from 1 μF to 2 μF, a direct relationship is observed between capacitance, current, and voltage. The current exhibits a consistent rise, aligning with typical behavior for capacitive loads, where higher capacitance enables a greater flow of current. Simultaneously, the line-to-line voltage experiences a corresponding increase from 415V to 430V, indicating that higher capacitance contributes to enhanced voltage output. Additionally, both current and voltage percentages relative to nominal values increase with higher capacitance, underscoring the generator's response to varying capacitive loads. In conclusion, the positive correlations observed in current and voltage behaviors provide valuable insights into the impact of capacitance on the 3-phase synchronous generator, offering valuable information for designing and optimizing electrical systems for efficient performance.

For part B:

The Synchronizing Circuit scenario reveals crucial insights into the behavior of the generator under increasing torque conditions. The stability in voltage at 380V across different torque levels is a fundamental indicator of effective synchronization with the main power lines, ensuring a consistent and reliable electrical output to the grid. The observed increase in current, power factor, input power (Pin), and output power (Pout) with higher torque levels aligns with expectations for a synchronized generator. These trends signify the generator's capacity to adapt and meet elevated electrical demands, showcasing the effectiveness of the Synchronizing Circuit in managing the connection to the main power lines. The improvements in power factor also highlight enhanced efficiency in converting electrical power, reinforcing the overall reliability and efficiency of the generator under varying torque conditions. Overall, the results affirm the successful operation of the Synchronizing Circuit in facilitating stable and efficient electrical power output from the generator to the grid.

6. Conclusion

In conclusion, the conducted experiments provided a comprehensive and insightful exploration into the behavior of synchronous generators across various operating conditions. The measurement and interpretation of no-load voltage, short circuit voltage, and load characteristics, along with the investigation of the synchronizing circuit, contributed to a deep understanding of generator performance. The open-circuit test revealed a linear voltage-current relationship, with deviations attributed to iron core saturation. Despite the absence of error bars, the well-distributed data points underscored the careful and reliable execution of the experiment, enhancing result credibility.

The short-circuit characteristic graph demonstrated the crucial correlation between field current and short-circuit current, essential for designing protective mechanisms. The identified peak short-circuit current at a specific field current provided valuable information for the swift interruption of the circuit, preventing overheating during short circuits.

The synchronous generator characteristics graph, incorporating the OCC and SCC, offered profound insights into the interplay between field current, open-circuit voltage, and short-circuit current. Despite the deviation in OCC due to iron core saturation, the SCC's linearity provided critical information about the generator's impedance characteristics. The calculated synchronous reactance (XS) derived from the graph emerged as a key parameter for optimizing operational parameters. The graph illustrating the relationship between relative line-to-line voltages (VL-L/VN) and normalized current (I/IN) for resistive, inductive, and capacitive loads showcased distinctive behaviors. Understanding how different load types affect voltage and current is vital for designing efficient electrical systems, and the intersection point introduced a nuanced perspective on load behavior. The Synchronizing Circuit scenario demonstrated effective synchronization with the main power lines, as indicated by stable voltage across varying torque levels. The observed increase in current, power factor, input power (Pin), and output power (Pout) aligned with expectations for a synchronized generator, affirming the successful operation of the Synchronizing Circuit in facilitating stable and efficient electrical power output. Overall, the experiments provided valuable learning experiences, not only in technical aspects such as open circuit and short circuit tests but also in collaborative work, problem-solving, and the importance of adherence to safety protocols. Despite small errors, the conducted work stands out as a well-executed exploration of synchronous generator behavior, laying a solid foundation for informed decision-making in power system design and operation. Continuous improvement and attention to detail will further enhance the quality and reliability of future experiments.

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