WIND TURBINES WITH ASYNCHRONOUS ELECTRICAL GENERATORS

He gave the wind its weight. Job 28:25.

In the last chapter we discussed some of the features of wind turbines synchronized with the electrical grid. There are a number of advantages to synchronized operation in that frequency and voltage are controlled by the utility, reactive power for induction generators is available, starting power for Darrieus turbines is available, and storage requirements are minimal. These advantages would indicate that most of the wind generated electricity in the United States will be produced in synchronism with the utility grid.

Historically, however, most wind electric generators have been attached to asynchronous loads. The most common load, especially before about 1950, has been a bank of batteries which in turn supply power to household appliances. Other loads include remote communication equipment, cathodic protection for buried pipelines, and direct space heating or domestic hot water heating applications. These wind electric generators have been small in size, usually less than 5 kW, and have usually been located where utility power has not been available.

We can expect the use of asynchronous electricity to continue, and perhaps even to grow, for a number of reasons. The use of wind power at remote communication sites for charging batteries can be expected to increase as less expensive, more reliable wind turbines are developed. Space heating and domestic hot water heating are natural applications where propane or oil are now being used. Existing fossil fueled equipment can be used as backup for the wind generated energy. Another large potential market would be the many thousands of villages around the world which are not intertied with any large utility grid. Economics may preclude the possibility of such a grid, so each village may be forced to have its own electric system if it is to have any electricity at all. An asynchronous system which could operate a community refrigerator for storing medicine, supply some light in the evening, and provide power for cooking meals (to help prevent deforestation) would be a valuable asset in many parts of the world.

One final reason for having asynchronous capability on wind turbines in the United States would be the possibility of its being needed if the electrical grid should fall apart. If any of the primary sources of oil, coal, and nuclear energy should become unavailable for any reason, there is a high probability of rotating blackouts and disassociation of the grid. Wind turbines may be able to provide power to essential applications during such periods if they are properly equipped. Such wind turbines will have to be capable of being started without utility power, and will also require some ability to maintain voltage and frequency within acceptable limits.

The three most obvious methods of providing asynchronous electricity are the dc generator, the ac generator, and the self- excited induction generator. Each of these will be discussed in this chapter. Various loads will also be discussed. The number of combinations of generators and loads is almost limitless, so only a few combinations will be considered in any detail.

1 ASYNCHRONOUS SYSTEMS

In the previous two chapters, we examined combinations of wind turbines, transmissions, and generators connected to the electrical grid. The electrical grid was assumed to be able to accept all the power that could be generated from the wind. The grid was also able to maintain voltage and frequency, and was able to supply any reactive power that was needed. When we disconnect ourselves from the grid, these advantages disappear and we must compensate by adding additional equipment. The wind system design will be different from the synchronous system and will contain additional features. A possible system block diagram is shown in Fig. 1.

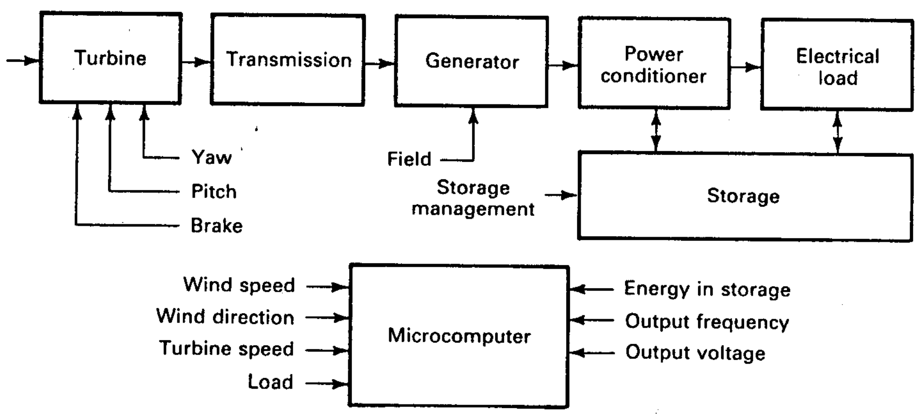

Figure 1: Block diagram of asynchronous electrical system.

In this system, the microcomputer accepts inputs such as wind speed and direction, turbine speed, load requirements, amount of energy in storage, and the voltage and frequency being delivered to the load. The microcomputer sends signals to the turbine to establish proper yaw (direction control) and blade pitch, and to set the brakes in high winds. It sends signals to the generator to change the output voltage, if the generator has a separate field. It may turn off non critical loads in times of light winds and it may turn on optional loads in strong winds. It may adjust the power conditioner to change the load voltage and frequency. It may also adjust the storage system to optimize its performance.

It should be mentioned that many wind electric systems have been built which have worked well without a microcomputer. Yaw was controlled by a tail, the blade pitch was fixed, and the brake was set by hand. The state of charge of the storage batteries would be checked once or twice a day and certain loads would be either used or not used depending on the wind and the state of charge. Such systems have the advantages of simplicity, reliability, and minimum cost, with the disadvantages of regularly requiring human attention and the elimination of more nearly optimum controls which demand a microcomputer to function. The microcomputer and the necessary sensors tend to have a fixed cost regardless of the size of turbine. This cost may equal the cost of a 3-kW turbine and generator, but may only be ten percent of the cost of a 100 kW system. This makes the microcomputer easier to justify for the larger wind turbines.

The asynchronous system has one rather interesting mode of operation that electric utilities do not have. The turbine speed can be controlled by the load rather than by adjusting the turbine. Electric utilities do have some load management capability, but most of their load is not controllable by the utilities. The utilities therefore adjust the prime mover input (by a valve in a steam line, for example) to follow the variation in load. That is, supply follows demand. In the case of wind turbines, the turbine input power is just the power in the wind and is not subject to control. Turbine speed still needs to be controlled for optimum performance, and this can be accomplished by an electrical load with the proper characteristics, as we shall see. A microcomputer is not essential to this mode of operation, but does allow more flexibility in the choice of load. We can have a system where demand follows supply, an inherently desirable situation.

As mentioned earlier, the variety of equipment in an asynchronous system is almost limitless. Several possibilities are shown in Table 6.1. The generator may be either ac or dc. A power conditioner may be required to convert the generator output into another form, such as an inverter which produces 60 Hz power from dc. The electrical load may be a battery, a resistance heater, a pump, a household appliance, or even exotic devices like electrolysis or fertilizer cells.

Not every system requires a power conditioner. For example, a dc generator with battery storage may not need a power conditioner if all the desired loads can be operated on dc. It was not uncommon for all household appliances to be 32 V dc or 110 V dc in the 1930s when small asynchronous wind electric systems were common. Such appliances disappeared with the advent of the electrical grid but started reappearing in recreational vehicles in the 1970s, with a 12-V rating. There are no serious technical problems with equipping a house entirely with dc appliances, but costs tend to be higher because of the small demand for such appliances compared with that for conventional ac appliances. An inverter can be used to invert the dc battery voltage to ac if desired.

TABLE 6.1 Some equipment used in asynchronous systems

- ELECTRICAL GENERATOR
  - DC shunt generator
  - Permanent-magnet ac generator
  - AC generator
  - Self-excited induction generator (squirrel cage rotor)

  - Field modulated generator
  - Roesel generator

- POWER CONDITIONER
  - Diode rectifier
  - Inverter
  - Solid-state switching system

- ELECTRICAL LOAD
  - Battery
  - Water heater
  - Space (air) heater
  - Heat pump
  - Water pump
  - Fan
  - Lights
  - Appliances
  - Electrolysis cells
  - Fertilizer cells

If our generator produces ac, then a rectifier may be required to deliver the dc needed by some loads or storage systems. Necessary switching may be accomplished by electromechanical switches or by solid state switches, either silicon controlled rectifiers (SCRs) or triacs. These switches may be used to match the load to the optimum turbine output.

The electrical load and storage components may have items which operate either on ac or dc, such as heating elements, on ac only, such as induction motors, lights, and most appliances, or dc only, such as electrolysis cells and batteries. Some of the devices are very long lived and inexpensive, such as heating elements, and others are shorter lived and more expensive, such as batteries and electrolysis cells. Some items can be operated in almost any size. Others, such as electrolysis cells and fertilizer cells, are only feasible in rather large sizes.

Economics must be carefully considered in any asynchronous system. First, a given task must be performed at an acceptable price. Second, as many combinations as possible should be examined to make sure the least expensive combination has been selected. And third, the alternatives should be examined. That is, a wind turbine delivers either rotational mechanical power or electrical power to a load, both of which are high forms of energy, and inherently expensive. If it is desired to heat domestic hot water to 40^oC, a flat plate solar collector would normally be the preferred choice since only low grade heat is required. If the wind turbine were driving a heat pump or charging batteries as a primary function, then heating domestic hot water with surplus wind power might make economic sense. The basic rule is to not go to any higher form of work than is necessary to do the job. Fixed frequency and fixed voltage systems represent a higher form of work than variable frequency, variable voltage systems, so the actual needs of the load need to be examined to determine just how sophisticated the system really needs to be. If a simpler system will accomplish the task at less cost, it should be used.

2 DC SHUNT GENERATOR WITH BATTERY LOAD

Most people immediately think of a simple dc generator and a battery storage system when small wind turbines are mentioned. Many such systems were placed in service in the 1930s or even earlier. They provided power for a radio and a light bulb or two, and occasionally power for some electrical appliances. Some of the machines, especially the Jacobs, seemed almost indestructible. A number of these machines have provided service for over fifty years. These machines nearly all disappeared between 1940 and 1950, partly because centrally generated electricity was cheaper and more reliable, and partly because some Rural Electrical Cooperatives (REC) would not supply electricity to a farm with an operating wind electric system.

Today, such small dc systems still have very marginal economics when centrally generated electricity is available. Their primary role would then seem to be to supply limited amounts of power to isolated loads such as weather data stations, fire lookout towers, and summer cottages. They may also provide a backup or emergency system which can be used when centrally generated power is not available due to equipment failure or fuel shortages.

A diagram of a simple dc shunt generator connected to a battery is shown in Fig. 2. This circuit has been widely used since copper oxide and selenium rectifiers (diodes) were developed in the 1930s. Silicon diodes with much superior characteristics were developed in the 1950s and are almost exclusively used today. The diode allows current to flow from the generator to the battery, but prevents current flow in the opposite direction. This prevents the battery from being discharged through the generator when the generator voltage is below the battery voltage.

The generator consists of a rotor or *armature* with resistance R_a and a field winding with resistance R_f on the stator. The armature current I_a is brought out of the machine by brushes which press against the *commutator*, a set of electrical contacts at one end of the armature. The generator terminal voltage V_g causes a field current I_f to flow in the field winding. This field current flowing in a coil of wire, indicated by an inductor symbol on the left side of Fig. 2, will produce a magnetic flux. The interaction of this flux and the rotating conductors in the armature produces the generated electromotive force (emf) E, which is given by

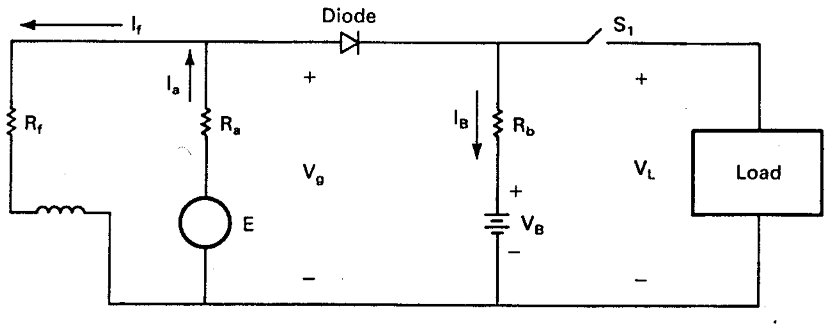

Figure 2: DC shunt generator in a battery-charging circuit.

$$E = k_s \omega_m \Phi_p \qquad \text{V} \tag{1}$$

where Φ_p is the magnetic flux per pole, ω_m is the mechanical angular velocity of the rotor, and k_s is a constant involving the number of poles and number of turns of conductors. We see that the voltage increases with speed for a given flux. This means that at low speeds the generated emf will be less than the battery voltage. This has the advantage that the turbine will not be loaded at low rotational speeds, and hence will be easier to start.

The generator rotational speed n can be determined from the angular velocity ω_m by

$$n = \frac{60\omega_m}{2\pi} \qquad \text{r/min} \tag{2}$$

The induced voltage E is in series with the resistance R_a of the rotor or armature windings. In this simple model, R_a would also include the resistance of the brushes on the commutator bars.

The current flow I_f (the *excitation current*) in the field winding around the poles is given by

$$I_f = \frac{V_g}{R_f} \qquad \text{A} \tag{3}$$

The field winding has inductance, but the reactance ωL is zero because only dc is involved. Therefore only the resistances are needed to compute currents or voltages.

The flux does not vary linearly with field current because of the saturation of the magnetic circuit. The flux will increase rapidly with increasing I_f for small values of I_f, but will increase more slowly as I_f gets large and the iron of the machine gets more saturated. Also, the flux is not exactly zero when I_f is zero, due to the residual magnetism of the poles. The iron tends to act like a permanent magnet after a flux has once been established. This means that the generated emf E will be greater than zero whenever the armature is spinning, even though the field current is negligible. These effects of the iron circuit yield a plot of E versus I_f such as shown in Fig. 3. E starts at a positive value, increases rapidly for small I_f, and finally levels off for larger I_f. Two angular velocities, ω_{m1} and ω_{m2}, are shown on the figure. Increasing ω_m merely expands the curve for E without changing its basic shape.

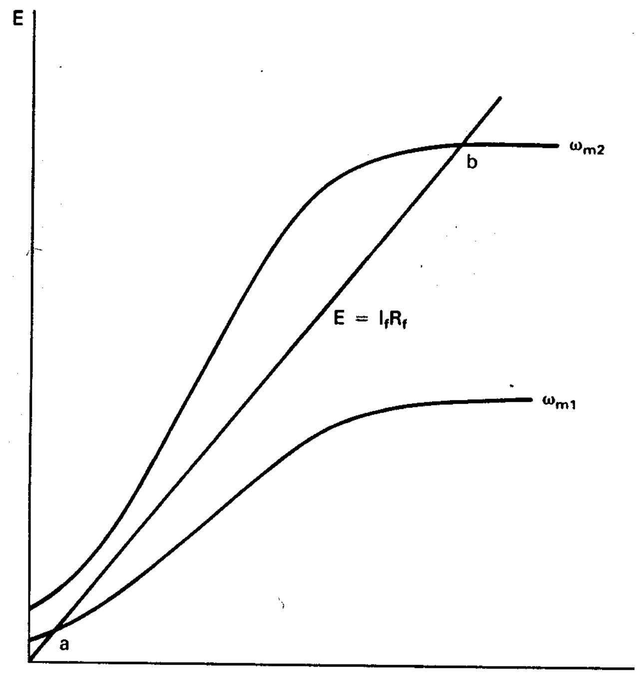

Figure 3: Magnetization curve of dc generator.

The generated emf E is given by Kirchhoff's voltage law as

$$E = I_a R_a + I_f R_f \qquad \text{V} \tag{4}$$

R_a is much smaller than R_f, so when the diode current is zero, which causes $I_a = I_f$, the $I_a R_a$ term is very small compared with $R_f I_f$. Therefore, to a first approximation, we can write

$$E \simeq I_f R_f \tag{5}$$

This equation is just a straight line passing through the origin of Fig. 3. We therefore have a voltage E being constrained by both a nonlinear dc generator and a linear resistor. The generator requires the voltage to vary along the nonlinear curve while the field resistor requires it to vary along the straight line. Both requirements are met at the intersection of the nonlinear curve and the straight line, and this intersection defines the equilibrium or *operating* *point*. When the generator is turning at the angular velocity ω_{m1}, voltage and current will build up only to point a. This is well below the capability of the generator and is not a desirable operating point. If the angular velocity is increased to ω_{m2} the voltage will build up to the value at point b. This is just past the *knee* of the magnetization curve and is a good operating point in that small changes in speed or field resistance will not cause large changes in E.

Another way of changing the operating point is to change the field resistance R_f. The slope of the straight line decreases as R_f decreases so the operating point can be set any place along the magnetization curve by the proper choice of R_f. There are some practical limitations to decreasing R_f, of course. R_f usually consists of an external variable resistance plus the internal resistance of a coil of many turns of fine wire. Therefore R_f can not be reduced below the internal coil resistance.

The mode of operation of this generator is referred to as a self-excited mode. The residual magnetism of the generator produces a small flux, which causes a small voltage to appear across the field winding when the generator rotor is rotated. This small voltage produces a small field current which helps to boost E to a larger value. This larger E produces a still larger field current, which produces a still larger E, until equilibrium is reached. The equilibrium point will be at small values of E for low speeds or high field resistance, and will increase rapidly to a point past the knee of the magnetization curve as speed or field resistance reaches some critical value. Once the voltage has built up to a value close to the rated voltage, the generator can supply current to a load.

We now want to examine the operation of the self-excited shunt generator as a battery charger, with the circuit of Fig. 2. We assume that switch S_1 is open, that the diode is an open circuit when E is less than the battery voltage V_B and a short circuit when E is greater than V_B, and that R_B includes the resistance of the diode and connecting wires as well as the internal resistance of the battery. When the diode is conducting, the relationship between E and V_B is

$$E = V_B + I_f R_a + I_B(R_a + R_b) \qquad \text{V} \tag{6}$$

The term $I_f R_a$ is a very small voltage and can be neglected without a serious loss of accuracy. If we do so, the battery current is given by

$$I_B \simeq \frac{E - V_B}{R_a + R_b} \qquad \text{A} \tag{7}$$

The electrical power produced by the shunt generator when the diode is conducting is given by

$$P_e = EI_a \simeq EI_f + \frac{E(E - V_B}{R_a + R_b} \qquad \text{W} \tag{8}$$

The electrical power delivered to the battery is

$$P_B = V_B I_B \qquad \text{W} \tag{9}$$

The electrical power can be computed as a function of angular velocity if all the quantities in Eq. 8 are known. In practice, none of these are known very precisely. E tends to be reduced below the value predicted by Eq. 1 by a phenomenon called armature reaction. The resistance of the copper wire in the circuit increases with temperature. R_a and R_b include the voltage drops across the brushes of the generator and the diode, which are quite nonlinear. And finally, V_B varies with the state of charge of the battery. Each system needs to be carefully measured if a detailed curve of power versus rotational speed is desired. General results or curves applicable to a wide range of systems are very difficult to obtain, if not impossible.

Example

The Wincharger Model 1222 is a 12-V, 15-A self-excited dc shunt generator used for charging 12-V batteries. By various crude measurements and intelligent estimates, you decide that $R_f = 15\ \Omega$, $R_a = 0.2\ \Omega$, $R_b = 0.25\ \Omega$, $V_B = 12$ V, and $E = 0.015n + 8$ V. This expression for E includes the armature reaction over the normal operating range, hence is much flatter than the ideal expression of Eq. 1. Assume the diode is ideal (no forward voltage drop when conducting) and plot E, I_B, and P_e for n between 0 and 600 r/min.

We first observe that $I_B = 0$ whenever $E \leq V_B$. The rotational speed at which the battery starts to charge is found by setting $E = V_B$ and solving for n.

$$0.015n + 8 = 12$$

$$n = \frac{4}{0.015} = 270 \ \text{r/min}$$

The battery current will vary linearly with E and therefore with the rotational speed, according to Eq. 7. We can plot the current I_B by just finding one more point and drawing a straight line. At n = 600 r/min, the battery current is given by

$$I_B \simeq \frac{0.015(600) + 8 - 12}{0.2 + 0.25} = 11 \ \text{A}$$

The electrical power generated is nonlinear and has to be determined at several rotational speeds to be properly plotted. When this is done, the desired quantities can be plotted as shown in Fig. 4. The actual generated E starts at zero and increases as approximately the square of the rotational speed until diode current starts to flow. Both flux and angular velocity are increasing, so Eq. 1 would predict such a curve. When the diode current starts to flow, armature reaction reduces the rate of increase of E. The flux also levels off because of saturation. E can then be approximated for speeds above 270 r/min by the straight line shown, which could then be extrapolated backward to intersect the vertical axis, at 8 V in this case.

The current will also increase linearly, giving a square law variation in the electrical power. The optimum variation of power would be a cubic function of rotational speed, which is shown as a dashed curve in Fig. 4. The discontinuity in E causes the actual power variation to approximate the ideal rather closely, which would indicate that the Wincharger is reasonably well designed to do its job.

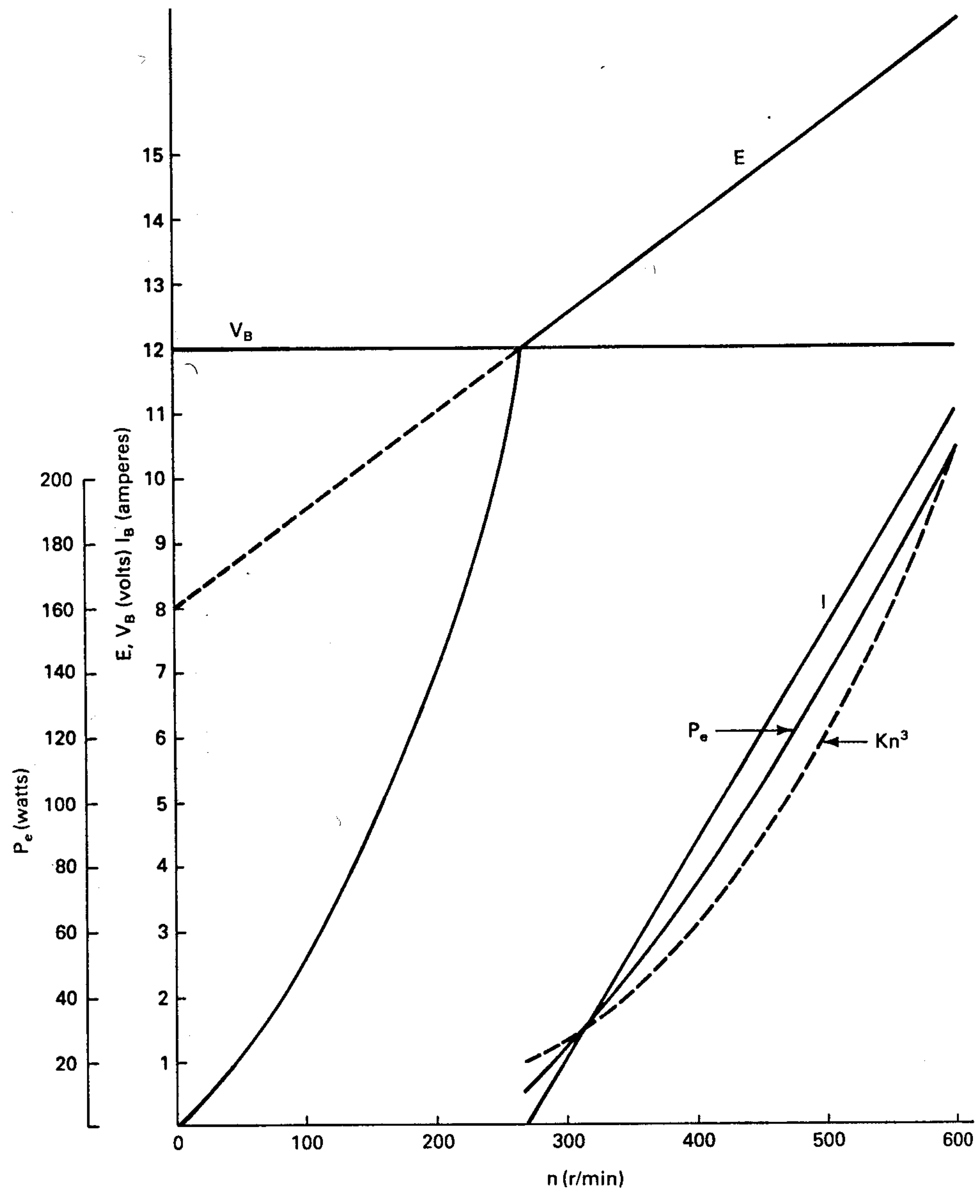

Figure 4: Variation of E, I_B, and P_e for Wincharger 1222 connected to a 12-V battery.

One other aspect of operating shunt generators needs to be mentioned. When a new generator is placed into service, it is possible that there is no net residual magnetism to cause a voltage buildup, or that the residual magnetism is oriented in the wrong direction. A short application of rated dc voltage to the generator terminals will usually establish the proper residual magnetism. This should be applied while the generator is stopped, so current will be well above rated, and should be applied for only a few seconds at most. Only the field winding needs to experience this voltage, so if the brushes can be lifted from the commutator, both the generator and the dc supply will experience much less shock.

3 PERMANENT MAGNET GENERATORS

A permanent magnet generator is like the synchronous or ac generator discussed in the previous chapter except that the rotor field is produced by permanent magnets rather than current in a coil of wire. This means that no field supply is needed, which reduces costs. It also means that there is no I^2R power loss in the field, which helps to increase the efficiency. One disadvantage is that the reactive power flow can not be controlled if the PM generator is connected to the utility network. This is of little concern in an asynchronous mode, of course.

The magnets can be cast in a cylindrical aluminum rotor, which is substantially less expensive and more rugged than the wound rotor of the conventional generator. No commutator is required, so the PM generator will also be less expensive than the dc generator of the previous section. These advantages make the PM generator of significant interest to designers of small asynchronous wind turbines.

One load which might be used on a PM generator would be a resistance heating system for either space or hot water. Such a system is shown in Fig. 5. The three line-to-neutral generated voltages E_a, E_b, and E_c are all displaced from each other by 120 electrical degrees. The line-to-neutral terminal voltages are also displaced from each other by 120^o if the three-phase load is balanced ($R_a = R_b = R_c$). The current I_a is given by

$$I_a = \frac{E_a}{R_s + jX_s + R_a} = \frac{V_a}{R_a} \qquad \text{A} \tag{10}$$

where X_s is the synchronous reactance, R_s is the winding resistance, and R_a is the resistance of one leg or one phase of the load resistance.

The neutral current I_n is given by the sum of the other currents.

$$I_n = I_a + I_b + I_c \qquad \text{A} \tag{11}$$

If the load is balanced, then the neutral current will be zero. In such circumstances, the wire connecting the neutrals of the generator and load could be removed without affecting any of the circuit voltages or currents. The asynchronous system will need the neutral wire connected, however, because it allows the single-phase voltages V_a, V_b, and V_c to be used for other loads in an unbalanced system. Several single-phase room heaters could be operated independently, for example, if the neutral wire is in place.

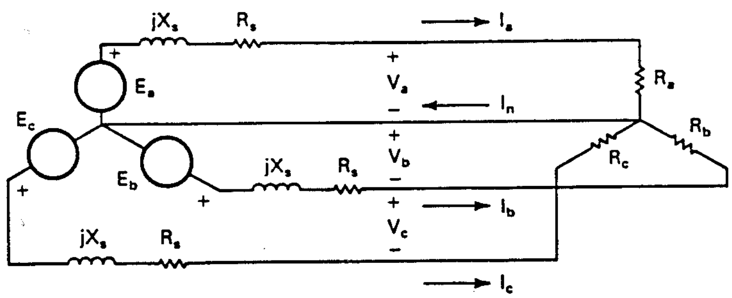

Figure 5: Permanent-magnet generator connected to a resistive load.

It is desirable to maintain the three line currents at about the same value to minimize torque fluctuations. It is shown in electrical machinery texts that a three-phase generator will have a constant shaft torque when operated under balanced conditions. A single-phase generator or an unbalanced three-phase generator has a torque that oscillates at twice the electrical frequency. This makes the generator noisy and tends to shorten the life of the shaft, bearings, and couplers. This is one of the primary reasons single-phase motors and generators are seldom seen in sizes above about 5 kW. The PM generator will have to be built strongly enough to accept the turbine torque fluctuations, so some imbalance on the generator currents should not be too harmful to the system, but the imbalance will need to be minimized to keep the noise level down, if for no other reason.

The electrical output power P_e (the power delivered to the load) of the PM generator per phase is

$$P_e = I_a^2 R_a \qquad \text{W/phase} \tag{12}$$

The magnitude of the current is

$$|I_a| = \frac{|E_a|}{\sqrt{(R_s + R_a)^2 + X_s^2}} \qquad \text{A} \tag{13}$$

Therefore the output power can be expressed as

$$P_e = \frac{E_a^2 R_a}{(R_s + R_a)^2 + X_s^2} \qquad \text{W/phase} \tag{14}$$

The generated voltage E_a can be written as

$$E_a = k_e \omega \qquad \text{V} \tag{15}$$

This is basically the same equation as Eq. 1. Here the constant k_e includes the flux per pole since the PM generator is a constant flux machine and also includes any constant factor between the mechanical angular velocity ω_m and the electrical angular velocity ω. A four pole generator spinning at 1800 r/min will have $\omega_m = 188.5$ rad/s and $\omega = 377$ rad/s, for example. The ratio of electrical to mechanical angular velocity will be 1 for a two pole generator, 2 for a four pole, 3 for a six pole, and so on.

This variation in generated voltage with angular velocity means that a PM generator which has an open-circuit rms voltage of 250 V line to line at 60 Hz when the generator rotor is turning at 1800 r/min will have an open circuit voltage of 125 V at 30 Hz when the generator rotor is turning at 900 r/min. Wide fluctuations of voltage and frequency will be obtained from the PM generator if the wind turbine does not have a rather sophisticated speed control system. The PM generator must therefore be connected to loads which can accept such voltage and frequency variations.

Lighting circuits would normally not be appropriate loads. Incandescent bulbs are not bright enough at voltages 20 percent less than rated, and burn out quickly when the voltages are 10 percent above rated. There will also be an objectionable flicker when the frequency drops significantly below 60 Hz. Fluorescent bulbs may operate over a slightly wider voltage and frequency range depending on the type of bulb and ballast. If lighting circuits must be supplied by the PM generator, consideration should be given to using a rectifier and battery system just for the lights.

It should be noticed that the rating of the PM generator is directly proportional to the rotational speed. The rated current is related to the winding conductor size, which is fixed for a given generator, so the output power V_aI_a will vary as E_a or as the rotational speed. The resistance R_a has to be varied as E_a varies to maintain a constant current, of course. This means that a generator rated at 5 kW at 1800 r/min would be rated at 10 kW at 3600 r/min because the voltage has doubled for the same current, thus doubling the power. The limitations to this increase in rating are the mechanical limitations of rotor and bearings, and the electrical limitations of the insulation.

In Chapter 4 we saw that the shaft power input to the generator needs to vary as n^3 for the turbine to operate at its peak efficiency over a range of wind speeds and turbine speeds. Since n and ω are directly proportional, and the efficiency is high, we can argue that the output power of the PM generator should vary as ω^3 for the generator to be an optimum load for the turbine. The actual variation can be determined by explicitly showing the frequency dependency of the terms in Eq. 14. In addition to E_a, there is the reactance X_s, which is given by

$$X_s = \omega L_s \qquad \Omega \tag{16}$$

The term L_s is the inductance of the generator windings. It is not a true constant because of saturation effects in the iron of the generator, but we shall ignore that fact in this elementary treatment.

The frequency variation of the electrical output power is then given by

$$P_e = \frac{k_e^2 \omega^2 R_a}{(R_s + R_a)^2 + \omega^2 L_s^2} \qquad \text{W/phase} \tag{17}$$

We see that at very low frequencies or for a very large load resistance that P_e increases as the square of the frequency. At very high frequencies, however, when ωL_s is larger than $R_s + R_a$, the output power will be nearly constant as frequency increases. At rated speed and rated power, X_s will be similar in magnitude to $R_s + R_a$ and the variation of P_e will be nearly proportional to the frequency.

We therefore see that a PM generator with a fixed resistive load is not an optimum load for a wind turbine. If we insist on using such a system, it appears that we must use some sort of blade pitching mechanism on the turbine. The blade pitching mechanism is a technically good solution, but rather expensive. The costs of this system probably far surpass the cost savings of the PM generator over other types of generators.

One alternative to a fixed resistance load is a variable resistance load. One way of varying the load resistance seen by the generator is to insert a variable autotransformer between the generator and the load resistors. The circuit for one phase of such a connection is shown in Fig. 6. The basic equations for an autotransformer were given in the previous chapter. The voltage seen by the load can be varied from zero to some value above the generator voltage in this system. The power can therefore be adjusted from zero to rated in a smooth fashion. A microcomputer is required to sense the wind speed, the turbine speed, and perhaps the rate of change of turbine speed. It would then signal the electrical actuator on the autotransformer to change the setting as necessary to properly load the turbine. A good control system could anticipate changes in turbine power from changes in wind speed and keep the load near the optimum value over a wide range of wind speeds.

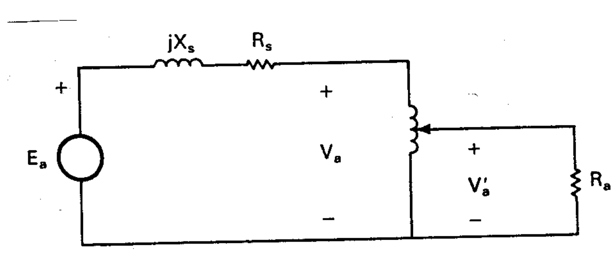

Figure 6: Load adjustment with a variable autotransformer.

One problem with this concept is that the motor driven three-phase variable autotransformer probably costs as much as the PM generator. Another problem would be mechanical reliability of the autotransformer sliding contacts. These would certainly require regular maintenance. We see that the advantages of the PM generator in the areas of cost and reliability have been lost in using a variable autotransformer to control the load.

Another way of controlling the load, which eliminates the variable autotransformer, is to use a microcomputer to switch in additional resistors as the wind speed and turbine speed increase. The basic circuit is shown in Fig. 7. The switches can be solid state (triacs) which are easily controlled by microcomputer logic levels and which can withstand millions of operating cycles. Costs and reliability of this load control system are within acceptable limits. Unfortunately, this concept leads to a marginally unstable system for the Darrieus turbine and possibly for the horizontal axis propeller turbine as well. The instability can be observed by examining the electrical power output of the Sandia 17 m Darrieus as shown in Fig. 8. The power output to an optimum load is seen to pass through the peak turbine power output for any wind speed, as was discussed in Chapter 4. The load powers for the four different resistor combinations are shown as linear functions of n around the operating points. These curves are reasonable approximations for the actual P_e curves, as was pointed out by the discussion following Eq. 17. We do not need better or more precise curves for P_e because the instability will be present for any load that varies at a rate less than n^3.

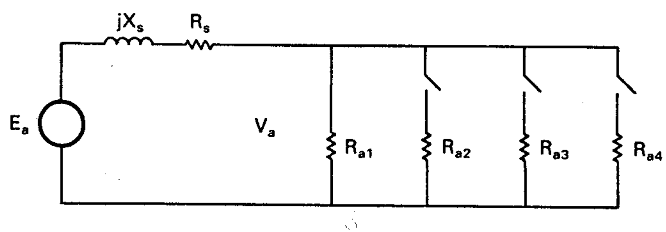

Figure 7: Load adjustment by switching resistors.

We assume that the load power is determined by the curve marked R_{a1} and that the wind speed is 6 m/s. The turbine will be operating at point a. If the wind speed increases to 8 m/s, the turbine torque exceeds the load torque and the turbine accelerates toward point b. If the second resistor is switched in, the load power will increase, causing the turbine to slow down. The new operating point would then be point c. If the wind speed drops back to 6 m/s, the load power will exceed the available power from the turbine so the turbine has to decelerate. If the load is not removed quickly enough, the operating point will pass through point f and the turbine will stall aerodynamically. It could even stop completely and need to be restarted. The additional load must be dropped as soon as the turbine starts to slow down if this condition is to be prevented.

Another way of expressing the difficulty with this control system is to note that the speed variation is excessive. Suppose the resistance is $R_{a1} + R_{a2} + R_{a3}$ and we have had a steady wind just over 10 m/s. If the wind speed would slowly decrease to 10 m/s, the turbine would go to the operating point marked d, and then as it slowed down further, the load would be switched to $R_{a1} + R_{a2}$. The turbine would then accelerate to point e. The speed would change from approximately 50 to 85 r/min for this example. This is a very large speed variation and may pose mechanical difficulties to the turbine. It also places the operating point well down from the peak of the power curve, which violates one of the original reasons for considering an asynchronous system, that of maintaining peak power over a range of wind speeds and turbine rotational speeds. We therefore see that the PM generator with a switched or variable resistive

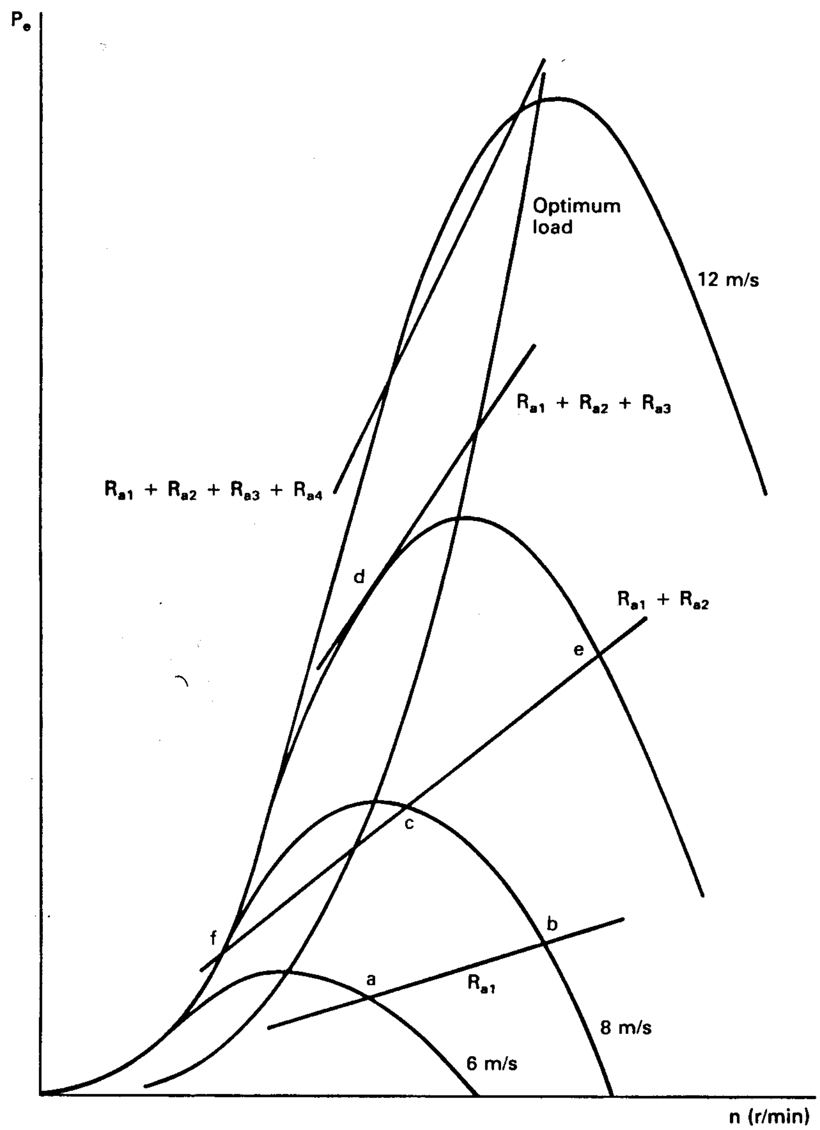

Figure 8: Electrical power output of Sandia 17-m Darrieus in variable-speed operation.

load is really not a very effective wind turbine load. The problems that are introduced by this system can be solved, but the solution will probably be more expensive than another type of system.

Another alternative for matching the load power to the turbine power is a series resonant circuit. This concept has successfully been used by the Zephyr Wind Dynamo Company to build a simple matching circuit for their line of very low speed PM generators. The basic concept is shown in Fig. 9.

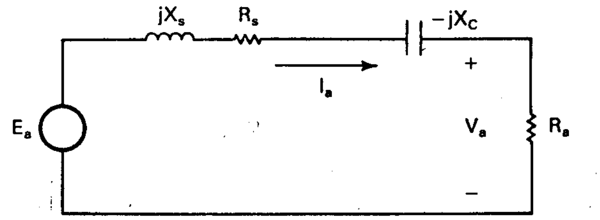

Figure 9: Series resonant circuit for a PM generator.

The capacitive reactance X_C is selected so the circuit becomes resonant ($X_C = X_s$) at rated frequency. The power output will vary with frequency in a way that can be made to match the available power input from a given type of wind turbine rather closely. Overspeed protection will be required but complex pitch changing controls acting between cut-in and rated wind speeds are not essential.

The power output of the series resonant PM generator is

$$P_e = \frac{k_e^2 \omega^2 R_a}{(R_s + R_a)^2 + (\omega L_s - 1/\omega C)^2} \qquad \text{W/phase} \tag{18}$$

Below resonance, the capacitive reactance term is larger than the inductive reactance term. At resonance, $\omega L_s = 1/\omega C$. The power output tends to increase with frequency even above resonance, but will eventually approach a constant value at a sufficiently high frequency. L_s can be varied somewhat in the design of the PM generator and C can be changed easily to match the power output curve from a given turbine. No controls are needed, hence reliability and cost should be acceptable.

Example

A three-phase PM generator has an open circuit line-to- neutral voltage E_a of 150 V and a reactance X_s of 5.9 Ω/phase at 60 Hz. The series resistance R_s may be ignored. The generator is connected into a series resonant circuit like Fig. 9. At 60 Hz, the circuit is resonant and a total three-phase power of 10 kW is flowing to a balanced load with resistances R_a Ω/phase.

1. Find C.
2. Find R_a.
3. Find the current I_a.
4. Find the total three-phase power delivered to the same set of resistors at a frequency of 40 Hz.

At resonance, $X_C = X_s = 5.9$ Ω and $\omega = 2\pi f = 377$ rad/s. The capacitance is

$$C = \frac{1}{\omega X_C} = \frac{1}{377(5.9)} = 450 \times 10^{-6} \text{ F}$$

The inductance is

$$L_s = \frac{X_s}{\omega} = \frac{5.9}{377} = 15.65 \times 10^{-3} \ \text{H}$$

The power per phase is

$$P_e = \frac{10,000}{3} = 3333 \ \text{W/phase}$$

At resonance, the inductive reactance and the capacitive reactance cancel, so $V_a = E_a$. The resistance R_a is

$$R_a = \frac{V_a^2}{P_e} = \frac{(150)^2}{3333} = 6.75 \ \Omega$$

The current I_a is given by

$$I_a = \frac{V_a}{R_a} = \frac{150}{6.75} = 22.22 \ \text{A}$$

At 40 Hz, the circuit is no longer resonant. We want to use Eq. 18 to find the power but we need k_e first. It can be determined from Eq. 15 and rated conditions as

$$k_e = \frac{E}{\omega} = \frac{150}{377} = 0.398$$

The total power is then

$$P_{\text{tot}} = 3P_e = \frac{3(0.398)^2[2\pi(40)]^2(6.75)}{(6.75)^2 + [2\pi(40)(15.65 \times 10^{-3}) - 1/(2\pi(40)(450 \times 10^{-6}))]^2}$$

$$= \frac{202,600}{45.56 + 24.10} = 2910 \ \text{W}$$

If the power followed the ideal cubic curve, at 40 Hz the total power should be

$$P_{\text{tot,ideal}} = 10,000 \left(\frac{40}{60}\right)^3 = 2963 \ \text{W}$$

We can see that the resonant circuit causes the actual power to follow the ideal variation rather closely over this frequency range.

4 AC GENERATORS

The ac generator that is normally used for supplying synchronous power to the electric utility can also be used in an asynchronous mode[14]. This machine was discussed in the previous chapter. It can be connected to a resistive load for space and water heating applications with the same circuit diagram as the PM generator shown in Fig. 5. The major difference is that the induced emfs are no longer proportional to speed only, but to the product of speed and flux. In the linear case, the flux is directly proportional to the field current I_f, so the emf E_a can be expressed as

$$E_a = k_f \omega I_f \qquad \text{V/phase} \tag{19}$$

where $\omega = 2\pi f$ is the electrical radian frequency and k_f is a constant.

Suppose now that the field current can be varied proportional to the machine speed. Then the induced voltage can be written as

$$E_a = k'_f \omega^2 \qquad \text{V/phase} \tag{20}$$

where k'_f is another constant. It can be determined from a knowledge of the rated generated voltage (the open circuit voltage) at rated frequency.

The electrical output power is then given by an expression similar to Eq. 17.

$$P_e = \frac{k'^2_f \omega^4 R_a}{(R_s + R_a)^2 + \omega^2 L_s^2} \qquad \text{W/phase} \tag{21}$$

The variation of output power will be as some function between ω^2 and ω^4. With the proper choice of machine inductance and load resistance we can have a power variation very close to the optimum of ω^3.

It may be desirable to vary the field current in some other fashion to accomplish other objectives. For example, we might vary it at a rate proportional to ω^2 so the output power will vary as some function between ω^4 and ω^6. This will allow the turbine to operate over a narrower speed range. At low speeds the output power will be very small, allowing the turbine to accelerate to nearly rated speed at light load. The load will then increase rapidly with speed so the generator rated power will be reached with a small increase of speed. As the speed increases even more in high wind conditions, some mechanical overspeed protection device will be activated to prevent further speed increases.

If the turbine has pitch control so the generator speed can be maintained within a narrow range, the field current can be varied to maintain a desired load voltage. All home appliances, except clocks and some television sets, could be operated from such a source. The frequency may vary from perhaps 56 to 64 Hz, but this will not affect most home appliances if the proper voltage is present at the same time. The control system needs to have discretionary loads for both the low and high wind conditions. Too much load in low wind speeds will cause the turbine to slow below the desired speed range, while very light loads in high wind speeds will make it difficult for the pitch control system to keep the turbine speed down to an acceptable value. At intermediate wind speeds the control system needs to be able to decide between changing the pitch and changing the load to maintain frequency in a varying wind. This would require a very sophisticated control system, but would provide power that is nearly utility quality directly from a wind turbine.

It is evident that an ac generator with a field supply and associated control system will be relatively expensive in small sizes. This system will probably be difficult to justify economically in sizes below perhaps 100 kW. It may be a good choice for villages separated from the grid, however, because of the inherent quality of the electricity. Most village loads could be operated directly from this generator. A small battery bank and inverter would be able to handle the critical loads during windless periods.

5 SELF-EXCITATION OF THE INDUCTION GENERATOR

In Chapter 5, we examined the operation of an induction machine as both a motor and generator connected to the utility grid. We saw that the induction generator is generally simpler, cheaper, more reliable, and perhaps more efficient than either the ac generator or the dc generator. The induction generator and the PM generator are similar in construction, except for the rotor, so complexity, reliability, and efficiency should be quite similar for these two types of machines. The induction generator is likely to be cheaper than the PM generator by perhaps a factor of two, however, because of the differences in the numbers produced. Induction motors are used very widely, and it may be expected that many will be used as induction generators because of such factors as good availability, reliability, and reasonable cost[3].

An induction machine can be made to operate as an isolated ac generator by supplying the necessary exciting or magnetizing current from capacitors connected across the terminals of the machine[8, 2, 14]. Fig. 10 shows a typical circuit for a three-phase squirrel-cage induction machine. The capacitors are shown in a delta connection primarily for economic reasons. That is, capacitors built for continuous duty, called motor-run capacitors, are most readily available in 370- and 460-V ratings. Most induction motors in sizes up to 100 kW or more are built with 208-, 230-, or 460-V ratings, so the available capacitors can readily handle the line to line voltages. If the capacitors were reconnected into a wye connection, the voltage across each capacitor is reduced to $1/\sqrt{3}$ of the delta connected value, and the reactive power supplied by each capacitor, ωCV^2, is then one-third of the reactive power per capacitor obtained from the delta connection. Three times as much capacitance is required in the wye connection, which increases the system cost unnecessarily.

The resistive load is shown connected in wye, but could be connected in delta if desired. There could be combinations of wye and delta connections if different voltage levels were needed.

The steady state balanced load case is usually analyzed in terms of an equivalent line to

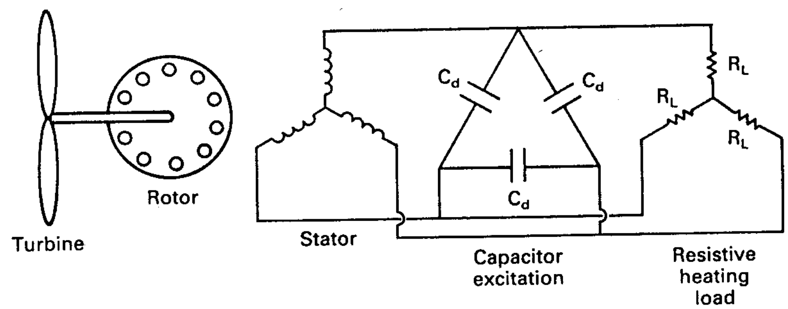

Figure 10: Self-excited induction generator.

neutral single-phase circuit, as shown in Fig. 11. This is the same circuit shown in Chapter 5, except for the capacitor and load resistor which replace the utility connection. For analysis purposes, the capacitor C is the equivalent wye connected capacitance. That is,

$$C = 3C_d \qquad \mu\text{F} \tag{22}$$

where C_d is the required capacitance per leg of a delta connection.

This circuit is very similar to that seen in electronics textbooks in a section on oscillators[13]. It is called a negative resistance oscillator. We have a resonant circuit where the capacitive reactance equals the inductive reactance at some frequency, so oscillation will occur at that frequency. Oscillation occurs much more readily when R_L is removed, so normal operation of the induction generator will have R_L switched out of the circuit until the voltage buildup has occurred.

The induction generator produces a small voltage from residual magnetism which initiates oscillation. The terminal voltage will build up from this small voltage to a value near rated voltage over a period of several seconds. Once the voltage has reached an operating value, the load resistance R_L can be switched back into the circuit.

It is possible to stop oscillation in any oscillator circuit by excessive load (too small a value of R_L). As R_L approaches this limit, the oscillator may operate in unexpected modes due to the nonlinearity of the circuit. The waveform may be bad, for example, or the slip of the induction generator may become unusually large. It should be a part of normal design procedures to determine that the maximum design load for a given generator is not too near this critical limit.

While the general operation of the circuit in Fig. 11 is not too difficult to understand, a detailed analysis is quite difficult because of the nonlinear magnetizing reactance. The available solutions have rather limited usefulness because of their complexity[10, 5, 6, 7]. Detailed reviews of these solutions are beyond the scope of this text, so we shall restrict ourselves to a discussion of some experimental results

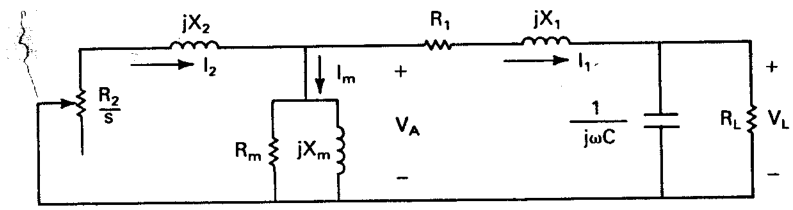

Figure 11: Single-phase equivalent circuit of self-excited induction generator.

First, however, we shall discuss some of the features of the machine parameters shown in Fig. 11. This should aid those who need to read the more detailed literature, and should also help develop some intuition for predicting changes in machine performance as operating conditions change.

The circuit quantities R_1, R_2, R_m, X_1, X_2, and X_m can be measured experimentally on a given machine. Techniques for doing this are discussed in texts on electric machinery. It should be mentioned that these machine parameters vary somewhat with operating conditions. R_1 and R_2 will increase with temperature between two temperatures T_a and T_b as

$$\frac{R_a}{R_b} = \frac{235 + T_a}{235 + T_b} \tag{23}$$

where T_a and T_b are in Celsius, R_a is the resistance R_1 or R_2 at temperature T_a, and R_b is the resistance at T_b. This expression is reasonably accurate for both aluminum and copper, the common conductors, over the expected range of generator temperatures. The change in resistance from an idle generator at -20^oC to one operating on a hot day with winding temperatures of 60^oC is (235 + 60)/(235 - 20) = 1.372. That is, the resistances R_1 and R_2 can increase by 37 percent over the expected range of operating temperatures. Such variations would need to be included in a complete analysis.

The resistance R_m represents the hysteresis and eddy current losses of the machine. The power lost to hysteresis varies as the operating frequency while the eddy current loss varies as the square of the operating frequency. There may also be some variation with operating voltage. The actual operating frequency will probably be between 40 and 60 Hz in a practical system so this equivalent resistor will vary perhaps 40 or 50 percent as the operating frequency changes. If the machine has low magnetic losses so that R_m is significantly greater than the load resistance R_L, then a single average value of R_m would yield acceptable results. In fact, R_m may even be neglected in the study of oscillation effects if the induction generator has high efficiency.

The reactances X_1, X_2, and X_m are given by ωL_1, ωL_2, and ωL_m where ω is the electrical radian frequency and L_1, L_2, and L_m refer to the circuit inductances. The frequency ω will vary with input power and the load resistance and capacitance for a given set of machine parameters.

The leakage inductances L_1 and L_2 should not vary with temperature, frequency, or voltage if the machine dimensions do not change. The air gap between rotor and stator may change with temperature, however, which will cause the inductances to change. A decrease in air gap will cause a decrease in leakage inductance.

The magnetizing inductance L_m is a strongly nonlinear function of the operating voltage V_L due to the effects of saturation in the magnetic circuit. In fact, stable operation of this system is only possible with a nonlinear L_m. The variation of L_m depends strongly on the type of steel used in the induction generator.

We obtain L_m from a no-load magnetization curve such as those shown in Fig. 12. These are basically the same curves as the one shown in Fig. 3 for the dc generator except that these are scaled in per unit quantities. The various per unit relationships were defined in Section 5.4. Each curve is obtained under no load conditions ($R_L = \infty$) so the slip is nearly zero and the rotor current I_2 is negligible. The magnetizing current flowing through L_m is then very nearly equal to the output current I_1. The vertical axis is expressed as $V_{L,\mathrm{pu}}/\omega_{\mathrm{pu}}$, so only one curve describes operation over a range of frequencies. Strictly speaking, the magnetization curve should be the airgap voltage V_A plotted against I_1 (or I_e) rather than the terminal voltage V_L. A point by point correction can be made to the measured curve of V_L versus I_1 by the equation

$$V_A = V_L + I_1(R_1 + jX_1) \tag{24}$$

The magnetization curve will have somewhat different shapes for different steels and manufacturing techniques used in assembling the generator. These particular curves are for a Dayton 5-hp three-phase induction motor rated at 230 V line to line and 14.4 A and a Baldor 40-hp three-phase induction motor rated at 460/230 V line to line and 48/96 A. Measured parameters in per unit for the 5-hp machine were $R_m = 13$, $R_1 = 0.075$, $R_2 = 0.045$, and $L_1 = L_2 = 0.16$. Measured parameters for the 40-hp machine in per unit were $R_m = 21.8$, $R_1 = 0.050$, $R_2 = 0.025$, and $L_1 = L_2 = 0.091$. The 40-hp machine is more efficient than the 5-hp machine because R_m is larger and R_1 and R_2 are smaller, thereby decreasing the loss terms.

We observe that for the 5-hp machine, rated voltage is reached when I_1 is about half the rated current. A terminal voltage of about 1.15 times the rated voltage is obtained for an I_1 of about 0.8 times the rated current. It should be noted that it is possible for the magnetizing current to exceed the machine rated current. The magnetizing current needs to be limited to perhaps 0.75 pu to allow a reasonable current flow to the load without exceeding machine ratings. This means that the rated voltage should not be exceeded by more than 10 or 15 percent for the 5-hp self-excited generator if overheating is to be avoided.

The 40-hp machine reaches rated voltage when I_1 is about 0.3 of its rated value. A terminal voltage of 130 percent of rated voltage is reached for an exciting current of only 0.6 of rated line current. This means the 40-hp machine could be operated at higher voltages than the

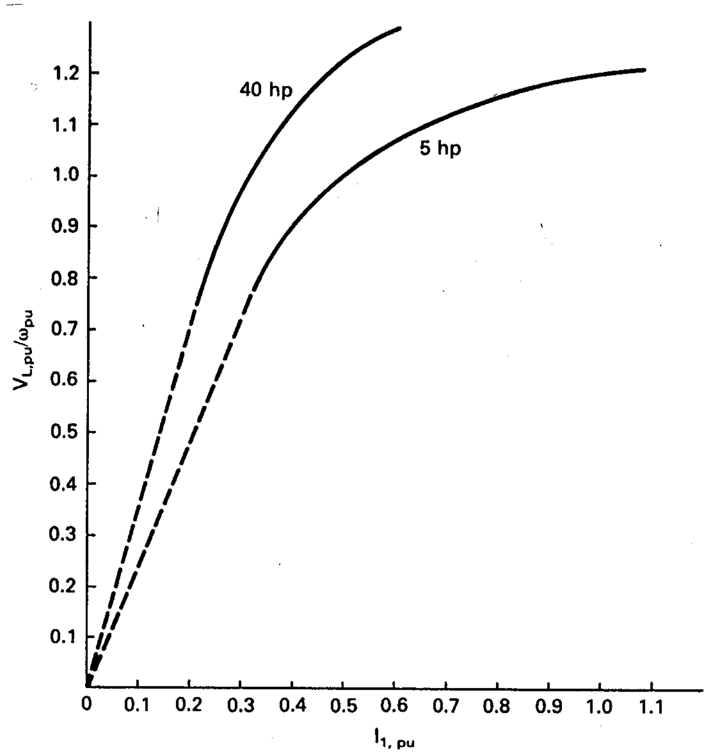

Figure 12: No-load magnetization curves for two induction generators.

5-hp machine without overheating effects. The insulation limitations of the machine must be respected, of course.

The magnetizing current necessary to produce rated voltage should be as small as possible for induction generators in this application. If two machines of different manufacturers are otherwise equal, the one with the smaller magnetizing current should be chosen. This will allow operation with less capacitance and therefore less cost. It may also allow more flexible operation in terms of the operating ranges of load resistance and frequency.

The per unit magnetizing inductance $L_{m,\mathrm{pu}}$ is defined as

$$L_{m,\mathrm{pu}} = \frac{V_{A,\mathrm{pu}}}{\omega_{\mathrm{pu}} I_{m,\mathrm{pu}}} \tag{25}$$

An approximation for $L_{m,\mathrm{pu}}$ which may be satisfactory in many cases is

$$L_{m,\mathrm{pu}} \simeq \frac{V_{L,\mathrm{pu}}}{\omega_{\mathrm{pu}} I_{1,\mathrm{pu}}} \tag{26}$$

This is just the slope of a line drawn from the origin of Fig. 12 to each point on the magnetization curve. Approximate curves for $L_{m,\text{pu}}$ for the two machines are presented in Fig. 13. We see that the inductance is constant for voltages less than about one-half of rated. The inductance then decreases as saturation increases.

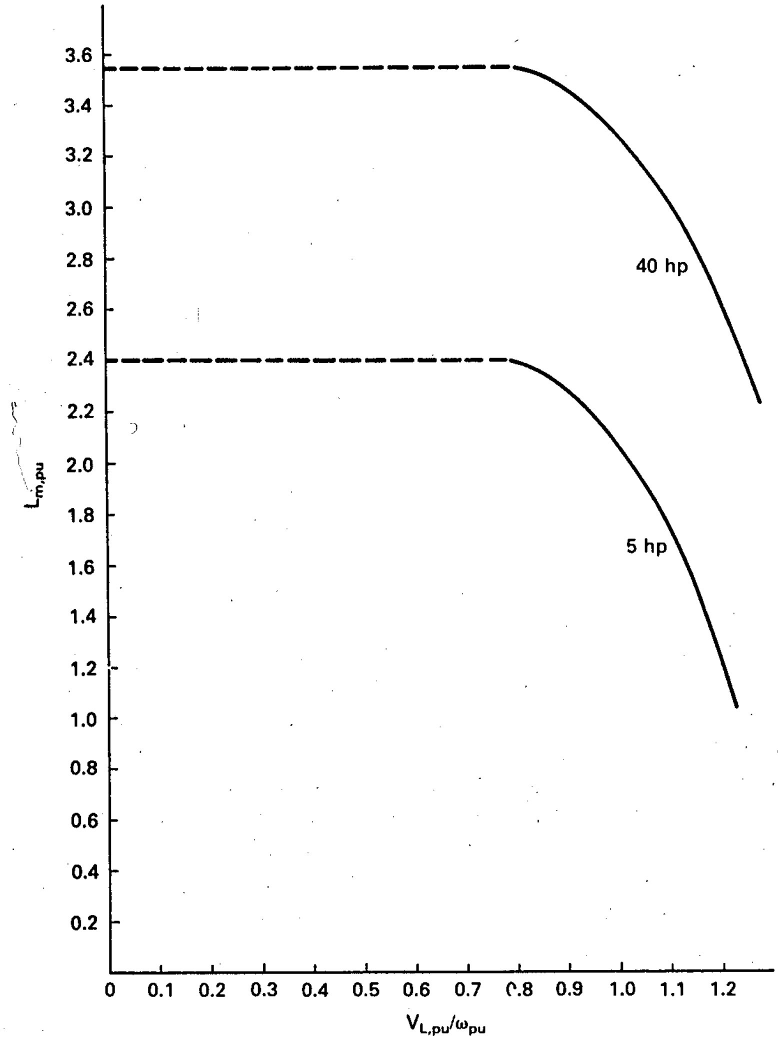

Figure 13: Per unit magnetizing inductance as a function of load voltage.

We see that any detailed analysis is made difficult because of the variability of the machine parameters. Not only must a nonlinear solution technique be used, the solution must be obtained for the allowable range of machine parameters. This requires a great deal of computation, with the results being somewhat uncertain because of possible inadequacy of the machine model and because of inadequate knowledge of the parameter values. We shall leave such detailed analyses to others and turn now to an example of experimental results.

Figure 14 shows the variation of terminal voltage with input mechanical power for the 40-hp machine mentioned earlier. The rated voltage is 230 V line to line or 132.8 V line to neutral. Actual line to neutral voltages vary from 90 to 150 V for the data presented here.

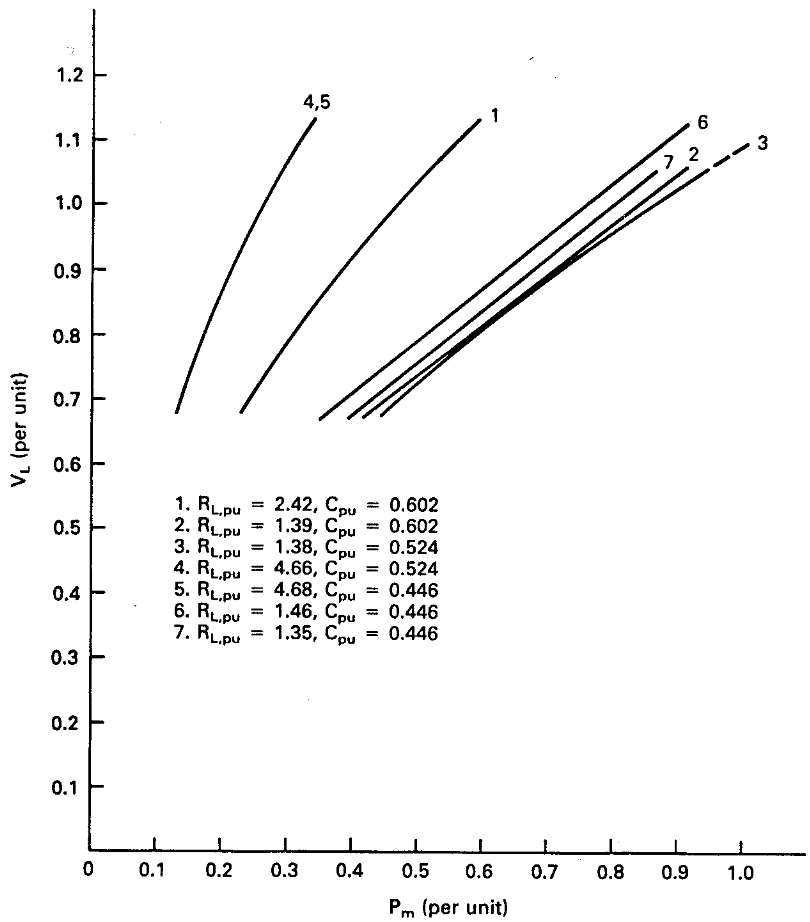

Figure 14: Variation of output voltage with input shaft power for various resistive and capacitive loads for a 40-hp self-excited induction generator.

All resistance was disconnected from the machine in order to establish oscillation. Once a voltage close to rated value was present the load was reconnected and data collected. Voltage buildup would not occur for speed and capacitance combinations which produce a final voltage of less than 0.8 or 0.9 of rated. For example, with 285 μF of capacitance line to line, the voltage would not build up for speeds below 1600 r/min. At 1600 r/min the voltage would slowly build up over a period of several seconds to a value near rated. The machine could then be operated at speeds down to 1465 r/min, and voltages down to 0.7 of rated before oscillation would cease.

The *base* power for this machine is $\sqrt{3}(230\text{ V})(96\text{ A}) = 38{,}240$ W. The *rated* power is $\sqrt{3}(230)(96)\cos\theta$, which will always be smaller than the base power. Because of this feature of the per unit system, the mechanical input power should not exceed 1.0 pu except for very short periods because the machine is already overloaded at $P_m = 1.0$ pu. The base impedance is $132.8/96 = 1.383\ \Omega$. The base capacitance is $1/(Z_{\text{base}}\omega_{\text{base}}) = 1/[(1.383)(377)] = 1918\ \mu$F line to neutral. A line to line capacitance of 385 μF, for example, would be represented in our analysis by a line to neutral capacitance of $3(385) = 1155\ \mu$F, which has a per unit value of $1155/1918 = 0.602$ pu. A good starting point for the capacitance on experimental induction generators in the 5-50 hp range seems to be about 0.6 pu. Changing capacitance will change performance, but oscillation should occur with this value of capacitance.

Returning to our discussion of Fig. 14, we see that for curve 1, representing a load of 2.42 pu and a capacitance of 0.602 pu, the voltage varies from 0.68 pu to 1.13 pu as P_m varies from 0.22 pu to 0.59 pu. The variation is nearly linear, as would be expected. When the resistance is decreased to 1.39 pu with the same capacitance, we get curve 2. At the same P_m of 0.59 pu, the new voltage will be about 0.81 pu. The electrical power out, V_L^2/R_L, will remain the same if losses do not change. We see that the voltage is determined by the resistance and not by the capacitance. Curves 2 and 3 and curves 4 and 5 show that changing the capacitance while keeping resistance essentially constant does not cause the voltage to change significantly.

Changing the capacitance will cause the frequency of oscillation to change and therefore the machine speed. We see how the speed varies with P_m in Fig. 15. A decrease in capacitance causes the speed to increase, for the same P_m. The change will be greater for heavy loads (small R_L) than for light loads. The speed will also increase with P_m for a given R_L and C. The increase will be rather rapid for light loads, such as curves 4 and 5. The increase becomes less rapid as the load is increased. We even have the situation shown in curve 7 where power is changing from 0.4 to 0.6 pu with almost no change in speed. The frequency will change to maintain resonance even if the speed does not change so we tend to have high slip where the speed curves are nearly horizontal. For this particular machine the efficiency stayed at about 90 percent even with this high slip and no other operational problems were noted. However, small increases in load would cause significant increases in speed, as seen by comparing curves 6 and 7. It would seem therefore, that this constant speed-high slip region should be avoided by adding more capacitance. Curves 7, 3, and 2 show that speed variation becomes more pronounced as capacitance is increased from 0.446 pu to 0.602 pu. We could conclude from this argument that a capacitance of 0.524 pu is the minimum safe value for this machine even though a value of 0.446 pu will allow operation.

We now want to consider the proper strategy for changing the load to maintain operation under changing wind conditions. The mechanical power output P_m from the wind turbine is assumed to vary from 0 to 1.0 pu. A capacitance value of 0.524 is assumed for discussion purposes. At $P_m = 1.0$ pu the voltage is 1.09 pu and the speed is 1.01 pu for $R_L = 1.38$ pu. These are good maximum values, which indicate that good choices have been made for R_L and C. As input power decreases to 0.44 pu the speed decreases to 0.944 pu. If input power is decreased still more, the induction generator gets out of the nonlinear saturation region and oscillation will cease. We therefore need to decrease the load (increase R_L). Note that there is a gap between curves 3 and 4, so we may have a problem if we change from $R_L = 1.38$ pu to 4.66 pu. The voltage will be excessive on the larger resistance and we may lose oscillation with the smaller resistance, while trying to operate in the gap area. We need an intermediate value of R_L such that the curve for the larger R_L will intersect the curve for the smaller R_L, as is the case for curves 1 and 2.

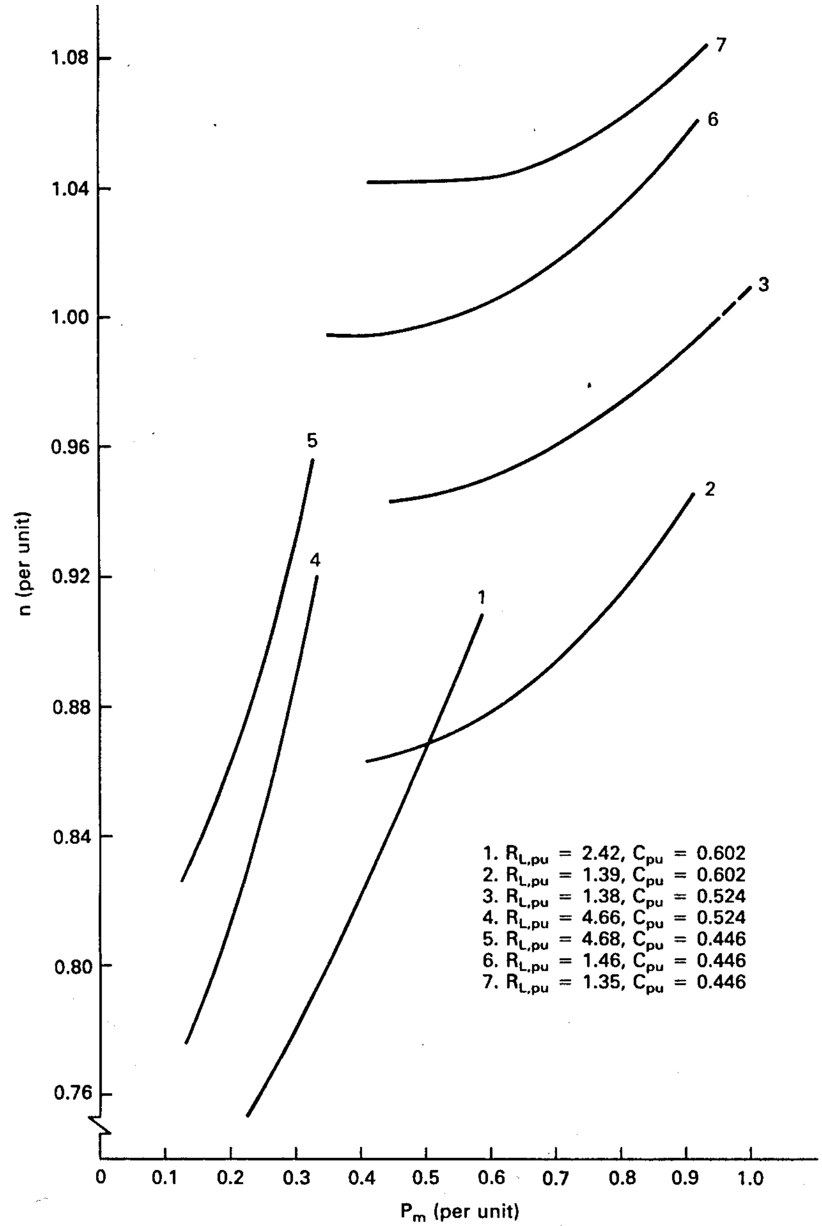

Figure 15: Variation of rotational speed with input shaft power for various resistive and capacitive loads for a 40-hp self-excited induction generator.

Curves 1 and 2 intersect at $P_m = 0.5$ pu so we can visualize a curve for a new value of R_L that intersects curve 3 at the same P_m. This is shown as curve 4′ in Fig. 16. If we are operating on curve 4′ at $P_m = 0.2$ pu, the speed is about 0.8 of rated. As shaft power increases to $P_m = 0.5$ pu the speed increases to about 0.95 of rated. Additional load can be added at this speed without causing a transient on the turbine since power remains the same. The speed then increases at a slower rate to 1.01 pu at $P_m = 1.0$ pu. If the wind is high enough to produce even greater power, the propeller pitch should be changed, brakes set, or other overload protection measures taken.

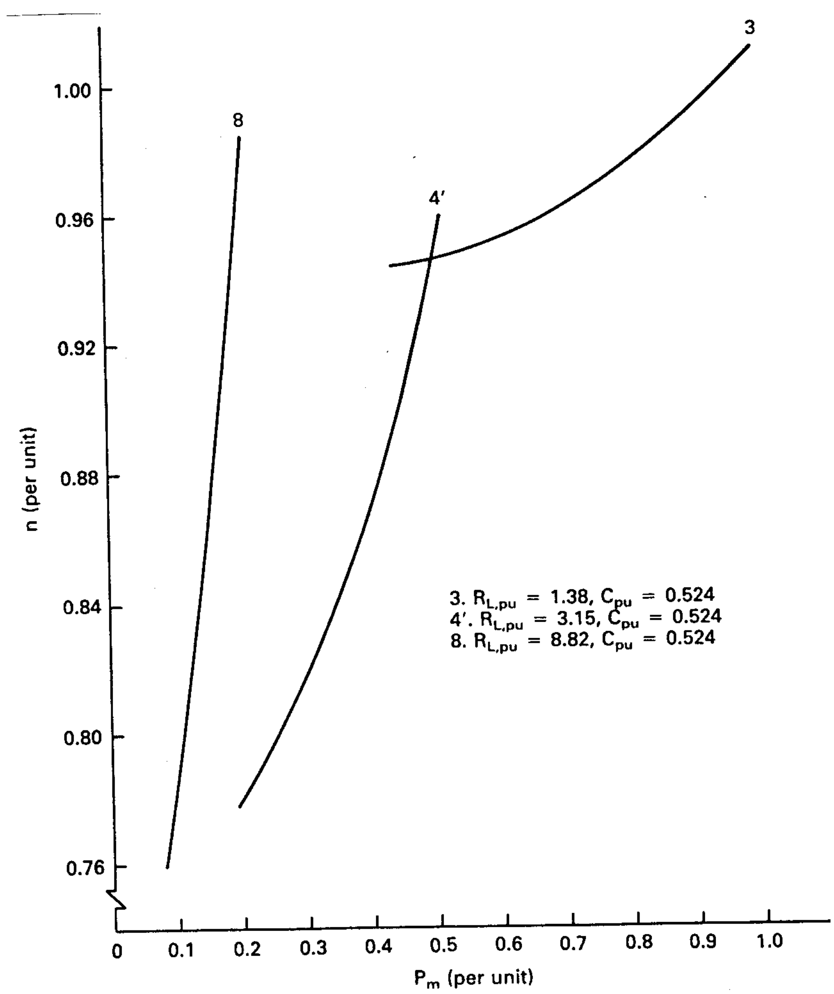

Figure 16: Variation of rotational speed with input shaft power for three well-chosen resistive loads for a 40-hp self-excited induction generator.

The resistance for curve 4′ can be computed from Figs. 14 and 15 and the relationship

$$R_L = \frac{V_L^2}{P_e} = \frac{V_L^2}{\eta_g P_m} \tag{27}$$

We are assuming an ideal transmission between the turbine and the generator so the turbine power output is the same as the generator input. If we want actual resistance, we have to use the voltage and power values per phase. On the per unit system, we use the per unit values directly. For example, for $V_L = 1.0$ pu on curve 3 in Fig. 14, we read $P_m = 0.86$ pu. If $R_L = 1.38$ pu, then $P_e = (1.0)^2/1.38 = 0.72$. But $P_e = \eta_g P_m$ so $\eta_g = 0.72/0.86 = 0.84$, a reasonable value for this size machine. If we assume $V_L = 1.15$, $P_m = 0.5$, and $\eta_g = 0.84$ for the curve $4'$, we find $R_L = (1.15)^2/(0.84)(0.5) = 3.15$ pu.

This value of R_L will work for input power levels down to about $P_m = 0.2$ pu. For smaller P_m we need to increase R_L to a larger value. We can use the same procedure as above to get this new value. If we assume a point on curve 8 of Fig. 16 where $V_L = 1.15$ pu, $P_m = 0.5$ pu, and η_g arbitrarily assumed to be 0.75, we find $R_L = (1.15)^2/(0.75)(0.2) = 8.82$ pu. This resistance should allow operation down to about $P_m = 0.08$, which is just barely enough to turn the generator at rated speed. Speed and voltage variations will be substantial with this small load. There will probably be a mechanical transient, both as the 8.82 pu load is switched in during startup, and as the load is changed to 3.15 pu, because the speed versus power curves would not be expected to intersect nicely as they did in the case of curves 3 and $4'$. These transients at low power levels and light winds would not be expected to damage the turbine or generator.

We see from this discussion that the minimum load arrangement is the one shown in Fig. 17. The switches S_1, S_2, and S_3 could be electromechanical contactors but would more probably be solid state relays because of their speed and long cycle life. The control system could operate on voltage alone. As the turbine started from a zero speed condition, S_1 would be closed as soon as the voltage reached perhaps 1.0 pu. When the voltage reached 1.15 pu, implying a power output of $P_m = 0.2$ pu in our example, S_2 would be closed. When the voltage reached 1.15 pu again, S_3 would be closed. When the voltage would drop below 0.7 pu, the highest numbered switch that was closed would be opened. This can be done with a simple microprocessor controller.

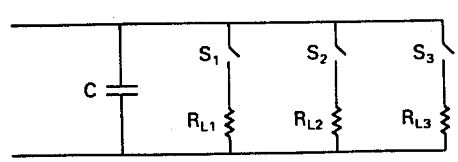

Figure 17: Minimum capacitive and resistive loads for a self-excited induction generator.

6 SINGLE-PHASE OPERATION OF THE INDUCTION GENERATOR

We have seen that a three-phase induction generator will supply power to a balanced three-phase resistive load without significant problems. There will be times, however, when single-phase or unbalanced three-phase loads will need to be supplied. We therefore want to examine this possibility.

Single-phase loads may be supplied either from line-to-line or from line-to-neutral voltages. It is also possible to supply both at the same time. Perhaps the most common case will be the rural individual who buys a wind turbine with a three-phase induction generator and who wants to sell single-phase power to the local utility because there is only a single-phase distribution line to his location. The single-phase transformer is rated at 240 V and is center-tapped so 120 V is also available. The induction generator would be rated at 240 V line to line or $240/\sqrt{3} = 138.6$ V line to neutral. The latter voltage is too high for conventional 120-V equipment but can be used for heating if properly rated heating elements are used.

A circuit diagram of the three-phase generator supplying line-to-line voltage to the utility network and also line-to-line voltage to a resistive load is shown in Fig. 18. Phases a and b are connected to the single-phase transformer. Between phase b and phase c is a capacitor C. Also shown is a resistor R_L which can be used for local applications such as space heating and domestic water heating. This helps to bring the generator into balance at high power levels. It reduces the power available for sale to the utility at lower power levels so would be placed in the circuit only when needed.

The neutral of the generator will not be at ground or earth potential in this circuit, so should not be connected to ground or to the frame of the generator. Some induction generators will not have a neutral available for connection because of their construction, so this is not a major change in wiring practice.

The induction generator will operate best when the voltages V_a, V_b, and V_c and the currents I_a, I_b, and I_c are all balanced, that is, with equal magnitudes and equal phase differences. Both voltages and currents become unbalanced when the generator supplies single-phase power. This has at least two negative effects on performance. One effect is a lowered efficiency. A machine which is 80 percent efficient in a balanced situation may be only 65 or 70 percent efficient in an unbalanced case. The other effect is a loss of rating. Rated current will be reached in one winding well before rated power is reached. The single- phase rated power would be two thirds of the three-phase rating if no balancing components are added and if the efficiency were the same in both cases. Because of the loss in efficiency, a three-phase generator may have only half its three-phase rating when connected directly to a single-phase transformer without the circuit components C and R_L shown in Fig. 18.

It is theoretically possible to choose C and R_L in Fig. 18 so that the induction generator is operating in perfect three- phase balance while supplying power to a single-phase transformer.

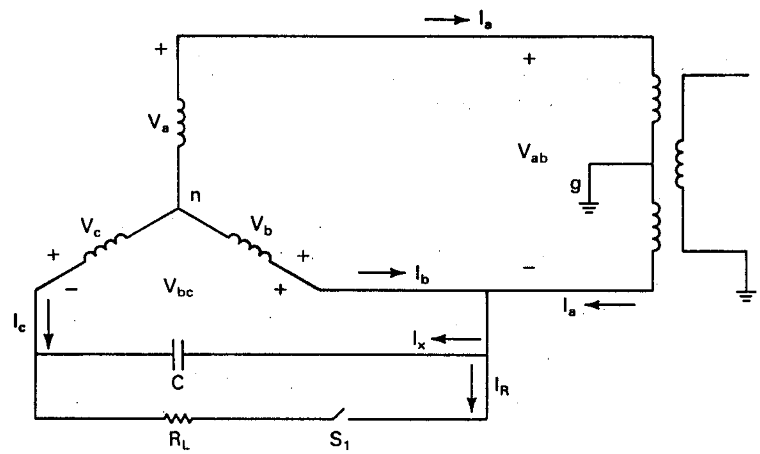

Figure 18: Three-phase induction generator supplying power to a single-phase utility transformer.

The phasor diagram for the fully balanced case is shown in Fig. 19. In this particular diagram, the capacitor is supplying all the reactive power requirements of the generator. This allows I_a to be in phase with V_{ab} so only real power is transferred through the transformer. In the fully balanced case, I_b and I_c must be equal in amplitude to I_a and spaced 120^o apart, which puts them in phase with V_{bc} and V_{ca}. The current I_R is in phase with V_{bc} and I_X leads V_{bc} by 90^o. By Kirchhoff's current law, $I_R + I_X = -I_c$. When we draw the necessary phasors in Fig. 19, it can be shown that $|I_R| = 0.5|I_a|$ and $|I_X| = 0.866|I_a|$. If we had a constant shaft power, such as might be available from a low head hydro plant, and if we had some use for the heat produced in R_L, then we could adjust C and R_L for perfect balance as seen by the generator and for unity power factor as seen by the utility. The power supplied to the utility is $V_{ab}I_a$ and the power supplied to the local load is $0.5V_{ab}I_a$, so two-thirds of the output power is going to the utility and one-third to the local load.

Unfortunately, a given set of values only produce balanced conditions at one power level. As the wind speed changes, operation will again be unbalanced. It is conceptually possible to have a sophisticated control system which would be continually changing these components as power level changes in order to maintain balance. This system could easily be more expensive than the generator and make the entire wind electric system uneconomical. We, therefore, are interested in a relatively simple system where one or more switches or contactors are controlled by rather simple sensors and logic circuitry. Hopefully, efficiency and unbalance will be acceptable over the full range of input power with this simple system. Capacitance and resistance would be added or subtracted as the power level changes, in order to maintain these acceptable conditions.

Perhaps the simplest way to illustrate the imbalance effects is with an example. Figure 20 shows the variation of the line to line voltages and the line currents for the 40-hp induction

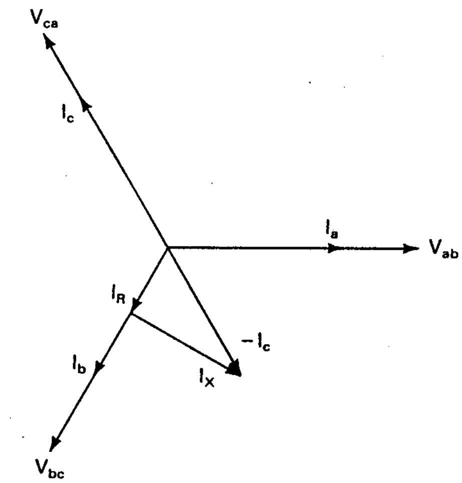

Figure 19: Phasor diagram for circuit in Fig. 18 at balanced operation at unity power factor.

generator described in the previous section. The capacitance $C = 0.860$ pu (actual value is 550 μF). The resistance R_L was omitted so all the power is being delivered to the utility. The generator voltage of 230 V line to line is used as the base, but the available utility voltage was actually a nominal 208 V. This explains why V_{ab} always has a value less than 1.0 pu, since the utility connection did not allow the generator voltage to reach 230 V.

At values of P_m near zero, the current I_a being supplied to the utility is also near zero. This forces I_b and I_c to have approximately the same magnitudes. As P_m increases, I_a increases in an almost linear fashion. The voltage V_{bc} across the capacitor and the current I_c through it remain essentially constant. The current in phase b decreases at first and then increases with increasing P_m. The voltage V_{ab} to the transformer increases from 0.92 pu to 0.99 pu as P_m increases, due to voltage drops in the transformer and wiring.

The current I_a reaches the machine rating at a value of P_m of about 0.6 pu. As mentioned earlier, a generator should supply up to two-thirds of its three-phase rating to a single-phase load, but because of lower efficiency the generator limit will be reached at a slightly lower value. For this particular machine, the three-phase electrical rating is about 32,500 W. Rated current was reached at 21,000 W as a single-phase machine or 0.646 of the three-phase rating. This is just slightly under the ideal value of 0.667.

The efficiency drops if a larger capacitor is used. This increases I_c, which increases ohmic losses in that winding without any compensating effect on the losses due to imbalance. A value of I_c of about half of rated seemed to give the best performance over this range of input power. This makes its value close to the average values of I_a and I_b for this range of P_m, which is probably close to the optimum value.

If there is enough power in the wind to drive the generator above two-thirds of its rating,

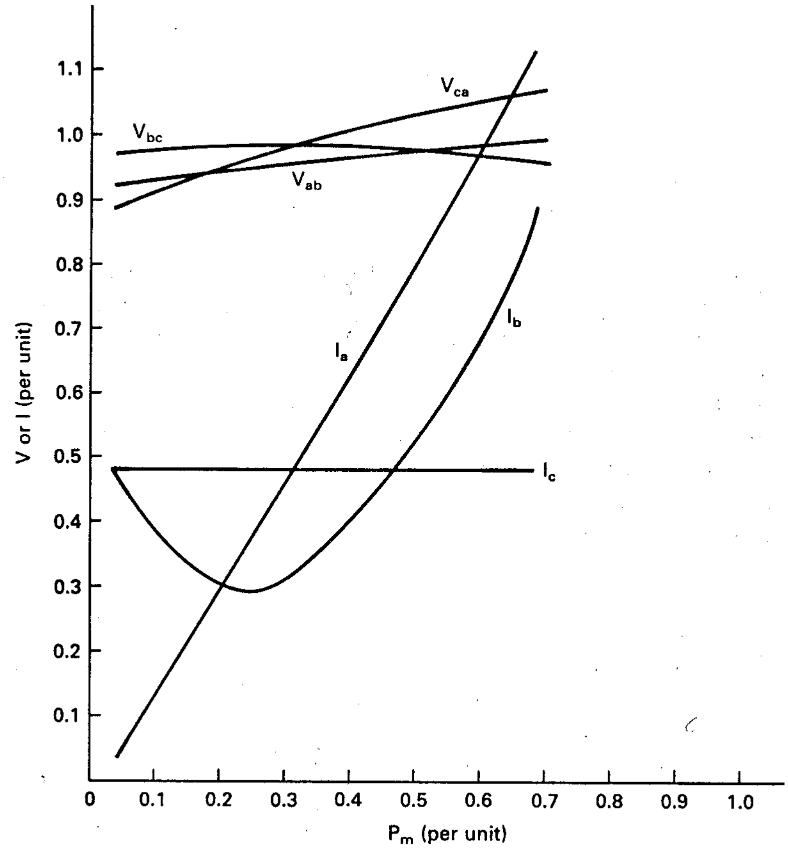

Figure 20: Variation of line-to-line voltages and line currents of 40-hp induction generator connected in circuit of Fig. 18. $R_L = \infty$; $C = 0.860$ pu.

then a resistance R_L can be added to draw off the extra power. As the total generator power increases, so does the reactive power requirements so utility power factor is improved if some additional capacitance is added in parallel with R_L. Figure 21 shows the variation in voltages and currents for $R_L = 3.72$ pu (actual value of R_L is 8.92 Ω) and $C = 1.09$ pu (actual value of C is 700 μF) for the circuit in Fig. 18. The voltage V_{bc} and the current I_c stay nearly constant, as before. The current I_b has a minimum at $P_m = 0.35$ pu and now I_a has a minimum at $P_m = 0.2$ pu rather than increasing monotonically as before. The important item to note is that the three currents and the three voltages are nearly equal at $P_m = 0.6$ pu. This indicates the generator is operating close to balanced conditions at this power level. Adjusting R_L and C will move this balance point either right or left. The balance point shown here is less than that for rated conditions, which means the generator will again be unbalanced when rated current is reached in one of the generator windings. In this particular case rated current is reached in line a for a total electrical power of 27,100 W or 0.834 of three-phase rating. A smaller resistance and a larger capacitance would be necessary to move the balance point toward that for rated conditions.

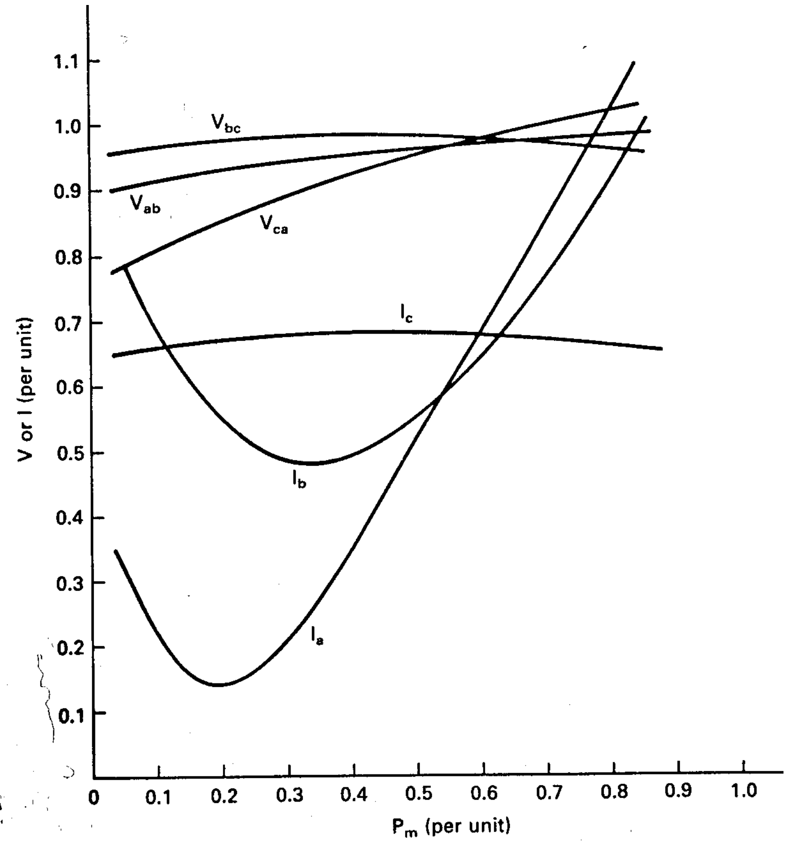

Figure 21: Variation of line-to-line voltages and line currents of 40-hp induction generator connected in circuit of Fig. 18. $R_L = 3.72$ pu, $C = 1.09$ pu.

We see that the three-phase induction generator supplies single-phase power to a utility in an effective manner by just adding a capacitor, or perhaps a capacitor and resistor, between phases b and c. It should be mentioned that the phase sequence connection is important. The phase sequence of the generator should be determined for its direction of rotation with a commercial phase sequence indicator and phases a and b (and *not* a and c) connected to the transformer, with the capacitor then connected between b and c.

Another important point is the matter of connecting the generator to the utility. As the brake is released on the wind turbine, acceleration may be quite rapid while there is no voltage or load on the generator. The single capacitor can produce self-excitation but this will probably not occur before the generator passes through synchronous speed. If the generator speed is substantially different from synchronous speed when the switch is closed, there will be both a mechanical transient on the turbine and an electrical transient on the utility. The generator may supply power levels well above rated to the utility while the generator is slowing down to operating speed. Such transients should be avoided as much as possible.

The proper connection procedure is therefore to sense generator speed and close the switch as close to synchronous speed as possible. For a four pole generator in the 20-50 hp range this should be done between 1800 and 1805 r/min. The mechanical impulse will be minimal with this approach but there will be a few cycles of high magnetizing currents while the magnetic flux is being established.

The same sensor can be used to disconnect the generator from the utility when generator speed falls below synchronous speed. This would mean that the generator has become a motor and is drawing power from the utility to operate the turbine as a large fan to speed air up on its passage through. This should be avoided for obvious economic reasons. The speed sensor therefore needs to be both precise and fast, able to disconnect the generator at, for example, 1798 r/min and reconnect it at 1802 r/min.

7 FIELD MODULATED GENERATOR

Thus far in this chapter we have considered the classical electrical machines that have been available for nearly a century. Other machines which have been developed in the last decade or two are also possibilities for wind turbine applications. One such machine is the field modulated generator developed at Oklahoma State University[11, 1].

This system uses a variable speed, variable frequency, three-phase generator to produce either single-phase or three- phase power at a precisely controlled frequency such as 60 Hz. The generator is operated at a high speed, perhaps 6000 to 10,000 r/min, and at a high frequency, at least 400 Hz. These machines were primarily developed for military applications where they have two significant advantages over conventional generators. One advantage is that they will operate nicely on simple gasoline engines with poor speed regulation in portable applications, and also when directly coupled to jet engines in aircraft. The other advantage is in the favorable kW/kg ratio obtained by higher speed operation. The power rating of a given size machine is directly proportional to speed or frequency so it is important to operate at a high frequency when weight is critical. This is why aircraft use 400 Hz rather than 60 Hz. Weight is not at all critical on wind turbines but the variable speed input, constant frequency output is of considerable interest.

The basic construction of the field modulated generator is that of the three-phase ac generator discussed in the previous chapter. Instead of the typical four poles and 1800 r/min, however, it may have 16 poles and be operated between 6000 and 10,000 r/min. The output frequency at 6000 r/min with dc applied to the rotor field would be $f = np/120 = 6000(16)/120 = 800$ Hz. In operation, the rotor field does not have dc applied to it but rather the desired power frequency, such as 60 Hz. The result in the generator output windings will be the same as in double- sideband suppressed-carrier modulation systems used in radio communications. Instead of 800 Hz there will be the sum and difference frequencies, 740 and 860 Hz. Therefore, the process of recovering the modulating or desired power frequency signal used in the rotor is simply one of demodulating and filtering the output waveform of the generator. The basic waveforms are shown in Fig. 22.

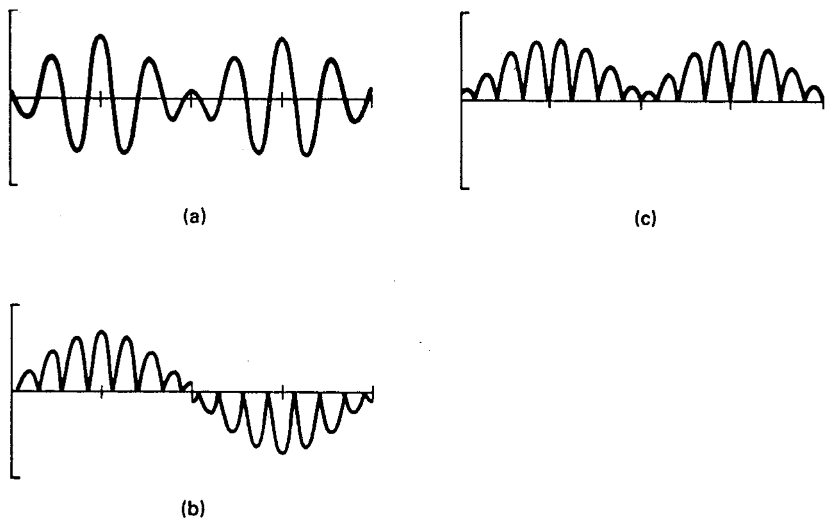

Figure 22: Waveforms of a field-modulated generator: (a) basic waveform; (b) basic waveform rectified; (c) basic waveform rectified and every other half-cycle inverted.

A simplified schematic of a field modulated generator with a single-phase output is shown in Fig. 23. At the far left is a field excitation source which supplies a sinusoidal signal to the field. The diode circuit in the field provides a signal of the same frequency but chopped off in amplitude at two diode drops, or about 1.4 V peak. It will be nearly a square wave and provides triggering information to the silicon controlled rectifiers in the generator output.

Tuning capacitors and a full-wave bridge rectifier are placed across the output of each phase of the generator. The output terminals of each of the three full-wave bridge rectifiers are tied in parallel and then fed into an SCR switching circuit. SCR1 and SCR4 will be turned on during one half cycle of the 60 Hz wave and SCR2 and SCR3 turned on the other half cycle. The desired power will flow into the transformer at the far right of the figure. The components L_1, C_1, L_3, and C_3 help to filter the higher frequency components out of the output waveform. The components L_2, C_2, SCR5, and SCR6 serve as a commutating circuit, to help the SCR switching network switch into a reactive load.

We have mentioned earlier that a three-phase generator needs a balanced load in order to maximize its output. This requires that each phase be conducting all the time, which is not obviously the case with the full-wave rectifiers tied together. It would be quite plausible to have one or two phases conducting at a time, with the remainder turned off because of a phase voltage that is too low during a portion of the cycle to overcome the output phase voltages of the other phases. With the proper choice of generator reactance and tuning capacitance, however, each phase will conduct for 360^o of an operating cycle. Therefore, at any instant of time all three phases of the generator are supplying current to the load, resulting in nearly

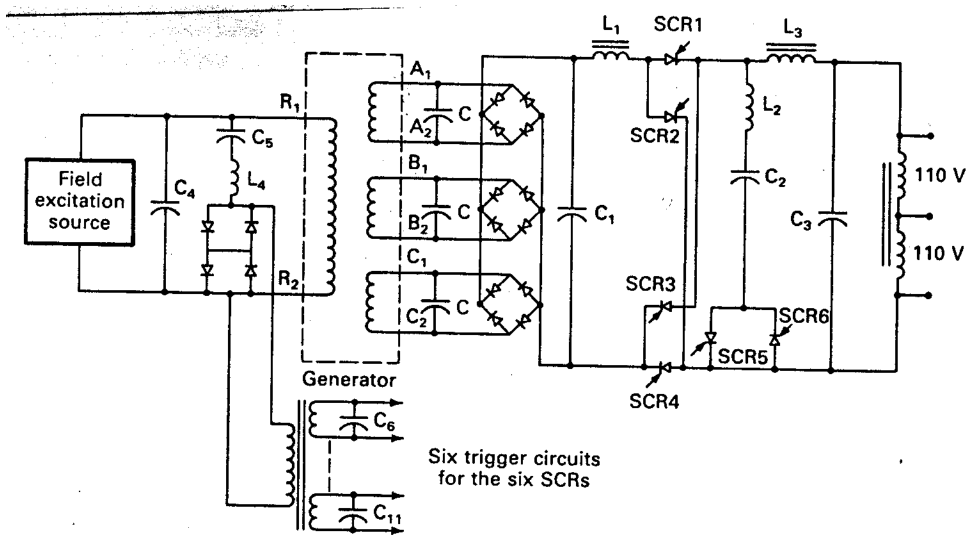

Figure 23: Simplified schematic of field-modulated generator.

balanced conditions as far as the generator is concerned.

The field modulated generator can also be used to generate three-phase power. This requires three separate rotor windings spaced along a single rotor, each with its own set of three stator windings. Each rotor winding is excited separately. Each set of three stator windings has the same electronics circuit as was shown in Fig. 23. The outputs of these three single-phase systems are then tied together to form a three-phase output.

Measured efficiency of a 60 kW field modulated generator tested at Oklahoma State University[1] was approximately 90 percent, quite competitive with other types of generators of similar size. The major disadvantage would be the cost and complexity of the power electronics circuit. It appears that this extra cost will be difficult to justify except in stand alone applications where precisely 60 Hz is required. Whenever frequency deviations of up to 10 percent are acceptable, induction generators or ac generators would appear to be less expensive and probably more reliable.

8 ROESEL GENERATOR

Another type of electrical generator which delivers fixed frequency power over a range of shaft speeds is the Roesel generator, named after its inventor, J. F. Roesel, Jr.[12, 9, 4]. To understand this generator we need to recall that the output frequency of all electrical generators is given by

$$f = \frac{np}{120} \tag{28}$$

where n is the rotational speed in revolutions per minute and p is the number of poles. All the electrical generators we have considered thus far have an even number of poles determined by physical windings on the generator rotor. This forces the output frequency to vary with the rotational speed. The Roesel generator is different in that the number of poles can be changed continuously and inversely proportional to n so that f can be maintained at a constant value.

The basic diagram of the Roesel generator is shown in Fig. 24. The stator, with its windings connected to an external load, is located on the *inside* of the generator. The rotor, which contains the field poles, rotates on the *outside* of the stator. The stator contains an excitation coil wrapped around the excitor head in addition to the usual output windings. The rotor is built in two layers, with the outer layer being high permeability laminated generator steel and the inner layer being a hard magnetizable material such as barium ferrite. Ferrites typically do not have the mechanical strength characteristics of steel, so this design helps to maintain mechanical integrity by having the steel carry the centrifugal forces. The ferrite would have to be much stronger if the rotor were inside the stator.

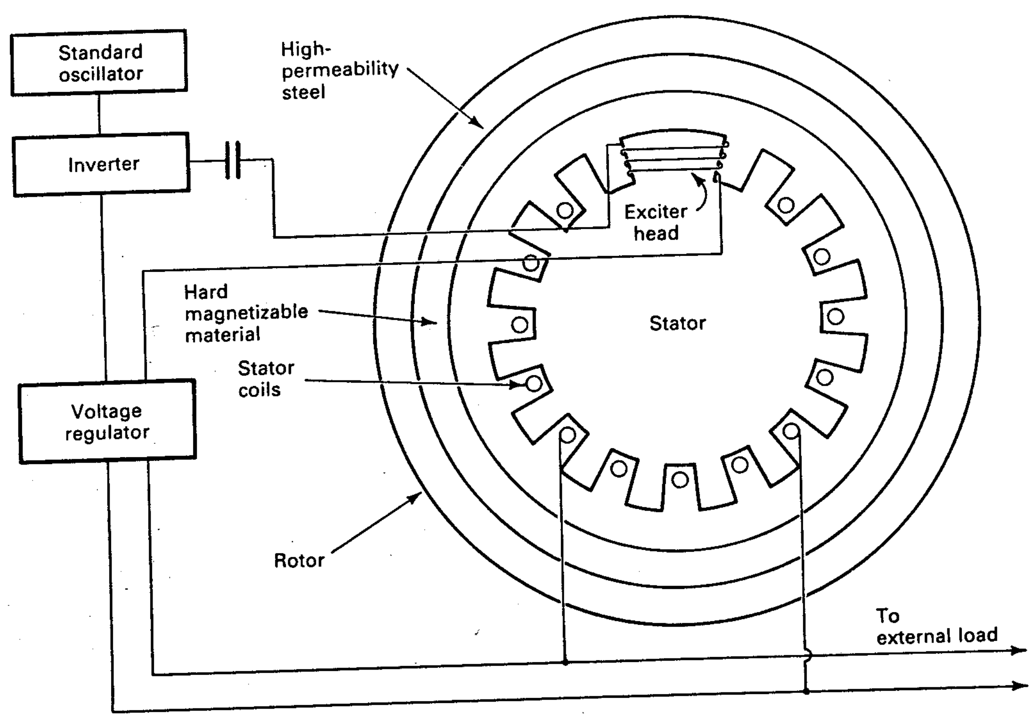

Figure 24: Basic diagram of Roesel generator.

A precise sinusoidal frequency is applied to the excitation coil and magnetizes a pole on the rotor as it turns around the stator. This is called *writing* a pole. This pole then induces a voltage in the stator windings at the same frequency. The output frequency then has the same precision as the input frequency, independent of shaft speed over a range of perhaps two to one. If the excitation coil is driven by a crystal controlled oscillator with a precision of 0.01 Hz, the output will have the same precision.

As rotor speed increases, the circumferential length of the poles increases, and fewer of them are written around the circumference of the rotor. As rotor speed decreases, the length of the poles shorten, so more of them are written around the periphery of the rotor. There will be an even pole synchronous speed where an even number of equal length poles are uniformly spaced around the rotor. At the other extreme, there will be an odd pole synchronous speed where an odd number of equal length poles are equally spaced around the rotor. Between these extremes there will be fractional poles in the vicinity of the excitor head as poles are being partially rewritten. At the even pole synchronous speed, the poles remain in the same position from one revolution to the next so no rewriting of poles actually takes place. There will be no rotor hysteresis loss in this case, since the rotor iron magnetization does not change with time. At the odd pole synchronous speed, however, every positive pole is being exactly replaced with a negative pole during each revolution, so rotor hysteresis losses will be a maximum at this speed. This loss can be made acceptably small with the proper choice of magnetic materials.

There is an inherent limitation to the range of allowable speeds with any Roesel generator. The stator will have windings that span a given fraction of the circumferential length. Performance will be best when rotor speed is such that one pole has the same circumferential length on the rotor as the stator winding has on the stator. At half of this speed there has to be twice as many poles on the rotor to maintain the same output frequency. We now have two poles spanning one stator coil, which produces a zero net magnetic flux in the coil. The output voltage now becomes zero since there is no time changing flux in the coil. The output voltage will also become zero at twice the original speed. That is, a Roesel generator with a nominal speed of 1800 r/min will have its output go to zero at 900 and 3600 r/min. Practical speed limits would probably be 1200 and 2800 r/min in this case. Voltage regulation would be possible over this range by changing the amplitude of the excitation current to thereby change the flux seen by the stator windings. Such a range of speed is more than adequate for most applications, including variable speed wind turbine generators.

The Roesel generator has several desirable features in its design. One is that there are no brushes or sliprings and no rotating windings. These features help to lower cost and improve reliability. Another feature is that the electronics only have to supply a single-frequency sinusoid of moderate voltage and current. No switching or filtering of the output power is required, with a resultant saving in cost as compared with the field modulated generator. Yet another advantage is that rotor speeds of perhaps 1200 to 1800 r/min represent good design values, as compared with the 6000 to 10,000 r/min of the field modulated generator. The lower speeds will simplify the gear box requirements and probably improve the overall efficiency.

Early versions of the Roesel generator, built in sizes of 1 to 10 kVA by the Precise Power

Corporation, demonstrated the technical feasibility of this concept. Development is continuing on larger sizes. Questions of generator efficiency, reliability, and expected life have not been fully answered but there seem to be no insurmountable problems.

9 PROBLEMS

1. The Jacobs Model 60 is a dc shunt generator used for charging 32-V batteries. It is rated at $I_B = 60$ A and $V_g = 40$ V at 300 r/min. The circuit is that of Fig. 2. Assume $V_B = 34$ V, $R_b = 0.1\ \Omega$, $R_a = 0.5\ \Omega$, and $R_f = 40\ \Omega$. Assume the diode is ideal and the load switch is open. The rotor diameter is 4.4 m and rated windspeed is 12 m/s.

   (a) Find E at 300 r/min when $I_B = 60$ A.

   (b) Find the generated power at 300 r/min

   (c) Find the electrical power delivered to the battery at 300 r/min.

   (d) Find the ratio of generated power P_e to the power in the wind P_w at rated load and rated windspeed. Assume standard conditions. (Note: The formula for P_w is given in Chapter 4.)

   (e) Find the rotor speed at which the batteries will just start to charge, ignoring armature reaction. Assume the generator is operating well into saturation so the flux is constant for small changes in I_f, which makes E vary only with rotational speed.

2. A three-phase PM generator connected into a resistive (unity power factor) load is rated at 5 kW, 225 V line to line, 60 Hz, at 1800 r/min. The no load voltage is 250 V line to line at 1800 r/min. The circuit is given in Fig. 5.

   (a) Find the rated current.

   (b) Find k_e of Eq. 15.

   (c) Assume $R_s = 0$ and find X_s.

   (d) What is the percentage change in P_e (given by Eq. 17) for a 10 percent decrease in speed, if the total three-phase power is 5 kW at 1800 r/min?

3. What is the rated power of the PM generator in the previous problem at 5400 r/min, assuming the rated current does not change with speed?

4. Zephyr Wind Dynamo Company sells a 15-kW, three-phase, 108-pole, 240-V, permanent-magnet ac generator for home heating applications where frequency is not critical. Rated power is reached at 300 r/min.

   (a) What is the frequency of the generated voltage at rated speed?

   (b) What rotor speed would yield an output frequency of 60 Hz?

(c) What is the machine power rating at 60 Hz, assuming rated current is the same at all frequencies?

5. A three-phase PM generator has a no load line-to-line voltage of 250 V at 60 Hz. It is rated at 5 kW, 225 V line to line at 60 Hz. It is connected into the series resonant circuit of Fig. 9. Assume the circuit is resonant at 60 Hz so E_a appears across R_a. Rated current is flowing. Find the necessary series capacitance C and the load resistance R_a. Evaluate P_e at 20 Hz and 40 Hz. Compare these values with the ideal values for a system where P_e varies as n^3.

6. A 100-kW three-phase ac generator has $X_s = 0.4\ \Omega$ when operated at 60 Hz. Rated terminal voltage is 230 V line-to-line. The circuit of Fig. 5 applies and the power output is assumed to be given by Eq. 21. The internal resistance R_s may be assumed to be zero.

   (a) Find the rated current.

   (b) Find the load resistance R_a which absorbs rated power at rated voltage and frequency.

   (c) Find L_s.

   (d) Find the change in P_e for a 10 percent decrease in frequency and also for a 10 percent increase in frequency. How does this compare with the optimum ω^3 variation?

7. A 50-hp three-phase induction motor costs \$1200 in 1982 dollars. The rated current is 58.5 A when connected as 460 V and 117 A when connected as 230 V. It is to be operated as a self- excited induction generator with the circuit shown in Fig. 10. The total reactive power required is 28 kvar reactive at full load and 60 Hz for either voltage. How much line-to-line capacitance is required for self-excitation with each connection, expressed as the total for all three legs? Discuss the economic advantages of using the higher voltage connection, assuming that 460 V (the only rating available) motor run capacitors cost \$0.50/μF.

References

[1] Allison, H. J., R. Ramakumar, and W. L. Hughes: "A Field Modulated Frequency Down Conversion Power System," *IEEE Transactions on Industry Applications*, Vol. IA-9, No. 2, March- April 1973, pp. 220-226.

[2] Bassett, E. D. and F. M. Potter: "Capacitive Excitation for Induction Generators," *Electrical Engineering*, May 1935, pp. 540-545.

[3] deMello, F. P. and L. N. Hannett: "Large Scale Induction Generators for Power Systems," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-100, No. 5, May 1981, pp. 2610-2618.

[4] Herman, L. R.: "The Roesel Generator, Constant Frequency with Variable Speed," Paper A 76 035-6, IEEE Power Engineering Society Winter Meeting, New York, January 25-30, 1976.

[5] Melkebeek, J. A. A., and D. W. Novotny: "Steady State Modeling of Regeneration and Self-Excitation in Induction Machines," IEEE Power Engineering Society Winter Meeting, New York, January 30-February 4, 1983.

[6] Melkebeek, J. A. A.: "Magnetising-Field Saturation and Dynamic Behavior of Induction Machines: Part 1. Improved Calculation Method for Induction Machine Dynamics," *IEE Proceedings*, Vol. 130, Pt. B, No. 1, January 1983, pp. 1-9.

[7] Melkebeek, J. A. A.: "Magnetising-Field Saturation and Dynamic Behavior of Induction Machines: Part 2. Stability Limits of a Voltage-Fed Induction Motor and of a Self-Excited Induction Generator," *IEE Proceedings*, Vol. 130, Pt. B, No. 1, January 1983, pp. 10-17.

[8] Mohan, N., and M. Riaz: "Wind-Driven, Capacitor-Excited Induction Generators for Residential Electric Heating," IEEE Power Engineering Society Winter Meeting, New York, January 29- February 3, 1978.

[9] Ott, R. R., R. J. Barber, and J. F. Roesel, Jr.: "The Roesel Generator: A Unique Variable-Speed, Constant-Frequency Generator," IEEE 75CH0964-7MAG.

[10] Ouazene, L., and G. McPherson, Jr.: "Analysis of the Isolated Induction Generator," IEEE Power Engineering Society Winter Meeting, New York, January 30-February 4, 1983.

[11] Ramakumar, R., H. J. Allison, and W. L. Hughes: "A Self- Excited Field Modulated Three-Phase Power System," Paper C 74 318-2, IEEE Power Engineering Society Summer Meeting, Anaheim, Calif., July 1974.

[12] Roesel, J. F., Jr.: *Electric Power Generator*, U.S. Patent 3,521,149, July 21, 1970.

[13] Seely, S.: *Electron-Tube Circuits*, McGraw-Hill, New York, 1958.

[14] Soderholm, L. H., and J. F. Andrew: *Field Control for Wind-Driven Generators*, U.S. Patent Application PB81-129,678, PAT- APPL-6-193 877, filed October 3, 1980.