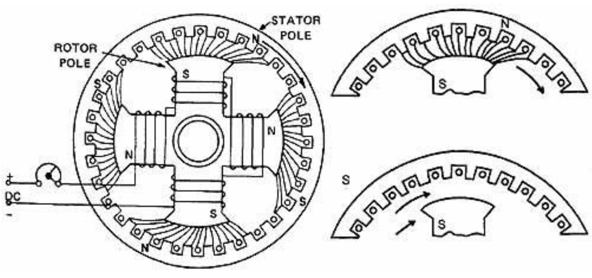
University of Glasgow
Electronics and Electrical Engineering
Power Systems / Electrical Energy Systems Laboratory

Synchronous Generator Operating Characteristics

1. Objectives

1) To conduct open-circuit and short-circuit tests on a three-phase synchronous generator.
2) To derive the synchronous reactance from results of the tests and to find out the per unit value.
3) To conduct load tests at one input power level to the machine operating as a synchronous generator in a large power system, and for three different field excitation levels to measure output current and power factor.
4) To construct, for the three conditions in the load tests, the phasor diagrams and, from these, to determine the rotor (load) angle and field excitation current and to compare these with measured values.



2. Introduction

A synchronous machine cannot be directly connected to a power system and self-start. If this is attempted with a machine of any significant size, excess current will flow and damage to equipment is likely. When connecting a synchronous machine to a power system, the machine terminal voltage must match the system voltage (as a phasor quantity) before connection is attempted. Once the synchronous machine is connected to the power system, the operating conditions of the machine can be adjusted for the application (motor, generator). Note that the synchronous machine will always run at power system speed and the operating power factor can be controlled (within reason) by adjusting the field excitation current of the machine. If the synchronous machine starts to lose synchronism with the power system, excess current will flow and fuses/circuit breakers will operate, disconnecting the machine from the supply.

On the bench the following equipment is provided -
A synchronous motor/generator on a frame coupled to a DC generator/motor with an optical shaft speed sensor. A variable DC power supply and associated Single-phase Wattmeter to drive the DC motor prime mover. A smaller variable DC power supply and an Ammeter (Digital Multimeter configured as Ammeter on 2A range) to set the synchronous machine field excitation current. A synchronising switch and a 3-phase Wattmeter to connect the power terminals of the synchronous machine to the power system. A red cased synchronous strobe light. This strobe light makes flashes of light synchronous to the mains power supply.

The Synchronising Unit (similar to a Synchroscope) will probably be unfamiliar. The internal circuit is shown in Figure 1, below. In its simplest form (selector switch set to 'intensity') it consists of an indicator lamp connected across each contact of a 3 pole switch. If the synchronous machine and the supply do not have matched (phasor) voltages then the lamps will light. If the lamps are dark, then there is no voltage across the switch contact and it is safe to close the switch. A refinement of this setup (selector switch set to 'rotation') is to connect 2 of the 3 lamps on different phases across the switch. The lights will now illuminate in a slowly changing pattern showing whether the machine is running slow or fast compared to the power system. The machine and the power system are synchronised when the top lamp is dark and the two lower lamps are equally brightly illuminated.
If the operation of the lamps at each selector switch position (Intensity, Rotation) is the opposite to that described above, this is because the 3-phase Power Supply and the Generator are "rotating" in opposite directions. To correct this, swap two of the connections (e.g. at U1 and V1 on the Synchronous Machine).

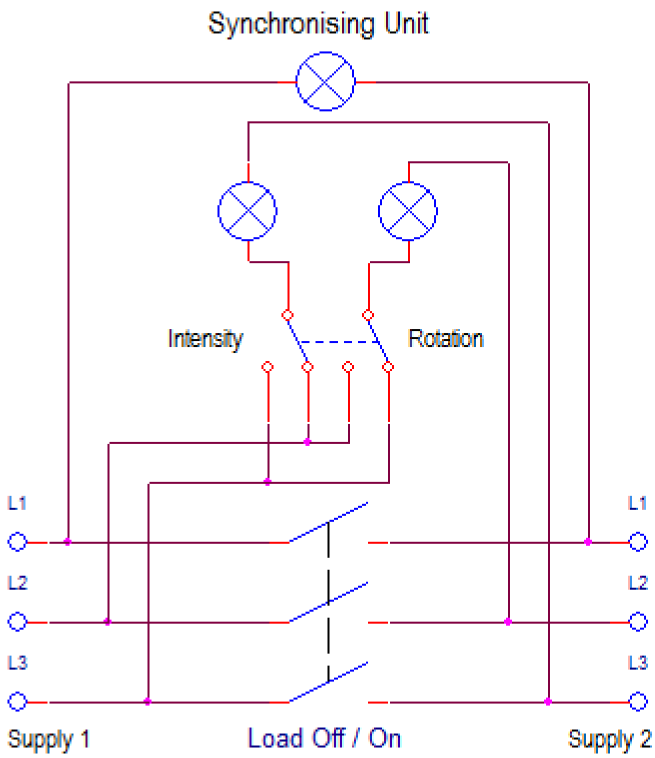


Figure 1 – Internal circuit of Synchronising Unit

3. Experiments

3.1. Preliminary Actions

1) Make sure the "Load Switch" on the Synchronising Unit is Off!
2) Examine the synchronous generator and calculate the nominal Line current based on the nameplate voltage and power. Determine the number of magnetic poles in the machine (operating frequency is 50 Hz).
3) Connect the items of equipment as shown in Figure 2 at the back of the laboratory sheet (the equipment may already be connected).
4) The DC Motor: Switch on the DC Power Supply to the DC Motor and increase the output. The motor will not start to turn until the supply is approximately 8 - 11V. Adjust the power to the DC Motor to make the Synchronous Generator run at synchronous speed.
5) Synchronous Generator: Switch on the second DC Variable Power Supply with minimum (zero) field excitation current supplied to the generator field rotor circuit. Increase the field excitation current and note how the generator AC line voltage changes as a result. Stop the machine.

3.2. Open-Circuit Test

Disconnect the three leads at "SUPPLY 2" of the Synchronising Unit (this leaves the 3-phase Wattmeter still connected to the Synchronous machine). Make sure that the output of the power supply for field excitation current is set to minimum (zero) and turn it on.
Calculate the value of Line Voltage that would be 20% above the rated value for the Machine.
Increase the DC motor speed to 1500 rpm (speed shown on Motor Speed Monitor).
Increase the Field Excitation Current, starting from 0 A, in steps of 0.05 A until the Generator Line Voltage (3-phase Wattmeter page 1) reaches the value calculated above.
At each step:-

(i) Record the field excitation current and the generator AC line voltage.
(ii) Ensure that the DC Motor/Generator speed is **maintained at 1500 rpm** by adjusting the input voltage to the DC Motor, if necessary.

Whenever there is a requirement to maintain the speed shown on the "Motor Speed Monitor" at a particular value, a value within +/-5 rpm is acceptable.

Stop the machine when finished.

3.3 Short-Circuit Test

With the machine stopped, short circuit the three leads which were unplugged from "SUPPLY2" earlier (connecting the lines at this point ensures that the 3-phase Wattmeter will still be able to measure the current from the machine). Ensure that the field excitation control is at the minimum (zero) position. Turn on the field supply and start the DC motor. Adjust the speed to 1500 rpm.
Increase the field excitation current, slowly, so that the line current increases from about 0 A to a **maximum line current of 1 A** in steps of 0.05A.
Note the field excitation current and the AC line current at each step. As before, **ensure that the DC motor/Generator speed is kept constant at 1500 rpm during the test.**

The Average Line current is shown on Wattmeter page1. However, because the value is low for the first few steps, you may have to take the average of the individual Line Currents (Wattmeter page3).

Stop the machine when finished.

3.4 Load Tests

1) Synchronizing the synchronous generator to the supply:
   Make sure that the "Load Switch" on the Synchronising Unit is Off. With the generator stopped, reconnect the wires between the Synchronizing Unit and the 3-phase Wattmeter. Start the DC motor and set the speed to 1500 rpm. Set the field excitation current so that the measured line voltage on the 3-phase Watt meter is the same as the supply voltage (in this case approximately 45V). Verify that the intensity/rotate switch on the synchronising unit is operating correctly – if it is not, reverse the electrical direction of rotation of the machine by swapping any two of the three output leads. Carefully adjust the DC Motor speed so that the synchronising lamps cycle as slow as possible (once every few seconds). **At the correct instant** (intensity selected– all lamps off, OR rotate selected – top lamp off, lower lamps both equally bright), turn the Synchronising Unit "Load Switch" on. The Synchronous machine is now connected to the supply and running. The operating conditions of the machine can now be adjusted as required for the application. In this case we will be using the machine as a generator into an infinitely large system (the building supply and national grid(via the transformer in the 3-phase Power Supply)), with the DC motor as a prime mover.

2) Adjust the field excitation current in the AC synchronous generator and the speed of the DC motor to give minimum AC stator current flow in the synchronous generator, i.e. as near to zero current as is possible. In this situation the synchronous generator is neither motoring nor generating, it is just keeping step with the supply and the prime mover is supplying the losses. In an ideal case (no harmonics, ideally wound machine) this current would be zero.

In the three experiments below, the three load tests are conducted at approximately the same power level (input power to the DC motor is constant and synchronous generator losses are almost independent of the current) but at three different power factors obtained by changing the field excitation current of the synchronous generator. Use the red cased synchronous stroboscopic lamp to observe the rotor (load) angle at each setting.

3) Increase the power input to the DC motor until the AC line current is about 2/3 of the nominal value (calculated in section 3.1.2). Adjust the field excitation current to the synchronous generator to get even closer to minimum Line current. Note the field excitation current, line current, line voltage, active power, power factor, prime mover input power, and rotor (load) angle.
4) With the power input to the DC motor unchanged, increase the field excitation current to the synchronous generator until the AC line current is at the nominal value. Note readings as above.
5) Reduce the field current to that measured in step (3). With the power input to the DC motor unchanged, decrease the field excitation current to the synchronous generator until the AC line current is at the nominal value. Note readings as above. Open the synchronising switch and stop the machine. Switch Off all power supplies.

4. Deductions

1) From the open-circuit and short-circuit test, and assuming that the short-circuit current varies linearly with field excitation current for the range of values being considered in this experiment, plot on one graph the open-circuit line voltages, short-circuit currents and the synchronous impedances, all against the field excitation current. For the impedance the following relation stands,

$$Z_S = \frac{V_{Ph}}{I_{Ph}}$$

   where Zs is the synchronous impedance,
   $V_{Ph} = V_L / \sqrt{3}$ is the phase voltage on open circuit,
   V_L is the line voltage on open circuit,
   I_{Ph} is the phase current.

2) Determine the base impedance from nameplate values. From the graph of synchronous impedance, determine the value corresponding to rated voltage and convert this to per unit.

3) With each of the results from the load test experiments, determine the power factor and also the per-unit AC line current and voltage. Construct to scale the phasor diagrams using measured values of per-unit voltage, per-unit current, per-unit reactance and power factor and determine from the diagrams the field excitation current and rotor (load) angle.

4) Comment briefly on the relationship between input and output power at varying excitation levels and on the relationship between excitation and power factor or reactive power, when the synchronous machine is connected to an infinite busbar.

5) Commercial operators of large grid-connected generators operate synchronous generators slightly over-excited to give an operating power factor of 0.8-0.85 lagging/inductive which is not the (electrically) most efficient operating point. Why? What would be more likely to happen if a generator in a large power system is operated under-excited?

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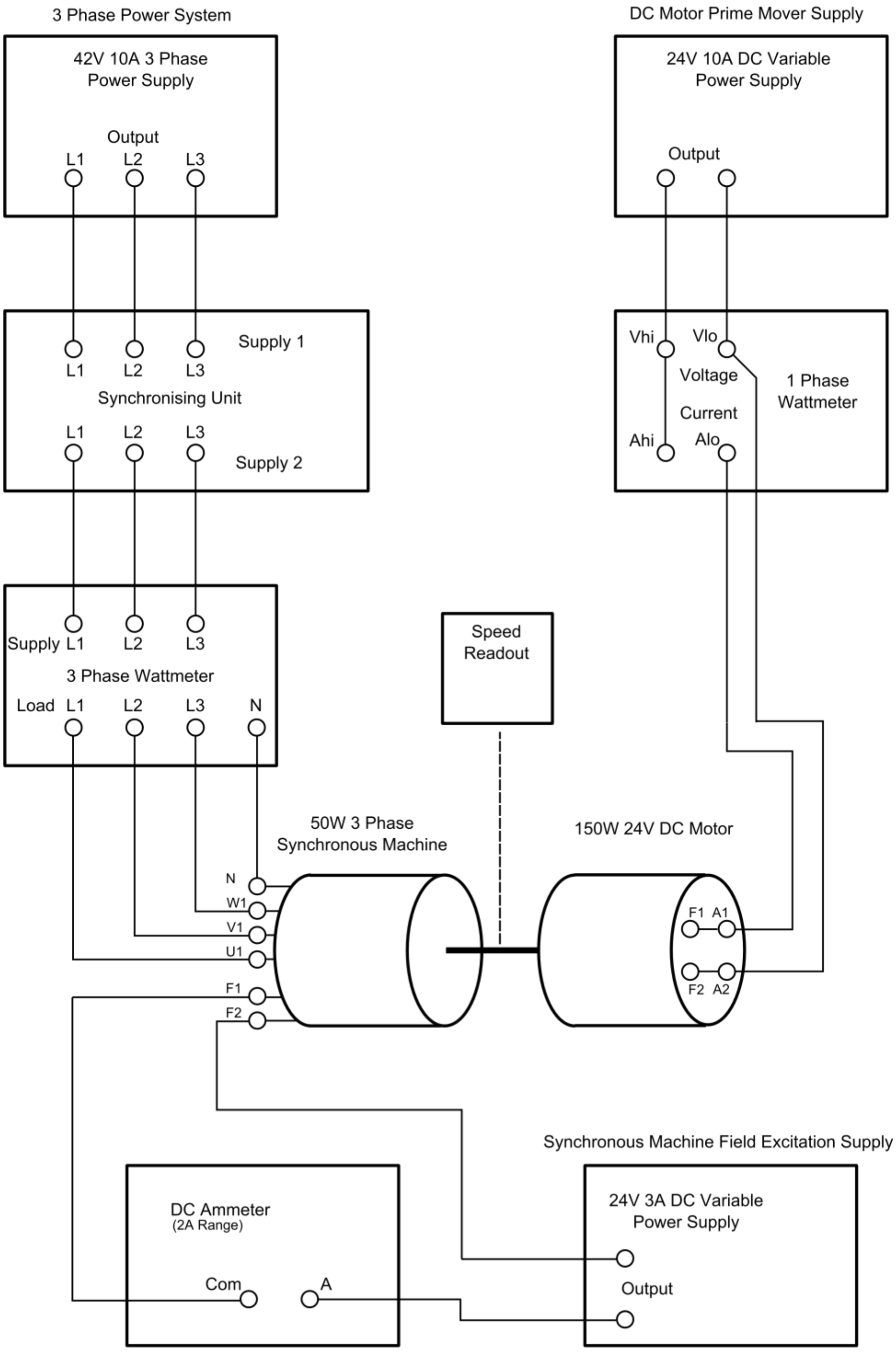
Synchronous Machine Connection Diagram



This equipment uses the old UK colour coding for wire colours:- L1, Red; L2, Yellow; L3, Blue; N, Black.
The new colour coding now used throughout Europe is:- L1, Brown; L2, Black; L3, Grey, N, Blue.
Because of the low voltages used, Earth (green/yellow) connections are not required with this equipment.
(For best accuracy, the Star Point of the Synchronous Machine is connected to the Neutral terminal of the Wattmeter.)

Figure 2