AC SYNCHRONOUS GENERATORS

Why do we study AC synchronous generators? The short answer is that 3-phase AC generators are the workhorse of the power generation arena. Why? They are not as power limited as DC generators and voltage-level shifting is less expensive using AC (via transformers) rather than DC (power electronics). Thus, terrestrially at your local power generation plant or shipboard, you will find a synchronous machine. Well, to be accurate, you will find not just a synchronous machine but also a prime mover and some source of fuel for the prime mover. A block diagram for the layout of a shipboard generation system is shown in Figure 5.1. Let's discuss the elements of this system before getting into the details of the synchronous machine.

On a surface combatant such as the Arleigh Burke-class destroyer, the engine (prime mover) that drives the synchronous generator is a gas turbine (Allison 501-34K). The gas turbine converts the F76 fuel into mechanical power. A governor connected to the prime mover regulates its speed and controls the amount of mechanical power transmitted to the generator. The generator in turn converts the mechanical power to electrical power. The automatic voltage regulator (AVR) and exciter connected to the synchronous machine adjust the rotor field current to maintain the required terminal voltage. Cables, switchboards, transformers, and circuit breakers then route the three-phase power to the many shipboard loads. On other ships, the prime mover may be a diesel engine or a steam turbine or some combination.

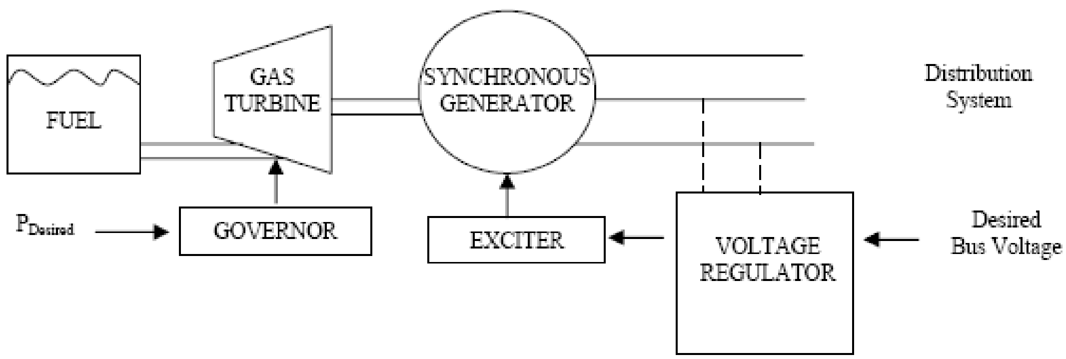

Figure 5.1 - Notional Portion of a Shipboard Electric Power Generation System

5.1 Principle of Operation

A three-phase synchronous machine consists of an inner rotating cylinder called the **rotor** and an outer stationary housing called the **stator** as shown in Figure 5.2. A shaft runs through the rotor and it is balanced on bearings.

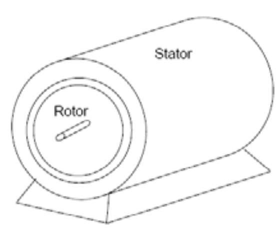

Figure 5.2 - Layout of a Synchronous Machine

The internal periphery of a three-phase stator normally has a number of slots, the number typically being an integer multiple of six. A three-phase machine will require three identical coils of wire, each with many turns, and each coil is distributed in multiple stator slots. An example of one phase winding is shown in Figure 5.3. These windings are normally called the **armature**. The angular distribution of the turns is called the **coil breadth**. The angular distance between the sides of a given turn is termed the **coil pitch.** The other two phase coils are positioned similarly about the stator periphery, with the centers of those coils spatially displaced by 120°.

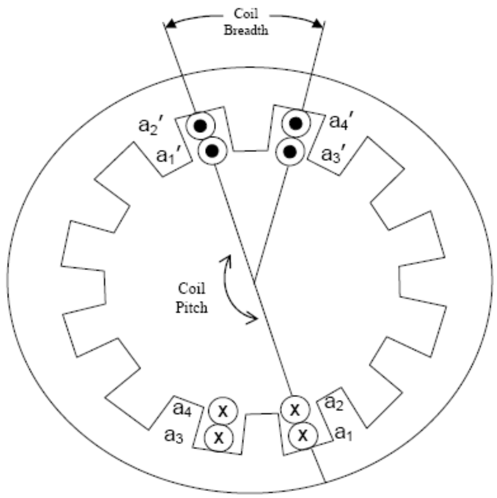

Figure 5.3 - Slotted Synchronous Machine Stator with Distributed A-Phase Winding

Instead of having to draw all of the slots and windings each time, we represent each distributed coil by a concentrated coil located in the center of the distribution. This is shown in Figure 5.4. The circle with a dot denotes that current is referenced *out of the page* while a circle with a cross indicates that current is referenced *into the page*. We use **a**, **b**, and **c** to reference the three stator phases represented in Figure 5.4.

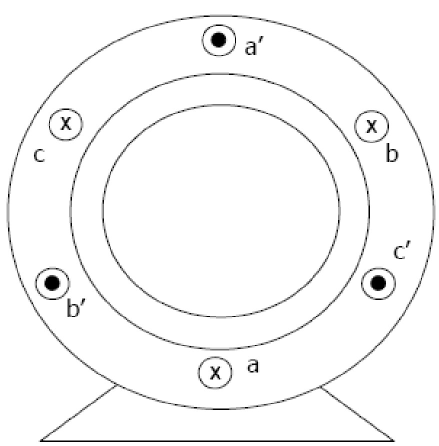

Figure 5.4 - Synchronous Machine Represented by Concentrated Stator Windings

The rotor of a synchronous machine contains a winding called the **field winding,** which generates the magnetic field needed to generate a voltage (remember Faraday's Law). For simplicity, we will consider the case of a round rotor with a uniform air gap about the circumference of the rotor. The rotor may be slotted with the turns of the field winding distributed in those slots. The field winding will be supplied with a DC current. You say, "Wait a second, the field winding is on the rotor, and the rotor is spinning. How can we supply DC current to something that is moving?" The simplest solution to this dilemma is to use **slip rings** and **brushes** as illustrated in Figure 5.5. Note that the end connections of the field winding are tied to two copper rings mounted on the rotor shaft. Stationary carbon brushes are then made to ride upon the rings. A stationary DC voltage source is then applied to the brushes allowing DC current to flow through the field winding. Since the brushes are not commutating (i.e., reversing the current) coils as in a DC machine, the wear and maintenance requirements are not as intensive.

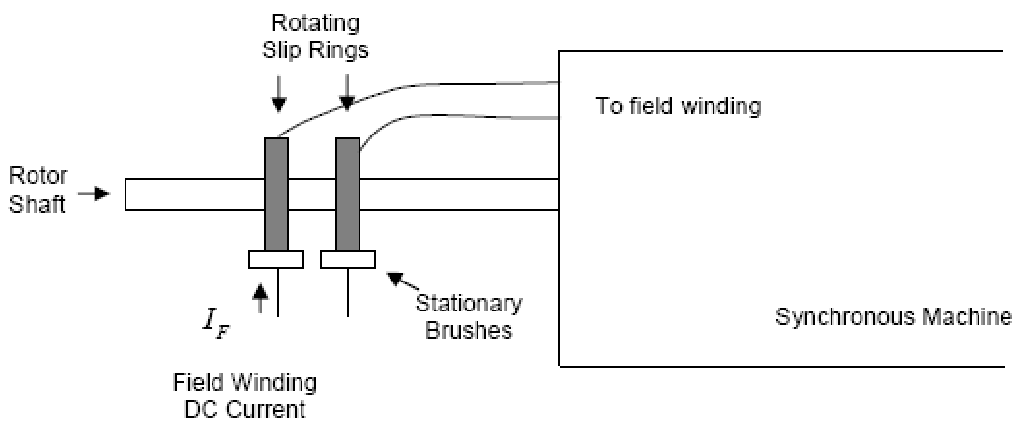

Figure 5.5 - Illustration of Slip Rings and Brushes for Supplying DC Current to a Synchronous Machine Field Winding

OK, here is the big picture. The DC current flowing in the field winding will set up a magnetic field on the rotor (think North and South poles). The prime mover (mechanical engine) will then spin the rotor at what we will soon refer to as **synchronous speed**. The magnetic field sweeping past the stationary stator coils will induce voltages. This phenomenon is described by Faraday's law, and was present as the back EMF in the DC motors you studied previously. Since the phase coils are spatially displaced, the induced voltages will be time displaced and will constitute a balanced set (i.e., same frequency, equal amplitude, and 120° displaced in phase).

The voltage produced by each phase coil is shown in Figure 5.6. If we imagine that the rotor magnetic field moves past the "**a**" stator phase first, we would expect a strong induced voltage for the **a**-phase. As the rotor turns and moves its magnetic field past the **b** and **c** coils, those coils would also show a surge in voltage respectively. The sequence of voltages shown in the figure is termed the **abc-phase sequence** since the **a**-phase takes its peak first, then the **b**-phase and finally the **c**-phase. Note that the voltages all have the same frequency and equal amplitude but are displaced from each other by 120°. (As the rotor turns and moves past the **a'**, **b'** and **c'**, the negative voltage peaks occur.)

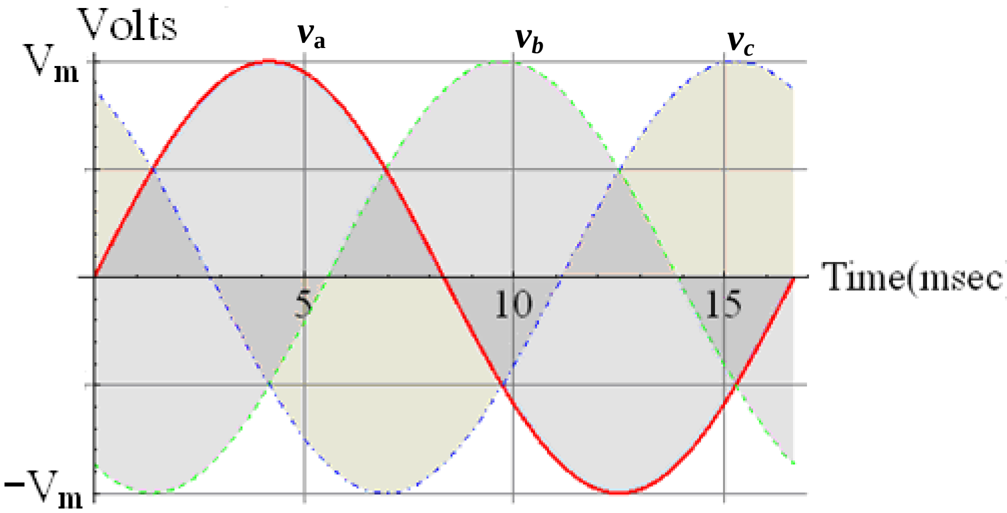

Figure 5.6: **ABC**-phase sequence

The time domain representation of the voltages are:

$$v_a(t) = V_m \sin \omega t \quad [V]$$

$$v_b(t) = V_m \sin (\omega t - 120°) \quad [V]$$

$$v_c(t) = V_m \sin (\omega t + 120°) \quad [V]$$

These voltages can be written in phasor form as:

$$\mathbf{V}_a = \frac{V_m}{\sqrt{2}} \angle 0° \qquad [V]$$

$$\mathbf{V}_b = \frac{V_m}{\sqrt{2}} \angle -120° \qquad [V]$$

$$\mathbf{V}_c = \frac{V_m}{\sqrt{2}} \angle +120° \qquad [V]$$

Note that as the rotor rotates one mechanical revolution, each phase exhibits 360 electrical degrees, or one cycle. Thus the angular speed of the rotating magnetic field must be equal to the angular frequency of the stator currents, or:

$$\omega_{mf} = \omega_e$$

That seems like an important result (and it is); however, we normally like to think about frequency in Hz (f_e) and rotational speed in rpm (N_{mf}), where:

$$f_e = \frac{\omega_e}{2\pi}$$

and

$$N_{mf} = \frac{30}{\pi} \omega_{mf}$$

Substituting yields:

$$\frac{\pi}{30} N_{mf} = 2\pi f_e$$

or simply:

$$N_{mf} = 60 f_e$$

Therefore, if 60 Hz currents are flowing in the stator phases, the rotor will rotate at:

$60 \times 60 = 3600$ rpm.

Note that the unit conversion (from *Hz* to *rpm*) is nestled inside the constant 60 out front.

Now in the case considered previously, the rotor magnetic field was traveling counter-clockwise. If we changed the direction to clockwise, the sequence of the voltages would change from **abc** to **acb**.

We can also design the rotor with an integer multiple of two poles (i.e., 4, 6, 8, etc.) In the case of 4 poles, one electrical cycle corresponds to half a mechanical revolution. Of course, the stator must also be rewired to accommodate the 4 pole configuration. (We will omit the details of how that is accomplished in this discussion of AC generators.) Now, from this we can deduce the following relationship for an arbitrary number of even poles, P, that:

$$N_{mf} = \frac{2}{Poles}\,\omega_e$$

Or in terms of rpm and Hz:

$$N_{mf} = \frac{120}{Poles}\,f_e$$

Substituting the first few permissible values of P, and assuming an electrical frequency of 60 Hz, we can create the following useful chart relating the number of poles to the rotational speed:

P	2	4	6	8	10
N_{mf} (rpm)	3600	1800	1200	900	720

We can also view this chart from the perspective of the prime mover. If we have a gas turbine that is designed to operate at 1800 rpm, then to produce 60 Hz AC we must have a 4-pole generator.