ECE-385L-001- Electric Machine Lab

Lab Instruction Sheet- Session 7 (Experiment-6)

Experiment #6: Synchronous Generator

The purpose of the experiment is to become familiar with the dc-to-ac alternator; to measure the open circuit and short circuit characteristic curves of the ac generator; and to measure the ac generator's performance under load. *(A dc-to-ac alternator is an electromechanical device that converts electric power from dc to ac. An alternator consists of a dc motor that works as the prime mover and a synchronous machine that works as the ac generator. The energy is converted by the dc motor from electric in dc form to mechanical in rotational form, and then by the synchronous generator from mechanical to electric in ac form.)*

1. Background

1.1 Synchronous Generator

Fig. 1 shows the winding arrangement of a three-phase two-pole synchronous generator. The stator carries three identical windings. The windings are usually distributed around the stator to achieve a flux distribution in the air gap that is close to sinusoidal (not shown in the figure). The rotor carries a single winding that is supplied by a constant current. This is the dc-excitation or –field winding of the generator.

The excitation current If generates a magnetic field BR in the air gap. The North-South pole line of this field defines the direct axis of the rotor.

In normal steady state operation, the rotor is run by the prime mover at a constant mechanical speed ω_s. (synchronous speed). The rotor field induces sinusoidal voltages to the phase windings given by (1) and shown in fig. 2.

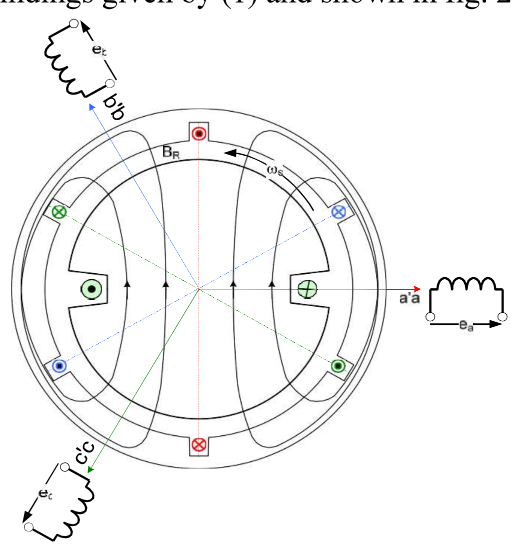

Figure. 1 The winding arrangement in a two-pole synchronous generator

$$e_a(t) = \sqrt{2}.E.\cos(\omega t)$$
$$e_b(t) = \sqrt{2}.E.\cos\left(\omega t - \frac{2\pi}{3}\right) \qquad (1)$$
$$e_c(t) = \sqrt{2}.E.\cos\left(\omega t + \frac{2\pi}{3}\right)$$

Where E is the rms value of the induced voltage given by (2) in terms of the rotor field, B_R, the stator angular frequency ω and the number of turns of the phase winding N; K is a constant that depends on the construction of the machine and the machine size. The electric angular frequency ω is related to the synchronous speed by (3), where P is the number of machine poles.

$$E = K.N.B_r.\omega \qquad (2)$$

$$\omega = \frac{P}{2}\omega_s \qquad (3)$$

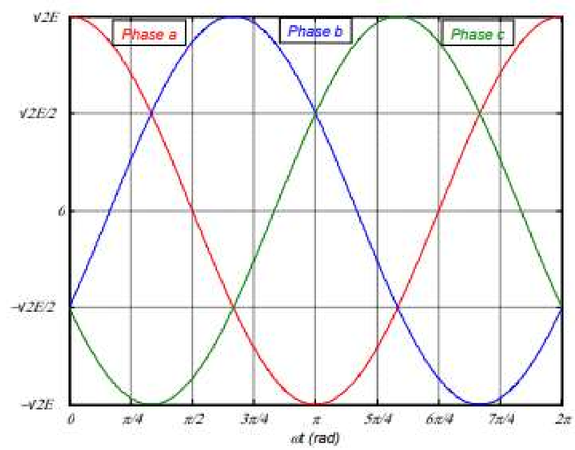

Fig. 2. The waveform of the generated three-phase voltage on the stator.

1.2 Stator Connections

The stator windings can be connected as Y or as Δ. A Y connection is shown in fig. 3: the negative terminals of the phase windings are connected to the common neutral node N. The neutral can be grounded. The positive terminals become the line terminals A, B, and C of the stator. The phasor diagram of the voltage is shown in the same figure. The line-to-line voltages are measured between the line terminals of the machine as E_{AB}, E_{BC}, and E_{CA}. As it can be seen in fig. 3, the line-to-line voltage leads the line-to neutral voltage by 30°. The rms value of the line-to-line voltage is: $E_{AB} = \sqrt{3}.E$

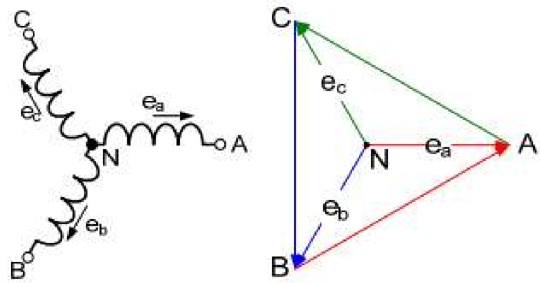

Fig. 3. The Y-connected machine: Winding connection and phasor diagram

In a Δ-connected machine, the positive terminal of one phase is connected to the negative terminal of the next, following the sequence: A-B, B-C, and C-A. This is depicted in fig. 4. The line currents lags the phase The line currents lags the phase currents by 30º and the rms of the line current is: $I_A = \sqrt{3}.I_{AB}$.

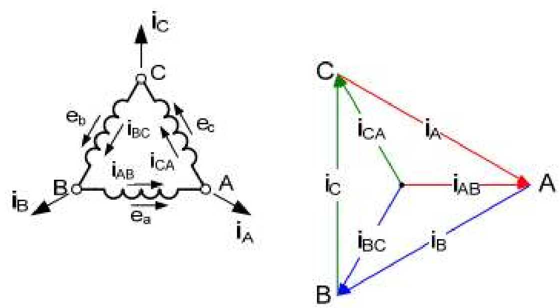

Fig. 4. The Δ-connected machine: Winding connection and phasor diagram

1.3 Machine Rating

The ratings that typically appear on the machine name plate include:

Rated rpm speed: This defines the synchronous speed of the machine in revolutions per minute.

Rated stator frequency: This is the electric frequency of the generated voltage at steady state. From the stator frequency and the rated rpm speed, we can deduce the number of poles in the machine (see (3)).

Rated stator voltage: This is the rms value of the line-to-line voltage that can be safely delivered at the stator terminals continuously. The armature reaction, when the generator operates under full load, modifies the internally generated voltage and, therefore, the net stator voltage is different.

Rated field current: This is the maximum field current under which the rotor can operate safely.

Rated power: This is the total (three-phase) power the machine can deliver to the load safely. The apparent power can be expressed in terms of the rms line-to-neutral voltage and rms line current or the rms line-to-line voltage and rms line current at the stator as per (4).

$$S_{3\varphi} = 3V_A . I_A = \sqrt{3} V_{AB} . I_A \quad (VA) \tag{4}$$

Rated power factor: This is the minimum power factor of the load that the machine can supply safely under rated voltage and current.

1.4 Machine Characteristic Curves

The open circuit characteristic curve (OCC) describes the relation between the generated voltage and the excitation current under open stator. The relation is shown in fig. 5(a). The OCC is obtained by running the machine rotor at synchronous speed and measuring the voltage across the stator open terminals for different values of the field current.

With reference to fig. 5(a), when the machine is weakly excited, the rotor and stator steel are unsaturated and the voltage increases linearly with the field current. This linear part of the OCC is the air-gap line. As the excitation increases, the steel becomes saturated and the same current increment results in less magnetic flux increment and, according to (2), in less voltage increment. In the figure, I_{f1} is the value of the field current at which the rated voltage is generated.

The short circuit characteristic (SCC) of the generator is the relation between the stator current under short-circuited stator and the rotor field current. The short circuit test is conducted by shorting the stator terminals and running the rotor at synchronous speed. One of the stator terminals is shorted through an ammeter and the short-circuit current of the stator is measured for different values of the field current. When the stator terminals are shorted the net induced voltage on the stator windings is zero. Therefore, the secondary magnetic field produced in the air-gap by the stator current (armature reaction) is equal in magnitude and opposite in direction to the rotor field. Therefore, the short-circuit current varies proportionally to the field current. This is seen in the SCC in fig. 5(b). In the figure, I_{f2} is the value of the field current resulting in rated circuit current flowing through the short-circuited terminals of the stator.

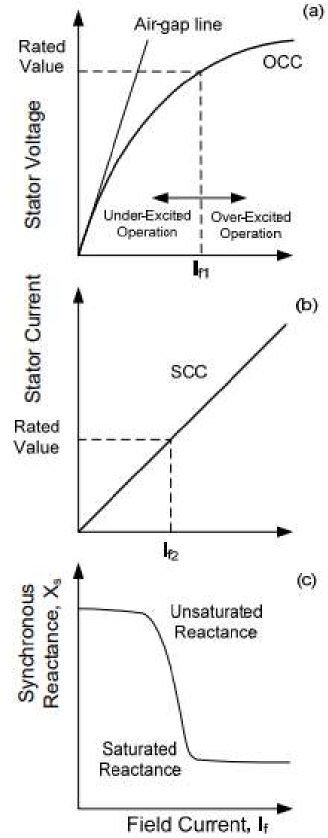

Fig. 5. Machine tests conducted at rated rpm: (a) Open Circuit test and Open Circuit Characteristic (OCC). (b) Short Circuit test and Short Circuit Characteristic (SCC); (c) Synchronous reactance

$$SCR = \frac{I_{f1}}{I_{f2}} \tag{5}$$

1.5 The Equivalent Circuit of the Machine

The per phase equivalent circuit of the generator seen from the stator terminals is depicted in fig. 6. E_S is the per-phase generated voltage obtained from the OCC. R_S is the ohmic resistance of the stator. X_S is machine synchronous reactance describing the armature reaction effect.

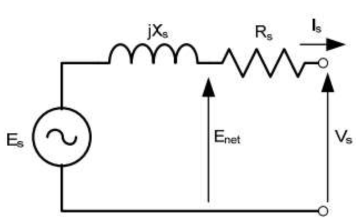

Fig. 6. The per-phase equivalent circuit of the synchronous generator

The net induced voltage E_{net} is what remains of the generated voltage E_S after subtracting the armature reaction:

$$E_{net} = E_S - jX_S.I_S \tag{6}$$

The terminal stator voltage is further reduced by the ohmic resistance of the winding:

$$V_S = E_S - \left(R_S + jX_S\right).I_S \tag{7}$$

Measurement of the Circuit Parameters: The generated voltage of the machine can be measured at the open stator terminals. The relationship between E_S and the field current is obtained from the OC test described above. The stator resistance can be measured across the winding terminals using an ohm-meter. (a) If the stator is Y-connected, the resistance measured between two-line terminals equals $2R_S$; (b) if the stator is Δ-connected, the resistance measured between two line terminals equals $\left(2R_S\right)//R_S = (2/3)\,R_S$.

The synchronous reactance can be computed from the data of the OCC and SCC measured experimentally. The total stator impedance is the ratio of the open-circuit voltage to the short-circuit current derived from the OCC and SCC respectively for the same value of the field current:

$$Z_S\left(I_f\right) = \sqrt{R_S^2 + X_S^2} = \frac{V_{OC}\left(I_f\right)}{I_{SC}\left(I_f\right)} \tag{8}$$

From (8):

$$X_S = \sqrt{Z_S^2 - R_S^2} \tag{9}$$

The synchronous reactance of the machine is shown in fig. 5(c) as a function of the field current. At low values of the field current, when the machine is unsaturated, the reactance remains nearly constant. The value of the reactance, however, decreases with increasing field current, as the machines enter saturation. Since in normal operation, the field current is around I_{f1}, where the machine has entered the saturation region, the saturated value of X_S is used in the equivalent circuit.

2. EXPERIMENTAL PROCEDURES

2.1 The DC-to-AC Alternator:

The purpose of this part is to become familiar with the operation of the alternator including secure shaft alignment, front panel connections, and speed regulation using the stroboscope; to measure the dc resistance of the stator.

Equipment: DC motor DM-100; Synchronous machine SM-100-3A; Metal plate (used as base) and guard for secure machine installation; Digital stroboscope DT-721 (handheld).
Instrumentation: available on the console panel, also handheld digital multi-meter.
Power supplies: 0-150 VDC and 0-125 VDC variable supplies available on the console.

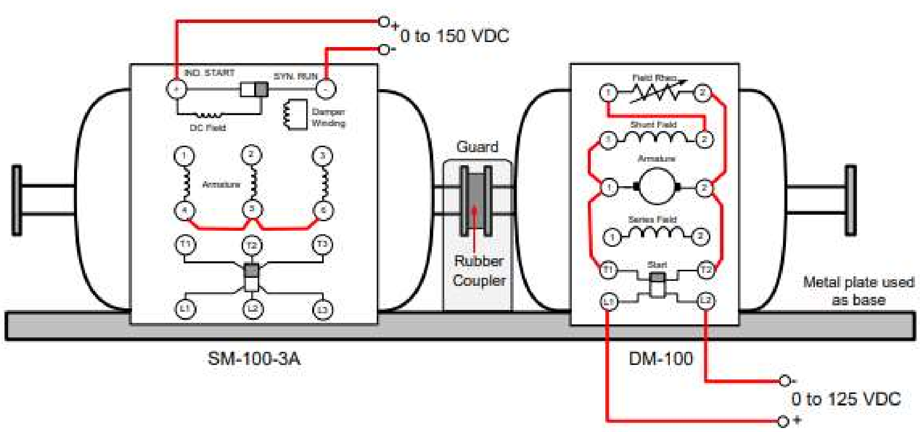

Fig. 8. The terminal panels of the alternator and terminal connections

Procedure:

1. Set the motor and generator on the metal base and couple the axes together through the double-head rubber coupler (see fig. 8). Use the guard around the coupling head. Spin the machine shaft manually to ensure the alignment is smooth. Turn the plate screw tight to preserve the alignment;

2. Record the data on the name plates of the synchronous generator and the dc motor. Keep these data handy;

3. Configure the terminal panel of each machine as shown in fig. 8. Make sure the console power is turned off. Do not connect to source or instruments yet. (a) Connect the dc motor as shunt (self- excited); adjust the field resistance to the minimum value; set the Start

switch to off (down position). (b) Connect the synchronous generator stator terminals as Y—stator terminals 1, 2, and 3 are the line terminals; terminals 4, 5, and 6 connect to the neutral—set the machine rotor circuit to synchronous run mode (top flip-switch);

4. Stator Resistance Measurement: Using the hand-held multi-meter, measure and record the resistance between any two-line terminals of the stator (say 1 and 2).

5. See fig. 9: connect the dc motor terminals (L1-L2) to the 0-125-V-DC variable source. Make sure the source knob is turned to zero. Connect the synchronous motor filed circuit to the 0-150-V-DC variable source through a dc ammeter; Make sure the source knob is turned to zero. The circuit is shown in fig. 9.

6. First turn on the console main power. Then turn on the 0-125-V-DC source. Set the start switch on the dc motor panel in the up position (start). Gradually increase the supply voltage, the motor will begin to run.
7. Speed Regulation: (a) Set the digital stroboscope rpm dial to the synchronous rpm of the generator; (b) hold the stroboscope against the rotor and press the trigger (held like a gun)—it will help if the stroboscope is aimed in the front of the rotor against the shaft head; (c) adjust the dc motor supply until the rotor appears to be still (or as close as you can possibly get it to be still). When the rotor appears still, the rotation speed equals the stroboscope dial setting; Practice adjusting the speed for a different value of the rpm. Do not power down continue to the next experiment.

2.2 Open Circuit Characteristic:

The purpose is to obtain the excitation curve of the generator.

Equipment: Same as in part B.

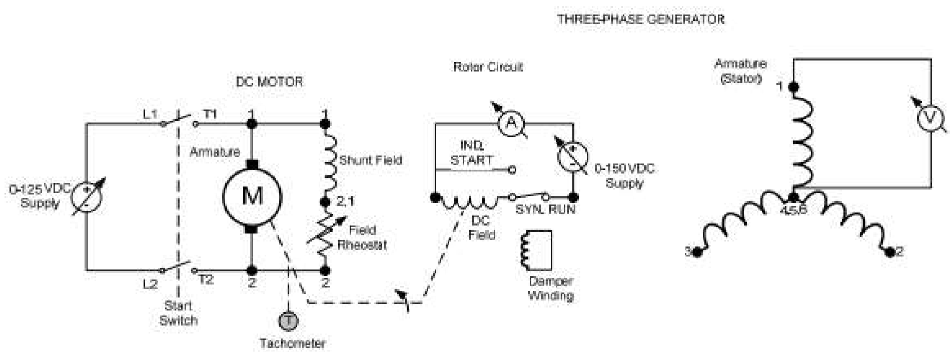

Fig. 9. Experiment setting for the open circuit test

Procedure (continued from preceding part. Configuration as in fig. 9):

1. With the dc motor running at synchronous speed, turn the 0-150-V-DC supply of the generator field on. Adjust the field supply as described in the steps below;

2. Beginning from zero, increase the generator field current in steps of 0.25 A until 1.25 A. At each step readjust the rotor speed to synchronous using the stroboscope; then measure the line-to-neutral rms voltage across the stator terminals as shown in fig. 9. Record the values of the field current and the stator voltage.

3. Power down the variable sources (knobs turned to zero). Power down the console. Do not disband the alternator. Get ready for the next part.

2.3 Short Circuit Characteristic

The Purpose is to obtain the SCC of the generator.

Equipment: Same as part B and C.

Procedure:

1. With all supplies off (knobs turned to zero) and the console off, short the stator terminals 1, 2, and 3. Short terminals 1 and 2 through an ac ammeter. The circuit diagram is as in fig. 10.

2. Power up the console and the dc motor supply. Gradually increase the motor speed to synchronous rpm.

3. Turn the generator field on and adjust the field current to zero. All measurements described below must be made at synchronous rpm—calibrate motor speed accordingly at each step before the measurement.

4. Measure the stator current (short circuit current) when the field current is zero; (b) slowly increase the field supply until the stator current is ¼ of its rated value. Record the field current; (c) slowly increase the field supply until the stator current equals ½ of its rated value. Record the field current; (d) slowly increase the field supply until the stator current equals its rated value. Record the field current.

5. Reduce the field current to zero. Power the field supply off. Reduce the motor speed to zero. Power the motor supply off. Power the console off. Do not disband the alternator. Get ready for the next part.

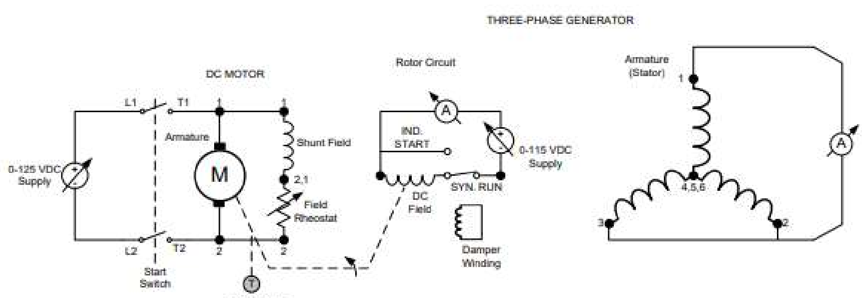

Fig. 10. Experiment setting for the short circuit test

Report:

- From the name-plate data of each machine. What is the rated stator power of the generator? How many are the generator poles?
- What is the stator resistance per phase?
- Why does the synchronous machine need a dc field on the rotor?
- Tabulate the data from the open circuit test in part b.2. Using MATLAB, draw the OCC. Show the air- gap line.
- Show on the OCC graph the under-excited and over-excited operating ranges of this generator?
- Tabulate the measurements in part b.3.
- Draw in MATLAB the SCC of the machine.
- What is the short circuit ratio of the machine?
- Using the tabulated values of the open circuit voltage and short circuit current and (8) and (9), calculate and plot the synchronous reactance of the machine. What is the unsaturated reactance?
- Draw the equivalent per phase circuit of the machine seen from the stator for rated excitation current. Use the correct parameters.