# WIND POWER PLANTS

The production of large quantities of electricity will require the installation of many wind turbines. There are many economical benefits if these turbines are installed in the clusters that we call wind power plants or windfarms. That is, installation can proceed more efficiently than if the turbines are widely distributed. Operation and maintenance can be done with minimum personnel. Collection of the electricity generated can be accomplished efficiently. The larger amounts of concentrated power can be more easily transformed to higher voltages and distributed on the utility grid.

This chapter presents some of the features of clustering wind turbines. We will examine the placement of turbines in an array, the installation of the turbines, and the required electrical system. There will be some optimum design for which the energy output per dollar of investment is maximum. We shall see how to make such a design in this chapter.

## 1 TURBINE PLACEMENT

Turbines will typically be placed in rows perpendicular to the prevailing wind direction. Spacing within a row may be as little as two to four rotor diameters if the winds blow perpendicular to the row almost all the time. If the wind strikes a second turbine before the wind speed has been restored from striking an earlier turbine, the energy production from the second turbine will be decreased relative to the unshielded production. The amount of decrease is a function of the wind shear, the turbulence in the wind, the turbulence added by the turbines, and the terrain. This can easily be in the range of five to ten percent for downwind spacings of around ten rotor diameters. Spacing the turbines further apart will produce more power, but at the expense of more land, more roads, and more electrical wire.

We will define two turbine spacings, $D_{cw}$ as the *crosswind* spacing within a row of turbines, and $D_{dw}$ as the *downwind* spacing between rows of turbines. These are calculated as a constant times the number of rotor diameters $D_r$. The terms are shown in Fig. 1.

For the mid United States from Texas to North Dakota, it appears that a reasonable spacing is four rotor diameters between turbines in a row and ten rotor diameters between rows. The rows would be aligned across the prevailing wind direction, usually in a east-west direction in this part of the world where strong winds are usually from the north or south. We will consider that spacings less than $3D_r$ in a row or $8D_r$ between rows will need special justification.

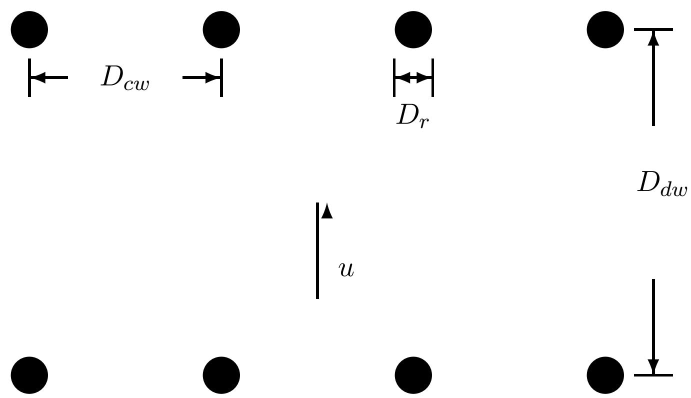


Figure 1: Dimensions of Turbines in a Windfarm

## 2 SITE PREPARATION

The first step in constructing a windfarm is to acquire the right to use the land. Land may be either purchased or leased, depending on the circumstances. Leasing land for energy production, such as oil or gas production, is common and well understood in this country. It holds the capital costs down to a minimum. It may be the only practical method of acquiring large tracts of ground from many owners if a large windfarm is planned. Depending on the type of turbine and the spacing, most of the land may still be usable for agricultural purposes. For example, a self supported multimegawatt turbine like the MOD-2 requires only a hectare or so (2-4 acres) around its base for maintenance. The probable density of this turbine would be perhaps 4 to 6 per square mile in the Great Plains, which would take less than 5 percent of the land out of production. Leasing should certainly be considered for such an installation.

On the other hand, multimegawatt turbines have not proven themselves cost effective, so windfarms are installed with smaller turbines, mostly in the 50 - 500 kW range. The smaller turbines will have a much greater density on the land and therefore interfere with farming operations to a greater extent. For example, the Carter 300, a guyed turbine rated at 300 kW, with a crosswind spacing of 4 diameters and a downwind spacing of 10 rotor diameters, would have 8 rows of 20 turbines each on a square mile of land. The access roads and guy wires would make it very difficult to grow row crops. It may be best to buy the land, plant it to grass to minimize erosion, and perhaps harvest the grass for cattle feed. The examples to be given later in the chapter will assume that the land is purchased.

In the Great Plains, land is typically sold by the square mile, called a section (640 acres), or by an integer fraction of a section. A half section contains 320 acres, a quarter section contains 160 acres, and so on. A quarter section can be split into two 80 acre tracts, with the dividing line either east-west or north-south. This places some constraints on the amount of land that must be purchased. If 80 acres is not enough, then the next allowable size is probably 160 acres. A half section would probably be the next step after a quarter section, and should be oriented east-west rather than north-south in order to take advantage of the prevailing winds. Land should always be estimated in increments of 80 acres.

Access roads will be required to each turbine, both for construction and for later maintenance. There may be some sites which do not require access roads because of rocky or sandy soil conditions, but most sites will require graded roads with a crushed rock or gravel surface so work vehicles can reach a turbine site in any kind of weather. The minimum length of access roads would be the total length of all the turbine rows plus the distance across the windfarm perpendicular to the rows plus the distance from the nearest existing road to the windfarm. Some turbine types, such as the Carter 300, may require two access roads per row of turbines. One road would be for access to the base of the turbine and the other road would be to reach the guy point from which the turbine is lowered to the ground for maintenance.

While the length of access roads and the length of electrical wire required to interconnect the turbines is easy to calculate for a given site with a given turbine layout, detailed economic studies involving different windfarm sizes, perhaps with different turbines, are more easily performed with simple formulas which determine these lengths for given assumptions. We will therefore develop the notation which will allow such studies to be performed in an efficient fashion.

We define the power rating of an individual turbine as $P_{tur}$ and the number of turbines in the windfarm as $N_{tfarm}$. The total power rating of the windfarm, $P_{wf}$, is then

$$P_{wf} = N_{tfarm} P_{tur} \tag{1}$$

Each row will have some length $D_{row}$ as determined by land and electrical constraints. In the Great Plains, county and township roads usually have a distance between road centerlines of one mile (5280 ft) so a row length of 5000 ft would allow the end turbines to be 140 ft from the road. This would usually be the practical maximum row length in this part of the world. The tentative number of turbines in a row, $N'_{trow}$, for a tentative row spacing $D'_{cw}$, would be given by

$$N'_{trow} = \frac{D_{row}}{D'_{cw}} + 1 \tag{2}$$

This calculation should be treated as integer arithmetic. That is, a result of 9.62 would be interpreted as either 9 or 10 turbines per row. Other constraints may require either a smaller or larger value. If four turbines are to be operated from a single transformer, for example, then it may be economically desirable to have the number of turbines in a row be some multiple of four, say 8 or 12 for our tentative calculation of 9.62 turbines per row.

One design choice which must be made is whether to hold the turbine separation at exactly four rotor diameters, for example, and let the row length be less than the maximum possible value, or to fill all available space and let the turbine separation differ from exactly four rotor diameters. One generally wants to use all available land but there may be cases where a small windfarm is to be installed on a large piece of ground that one would just use the nominal turbine spacing.

Once the actual number of turbines per row, $N_{trow}$, has been selected, along with the actual row length $D_{row}$, the actual turbine spacing in a row $D_{cw}$ is given by

$$D_{cw} = \frac{D_{row}}{N_{trow} - 1} \tag{3}$$

The number of rows and the corresponding length of a column of wind turbines, $D_{col}$, will be determined in a similar fashion. The size of the piece of land and zoning requirements will determine the maximum column length. The maximum number of rows would be used to compute the total number of turbines in the windfarm and the total electrical power rating. There may be financial or technical limitations on the number of turbines or the total power, so fewer rows may be necessary. There may also be a requirement for an even or odd number of rows for economic efficiency of windfarm layout. A rectangular piece of ground would be expected to have the same number of turbines in each row although local terrain features may require some turbines to be omitted from the spot they would otherwise occupy. There may need to be some iteration between the calculation of the number of turbines per row and the number of rows.

Once the column length $D_{col}$ and the number of rows $N_{rows}$ has been selected, the actual down wind spacing $D_{dw}$ can be calculated.

$$D_{dw} = \frac{D_{col}}{N_{rows} - 1} \tag{4}$$

The length of a rectangular fence around the perimeter of the wind farm would be

$$D_{fence} = 2(D_{row} + 2h_t + D_r) + 2(D_{col} + 2h_t + D_r) \tag{5}$$

where $h_t$ is the hub height of a turbine and $D_r$ is the rotor diameter. Increasing the fence length by the hub height plus half the rotor diameter on each side will allow each turbine to be laid down in any direction without the rotor striking the fence. If the turbines do not fill the entire purchased area, then the fence would be longer since it would normally be placed at the boundary. If a section of land was purchased, the length of fence would be approximately four miles.

## 3 ELECTRICAL NETWORK

We now turn our attention to the electrical network necessary to connect the wind turbines to the electric utility. Most wind turbines generate power at 480 V, three phase, a voltage too low to transmit long distances. One or more transformers will therefore be required to step up the voltage to the proper level.

The installation must be safe for people to operate and maintain. The wind farm must not adversely affect the utility, and likewise the utility must not damage the wind turbines by normal switching operations. The National Electrical Code (NEC) addresses many situations and may be considered a minimum standard (rather than a design handbook). That is, one can always add more safety equipment beyond the basic requirements of the NEC. The utility will probably require several protective relays and other devices in addition to the NEC requirements to insure compatibility with their system. Utility requirements will probably be higher at first, while wind farms are new, with some relaxation probable with favorable experience.

Cost is also an important factor, so the temptation to add unnecessary safety equipment should be resisted. Safety equipment can fail like any other equipment, so a complex system will require more maintenance than a simple system. A complex system is more difficult for the technician to understand and trouble shoot, increasing the possibility of human error and injury accident. It is good to ask why each utility requirement is listed, to make sure that each item will indeed improve either operator safety or equipment reliability. The same attitude may even be appropriate regarding some of the NEC requirements. For example, if the NEC requires a cable to be buried 24 inches, this would be a consensus figure for acceptable safety for people digging in the earth without knowing the location of the cable. It can be argued that a depth of 5 feet would be safer by a slight margin, but more expensive by a large margin. It may be that in the controlled space of a wind farm that 18 inches or even 12 inches would have acceptable safety. If the wind farm was located in an area with thin soil over thick rock ledges, the difference in cable burial depths could have a substantial cost difference with no significant difference in safety. In such cases, a request to the zoning authorities for a *variance* (formal authorization to construct in a manner different from code specification) might be appropriate.

We will now proceed to discuss the design of a simple windfarm electrical system. An actual design will be somewhat more complex because of local utility requirements or characteristics of the particular wind turbine that is used. We will not discuss details of metering or protective relaying. These are discussed in other courses. The intent is to present an overview of electrical system design, but with enough detail that the general design philosophy can be understood, a rough estimate of costs can be obtained, and the right questions can be asked if one does a complete design.

A one line diagram of a possible electrical system is shown in Fig. 2. There are actually three lines where one is shown because of the three- phase nature of the power system, but one line is easier to draw. The wind turbine generators are shown as small circles. These would have an electrical power output of $P_{tur}$, probably in the 30-500 kW size range. In this size range, the most likely voltage is 480 V line to line. The MOD-2 class of turbine would use the next higher voltage level of 4160 V line to line. The most common generator type would be the induction generator, but the synchronous generator could also be used, especially in the larger sizes where the field control equipment is not such a large fraction of cost.

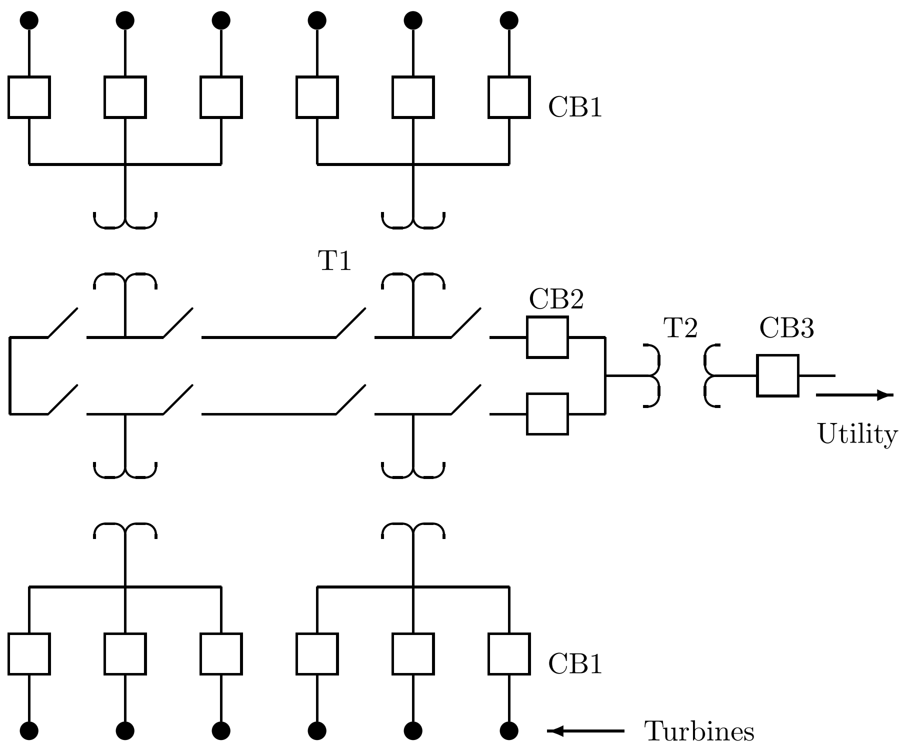


Figure 2: One Line Diagram of Windfarm Electrical Network

Buried conductors connect each generator to a low voltage circuit breaker, which is a part of what is called a unit substation. The circuit breaker must be electrically operated so the generator can be connected to the grid when the wind is adequate and disconnected automatically in low wind conditions. It might be an electromechanical device with a coil and movable contacts or it might be a solid state device with silicon controlled rectifiers doing the switching. The solid state circuit breaker may have greater reliability because of the large number of switching cycles which will be required. It could also be cheaper and easier to maintain.

Next to the bank of circuit breakers will be a stepup transformer to increase the voltage to an efficient level for transmission around the windfarm. The most common value for this will be the 12.47 kV level (line-to-line), with other possible values being 7.2 kV, 12.0 kV, 13.2 kV, and 13.8 kV. The high voltage side of the transformer contains two loadbreak switches for this loop feed circuit. A switch is different from a circuit breaker in that it cannot interrupt a fault current. It will be able to interrupt the rated current of the transformer, however. Both switches would be opened whenever it is necessary to work on the attached wind turbine, the circuit breaker, or the transformer. The advantage of the loop feed is that the remainder of the windfarm can be kept in operation while one unit substation is being repaired. It also allows for isolation of any section of underground cable that has a fault in it.

The two ends of the loop are connected to circuit breakers labeled $CB2$. These are connected together on the low voltage side of another stepup transformer which increases the voltage from 12.47 kV to that voltage required for transmitting power to the utility. This may be 34.5, 69, 115, 169, 230, or 345 kV, depending on the utility and the existing transmission lines near the windfarm site. There will be another circuit breaker CB3 on the high voltage side of this transformer, so the entire windfarm can be isolated from the utility if desired.

Figure 2 shows three turbines connected to each unit transformer. This number may be either smaller or larger depending on detailed economic studies. The transformers are a relatively expensive part of the distribution network and are proportionally less expensive in larger sizes, so it will probably be desirable to have $T_1$ be rated at perhaps 1000 kVA or even larger if available. This means that 20 to 30 turbines rated at 50 kVA could be connected to one transformer. The limitation to this would be the cost, losses, and voltage drops in very long sections of 480 V cable. A good windfarm design would include a check of at least two transformer sizes and the total cost of transformers plus underground cable for each size.

# 4 SELECTION OF SIZES, LOW VOLTAGE EQUIPMENT

Once the windfarm network is selected, sizes of transformers, circuit breakers, and conductors can be selected. These sizes will vary with the rating of the wind turbine and with the total number of turbines in the windfarm. Any rearrangement of the network of Fig. 2 will also cause sizes to be changed. The following discussion presents some of the key features of selecting component sizes, but should not be considered complete or adequate to actually prepare construction plans for a windfarm.

## Circuit Breakers

The circuit breaker $CB1$ of Fig. 2 might be designed and sold as a part of the wind turbine package, in which case it would not need to be considered here. Some manufacturers do not include it as a part of the turbine, so we will discuss it briefly. There are two separate functions required here. One is the interruption of high currents during a fault and the other is the more frequent connecting and disconnecting of the generator from the utility grid in daily operation. These functions are typically performed by two separate pieces of equipment, the first being called a circuit breaker, and the second being called a *contactor* or *starter*. They are normally mounted in a steel enclosure and sold as a package.

Table 9.1 shows some selected prices from a Westinghouse catalog for the Class A206 full voltage starter, sold as an enclosed combination with a circuit breaker. The prices are list for the year 1989. Actual costs may vary substantially from those listed, but the relative costs should be valid.

Table 9.1. Price list for motor starters

| NEMA Size | Rated Current | List Price |
|---|---|---|
| 0 | 18 | 906 |
| 1 | 27 | 936 |
| 2 | 45 | 1326 |
| 3 | 90 | 1896 |
| 4 | 135 | 4314 |
| 5 | 270 | 9627 |
| 6 | 540 | 19659 |
| 7 | 810 | 26403 |
| 8 | 1215 | 38745 |
| 9 | 1800 | 51273 |

The left hand column shows the NEMA (National Electrical Manufacturers Association) size. The larger sizes indicate larger enclosures with greater rated currents, shown in the next column. Each NEMA size can be purchased for nominal motor voltages of 200, 230, 460, and 575 V. The corresponding nominal line voltages are 208, 240, 480, and 600 V. A windfarm in the United States would most likely use 480 V.

There are actually several different types of enclosures. For example, the general purpose enclosure would be used in indoor, dry locations. The watertight enclosure would be used in very wet locations, like a dairy barn where a high pressure hose may be used to clean equipment. The hazardous location starter would be used in grain elevators or refineries where dust or fumes could be a problem. The values given in this table are for a dust tight and rain proof enclosure which would be appropriate for a windfarm.

The turbine generator should have a rated operating current listed on its nameplate. If not, this can be computed from the maximum generator power and the voltage. For a voltage of 480 V and a power of $P_{tur}$, this is

$$I_{trat} = \frac{P_{tur}}{\sqrt{3}(480)\cos\theta} \tag{6}$$

If the power factor $\cos\theta$ is not specified, it can be assumed as being about 0.85 without serious error.

The circuit breaker $CB1$ would be located at the base of the turbine tower if supplied by the turbine manufacturer or at $T_1$ if supplied by the windfarm developer.

## Wire Sizes

Once the circuit breaker is selected, we must choose underground conductors with adequate ampacity to go between the turbine and the transformer $T_1$. *Ampacity* refers to the ability of a conductor to safely carry a given current. That is, the surrounding medium must be able to carry away the heat generated in the conductor without the conductor insulation getting too warm. The 1990 National Electrical Code (NEC) listed 27 different types of conductor insulation, ranging from an operating temperature of $60^o$ C for types TW and UF to $250^o$ C for types PFAH and TFE. Ampacity of a given size conductor increases with the temperature rating of the conductor insulation.

The ampacity also varies with the surrounding medium and its ability to conduct heat away. The ampacity of a conductor buried in wet soil (swamps, coastal regions) is about double the ampacity of the same size conductor buried in very dry soil. The pattern of load flow also makes a significant difference. Starting at ambient temperatures, it requires a day or two of full rated current flow to raise the conductor temperature to its final temperature. This time period is called the *thermal time constant*. Windfarms rarely operate at rated conditions for more than 24 hours continuously, so only extended periods of high winds would be expected to raise the temperature of windfarm wiring to the thermal limit of the insulation, if the conductors were designed for 100 percent load factor.

Given all these factors, it is very difficult to specify a fixed value of ampacity for a given conductor that will apply in every situation. The NEC recognizes this situation and allows engineers with the appropriate training in soils and heat transfer to choose wire sizes based on a detailed analysis for a given installation. Most students in this course do not have such a background, so we will use a NEC table (B-310-10 in the 1990 NEC) that has been prepared for average conditions. Selected values from this table are reproduced in Table 9.2. It applies to the case of three single insulated conductors rated at less than 2000 V which are direct buried in the earth. The ambient earth temperature is assumed to be $20^o$ C, the load factor is assumed to be 100 percent, and the thermal resistance is assumed to be 90. This value of thermal resistance applies to perhaps 90 percent of the soils in the U.S.A. It varies from about 60 for damp soil (coastal areas, high water table) to about 120 for very dry soil.

This table shows ampacities for both copper and aluminum cables. Copper has a higher ampacity for a given wire size but aluminum cables of the same ampacity are perhaps 30 percent cheaper than copper cables. Aluminum cables require special attention at fittings because of the tendency of aluminum to cold flow under pressure. They also require special care because of oxidation problems. At the present time, copper is used for most indoor wiring, except perhaps for the very large sizes, and aluminum is used for most outdoor wiring, both overhead and underground.

Cables are sized according to AWG (American Wire Gauge) or kcmil (thousands of circular mils). A circular mil is a measure of area, like $\mathrm{m}^2$ or acres. It is determined by squaring the diameter of a cylindrical conductor when expressed in thousandths of an inch. That is, a cylindrical conductor of diameter 0.5 inch (or 500 mils) would have an area of $(500)^2$ =

250,000 circular mils = 250 kcmil.

Table 9.2. Ampacities of three single insulated conductors, 600 V class.

| | COPPER | | ALUMINUM | |
|---|---|---|---|---|
| AWG kcmil | one circuit | two circuits | one circuit | two circuits |
| 8 | 98 | 92 | 77 | 72 |
| 6 | 126 | 118 | 98 | 92 |
| 4 | 163 | 152 | 127 | 118 |
| 2 | 209 | 194 | 163 | 151 |
| 1 | 236 | 219 | 184 | 171 |
| 1/0 | 270 | 249 | 210 | 194 |
| 2/0 | 306 | 283 | 239 | 220 |
| 3/0 | 348 | 321 | 272 | 250 |
| 4/0 | 394 | 362 | 307 | 283 |
| 250 | 429 | 394 | 335 | 308 |
| 350 | 516 | 474 | 403 | 370 |
| 500 | 626 | 572 | 490 | 448 |
| 750 | 767 | 700 | 605 | 552 |
| 1000 | 887 | 808 | 706 | 642 |
| 1250 | 979 | 891 | 787 | 716 |
| 1500 | 1063 | 965 | 862 | 783 |
| 1750 | 1133 | 1027 | 930 | 843 |
| 2000 | 1195 | 1082 | 990 | 897 |

Older literature will show the units of thousands of circular mils as MCM rather than kcmil. The first "M" in MCM stands for the Roman unit of one thousand, and would be a translation of the Greek *kilo* for the same quantity. Changing the name of the unit from MCM to kcmil is a big improvement because it allows a consistent use of multipliers. Using English units is bad enough without also using the Roman notation for multipliers!

The AWG numbers get smaller as the cable diameter gets larger, which is always confusing to the newcomer. There are also four AWG sizes larger than the AWG number 1, which is also confusing. These are 0, 00, 000, and 0000, (or 1/0, 2/0, 3/0, and 4/0) pronounced one ought, two ought, three ought, and four ought. See Appendix C for a more detailed discussion of wire sizes and resistance.

This ampacity table is for insulation rated at $75^o$ C. Higher temperature insulations can also be used, as mentioned earlier, but this is a commonly used value, mostly for economic reasons.

The headings of the columns refer to "one circuit" and " two circuits". The one circuit case for a three-phase system requires three conductors, plus a neutral conductor of the same size. The neutral carries a very small current in normal operation, so does not enter into the thermal calculations. A trench is dug, perhaps 18 inches wide by 24 to 36 inches deep. A layer of sand is placed on the bottom, to prevent mechanical damage to the conductor insulation from sharp rocks. The three phase conductors are laid in the trench with a nominal separation of 7.5 inches. The neutral conductor is placed anywhere in the trench. Another layer of sand is placed on top of the four conductors before the trench is backfilled with dirt.

If the ampacity of a single circuit is not adequate for a particular installation, a second circuit is added in parallel with the first. The conductors of each circuit must be the same size, so that both the resistance and inductive reactance of each circuit will be the same, so that current will divide evenly between the circuits. The trench for the double circuit case is much wider, approximately 60 inches, to allow a separation of at least 24 inches between circuits. Even with this separation, the heat dissipated by one circuit will raise the temperature of the other circuit. This lowers the allowable ampacity. For example, a 4/0 aluminum circuit will carry 307 A in isolation, but only 283 A when a second circuit is 24 inches away.

The table should have a correction factor applied when the ambient temperature is different from $20^o$C. At a depth of 36 inches, the ambient soil temperature has a rather small annual variation, being very close to the annual average air temperature above the soil. It makes sense that circuits in Minnesota could carry more current that similar circuits in southern Arizona since the soil temperatures will be different. For example, if the ambient temperature is less than $10^o$C, the ampacity is increased by 9 to 12%, while if the ambient temperature is greater than $26^o$C, the ampacity is reduced by 10 to 13%.

Once we find the rated current of the turbine from Eq. 6, we are ready to find the rated current of the conductors connected to the turbine. These currents are not necessarily identical because of code requirements. The National Electrical Code requires "The ampacity of the phase conductors from the generator terminals to the first overcurrent device shall not be less than 115 percent of the nameplate current rating of the generator", Article 445-5. One reason for this rule is that generators can be operated above their rating by as much as 15% for extended periods of time, and we would not want the conductors to fail before the generator. This rule only applies to this particular section of wire. The remainder of the windfarm circuits are sized according to actual current flow.

For example, a 100 kW, 480 V generator with a power factor of 0.8 will have a rated current of 150 A. We assume that the conditions of Table 9.2 apply. The cable needs a rating of $(1.15)(150) = 173$ A. This is met by a single circuit of AWG 2 copper at 209 A, or by a single circuit of AWG 1 aluminum at 184 A. It is also met by a double circuit of two AWG 8 copper conductors in parallel, which will carry $2(92)$ A $= 184$ A, which would meet the generator requirements. Two AWG 6 aluminum conductors in parallel will have the same ampacity.

In smaller wire sizes, the cost of the extra (or wider) trench probably makes a double circuit more expensive than a single circuit. For larger wire sizes, a double circuit may be less expensive and even essential to get the required current. Doubling the wire size does not double the ampacity. For example, a single circuit of 1000 kcmil copper will carry 887 A, while a double circuit of 350 kcmil copper will carry 2(474) = 948 A. The double circuit case requires seventy percent of the copper ((2)(350) = 700 as compared with 1000 kcmil) and will carry seven percent more current in this case. This saving in copper can easily pay for the cost of a second trench.

## Transformers

The next element to be sized is the transformer $T_1$. Transformers are always rated in terms of kVA (or MVA) so we have to convert from the generator rating in kW by using the power factor. If the generator is rated at 100 kW with a power factor of 0.8, the kVA rating would be 100/0.8 = 125 kVA. Since $N_{tc}$ generators are connected to a transformer in this cluster network, the transformer rating would be $N_{tc}$ times this value. Actual available ratings may not match this calculated value, of course. Table 9.3 gives the available sizes and 1991 prices for a popular manufacturer of three-phase distribution transformers.

These particular transformers are padmounted, that is, mounted on a small concrete pad at ground level. They are built as three-phase transformers rather than individual single-phase transformers connected in three-phase.

There are two choices as to the type of connection, either radial feed or loop feed. Radial feed refers to a single path between source and load. If a transformer or distribution line along this path is not operative, then there will not be any electrical service downstream from this point. This connection is cheap and simple, and most residential loads are served from a radial feed for this reason.

Table 9.3. Transformer costs, 480Y/12470Δ

| kVA | NLL | LL | COST |
|---|---|---|---|
| 112.5 | 334 | 834 | $4500 |
| 150 | 353 | 1170 | 5000 |
| 225 | 481 | 1476 | 6000 |
| 300 | 554 | 1872 | 6500 |
| 500 | 817 | 2982 | 8000 |
| 750 | 1112 | 5184 | 10000 |
| 1000 | 1364 | 5910 | 12500 |

| Adders per transformer for: | |
|---|---|
| Loop Feed | $600 |
| LBOR Switches | 500 |
| Lightning Arresters | 400 |

A loop feed, on the other hand, allows electrical power to reach a transformer in one of two paths, as was shown in Fig. 2. A short in a buried distribution line can be isolated in a loop so that repair work can proceed without power production from any turbine being interrupted. A loop connection is therefore very desirable if it can be justified economically. A windfarm with two transformers $T_1$ may not be able to justify a loop but one with ten or more transformers would almost certainly need a loop. This adds a total of \$600 to the cost of each $T_1$, as seen in Table 9.3.

The switches in a loop are typically of the LBOR (loadbreak oil rotary) type. There are two switches, one for each direction of the loop. Each switch has two positions, on and off. If one switch is on and the other is off, power is coming to the transformer from only one direction and the loop is open at this point. If both switches are off the loop is open and the transformer and the associated wind turbines are not energized. If it is desired to have the loop closed at this point but for the transformer to not be energized, then the circuit between the loop and the transformer must be opened with another device, typically a fuse on the transformer itself. Two of these LBOR switches costs an additional \$500 over the base cost of the transformer.

Also important are lightning arresters, which are devices connected between a phase conductor and ground which start to conduct when the voltage exceeds some rated value, as will happen when lightning strikes the conductor. In a windfarm, lightning will probably hit one of the wind turbines rather than a padmounted transformer or a buried distribution cable, so arresters may not be absolutely essential at this point. However, the windfarm location is likely to be the highest point within several miles, with poorly conducting soils (or rocks). Every thunderstorm is likely to produce several lightning strikes within the confines of the windfarm. Given the unpredictability of lightning, it is probably wise to put arresters on each transformer, at an additional cost of \$400.

The column labeled NLL indicates the No Load Losses for each transformer. The 750 kVA transformer consumes 1112 W continuously while energized, even when no power is flowing through the transformer. This means that 9741 kWh will be dissipated as heat in a one year period, if the transformer is continuously energized. If electricity is worth \$0.05/kWh, this amounts to \$487/year, or almost 5% of the initial cost of the transformer. Less efficient transformers can be manufactured at a lower price, but these can rarely be justified by a careful economic analysis.

The next column, labeled LL, shows the Load Losses in watts for full load conditions. These are the copper losses for the transformer. (We refer to $I^2R$ losses as copper losses even if the transformer is actually wound with aluminum wire.) The economically optimum ratio of LL/NLL depends on the price of electricity and on the duty factor of the transformer. A transformer which is only occasionally operated at full load can have a somewhat higher value of LL as compared with the transformer being operated with a very high duty factor. The values given in Table 9.3 are close to the economic optimum for a typical utility in 1991.

Suppose that the combined rating of a cluster of wind turbines is not exactly equal to a nominal transformer rating. Should we select the next larger size of transformer, or might we get by with the next smaller size?

*Example*

Assume that we have five turbines rated at 50 kVA each. Should we select a 300 kVA transformer or a 225 kVA transformer?

The smaller transformer would be operated at 11 percent over its rated value during the times when all turbines were operating at full power. We would save \$6500 - \$6000 = \$500 of initial cost, and 554 - 481 = 73 W of no load losses, amounting to 648 kWh/year. The load losses are higher, of course. Copper losses are proportional to the square of the current, and the current is proportional to the load kVA (since voltage is essentially fixed). Therefore the copper losses at 250 kVA would be, for each transformer,

$$P_{\text{loss},225} = \left(\frac{250}{225}\right)^2 (1476) = 1822 \ \text{W}$$

$$P_{\text{loss},300} = \left(\frac{250}{300}\right)^2 (1872) = 1300 \ \text{W}$$

The transformers must be operated at this power level for over 1200 hours per year before the extra copper losses exceed the reduced eddy current and hysteresis losses (no load losses) of the smaller transformer. The larger transformer will always have smaller load losses than the smaller transformer for the same load, but the total loss will be less for the smaller transformer whenever the load is less than about 20% of rated. This will be the situation for more than half the time at most wind farms, so a detailed economic study could easily show the smaller transformer to be the economic choice.

But what about damage to the transformer by operating it in an overloaded condition? It turns out that these transformers can be operated at 113 percent of rated power for up to four hours in ambient temperatures of $40^o$ C ($104^o$ F) without a reduction in normal life. This would be a no wind condition, but full power operation in a windfarm would always be accompanied by strong winds with resultant cooling. Also it would be rare indeed for full power to be maintained for over four hours at temperatures as high as $40^o$ C. Lower ambient temperatures would also increase the allowable overload. Therefore, it may be appropriate to select a transformer with a rating up to about 10 percent smaller than the generator rating, rather than the next size larger. If this is done, it may be necessary to monitor the transformer temperature during extended periods of high power operation. If the transformer temperature should exceed a safe level, one of the turbines can be shut down until the transformer has cooled down.

# 5 SELECTION OF SIZES, DISTRIBUTION VOLTAGE EQUIPMENT

The next step is to select the wire size on the high voltage side of $T_1$. The rated current is determined from

$$I = \frac{S_{wf}}{\sqrt{3}V} \tag{7}$$

where $S_{wf}$ is the total three-phase VA of the turbines connected to each loop and $V$ is the high side line to line voltage. For the case of 10,000 kVA and a high side voltage of 12,470 V, this is a current of 464 A. The conductor in the loop type circuit needs to be sized to handle all the current of all the generators in case one of the circuit breakers $CB2$ is open.

The appropriate tables in the NEC then need to be consulted. These are Tables 310-81 and 310-82 of the 1990 NEC for copper and aluminum conductors, respectively. The ampacity values for conductors rated at 15 kV are summarized in Table 9.4. The table also includes ampacities for three conductors in a trench or six conductors in two adjacent trenches (or a single wide trench), similar to the low voltage case discussed in the previous section.

Table 9.4. Ampacities of buried conductors, 15 kV class

| AWG | COPPER | | ALUMINUM | |
|---|---|---|---|---|
| kcmil | one circuit | two circuits | one circuit | two circuits |
| 6 | 130 | 120 | 100 | 95 |
| 4 | 170 | 160 | 130 | 125 |
| 2 | 210 | 195 | 165 | 155 |
| 1 | 240 | 225 | 185 | 175 |
| 1/0 | 275 | 255 | 215 | 200 |
| 2/0 | 310 | 290 | 245 | 225 |
| 3/0 | 355 | 330 | 275 | 255 |
| 4/0 | 405 | 375 | 315 | 290 |
| 250 | 440 | 410 | 345 | 320 |
| 350 | 535 | 495 | 415 | 385 |
| 500 | 650 | 600 | 510 | 470 |
| 750 | 805 | 740 | 635 | 580 |
| 1000 | 930 | 855 | 740 | 680 |

The required wire size for a 10,000 kVA collection of turbines (rated current 464 A at 12.47 kV) would be a single circuit of 500 kcmil aluminum, or a double circuit of 3/0 aluminum. The double circuit case would have about half the aluminum of the single circuit case because of better heat transfer characteristics. For typical costs of aluminum conductors and trenching, the single circuit configuration is least expensive up to wire size AWG 4/0, which represents a kVA rating of $\sqrt{3}(12.47)(315) = 6804$ kVA. For a slightly higher rating, say 7200 kVA, it is cheaper to use a double circuit with wire size AWG 1.

Table 9.4 shows that the maximum allowable current is 680 A per circuit for the double circuit case, or a total of 1360 A. This would correspond to a kVA rating of $\sqrt{3}(12.47)(1360)$

= 29,400 kVA. A windfarm with a rating larger than this would need to have two loops, each loop having two circuit breakers $CB2$ connected to the low voltage bus on transformer $T_2$. It might be cheaper and more efficient to design for two loops for power levels well under this level. Two single circuit loops of approximately the same length as one double circuit loop would certainly be cheaper. The question would be whether the savings in cable would offset the cost of two additional circuit breakers.

Costs for underground conductors in dollars per 1000 ft are given in Table 9.5. The table includes both the 600 V and the 15,000 V rating. The former would be used between the turbine and the transformer $T_1$ and the latter after $T_1$. The thicker insulation of the 15 kV conductor obviously makes it substantially more expensive. There will be three of these conductors in a three-phase circuit (six for the double circuit case), so these prices must be multiplied by three (or six) to get the circuit cost per foot. The price of the 15 kV wire includes a neutral wrapped around the insulation of each conductor, so no additional neutral wire needs to be purchased.

In addition to the cost of conductors, we have the cost of trenching. This will cost about one dollar per foot for the single circuit case in good trenching situations and more where there are rocks or other problems. The cost of trenching will approximately double for the double circuit case.

Table 9.5. Underground aluminum conductor cost in dollars per 1000 ft of conductor

| Size | 600 V | 15 kV |
|---|---|---|
| 6 | $107 | |
| 4 | 135 | |
| 2 | 178 | $690 |
| 1 | 253 | 780 |
| 1/0 | 287 | 860 |
| 2/0 | 303 | 1070 |
| 3/0 | 363 | 1280 |
| 4/0 | 425 | 1500 |
| 250 | 585 | 2060 |
| 350 | 799 | 2800 |
| 500 | 1100 | 3850 |
| 750 | 1600 | 5300 |
| 1000 | 2063 | 7220 |

The total trench length required for both the low voltage and distribution voltage circuits can be best calculated from a sketch of the site layout. For cases where several turbines are to be connected to one unit transformer it would be wise to check total trench length for more than one possible configuration. For example, if eight turbines are to be connected to one transformer, is it better to put all eight in one row, or should the transformer be connected to four turbines in one row and four in the adjacent row? We will try to answer this question by example to illustrate the procedure for other configurations.

Figure 4 shows the trenches needed for the 8 turbines connected in one long row or two short rows. The transformer $T_1$ is physically small compared with $D_{cw}$, and so is the separation between adjacent trenches. Such small corrections will be ignored in this analysis, but allowance should be made for splices, connections, vertical runs of cable, and crooked trenches when actually ordering the cable. The two turbines nearest to $T_1$ require a trench length of only $0.5D_{cw}$ in the 1 by 8 configuration, but the two most distant turbines require a trench length of $3.5D_{cw}$. Separate trenches are required because of heating effects. The total trench length for this configuration is then $16D_{cw}$.

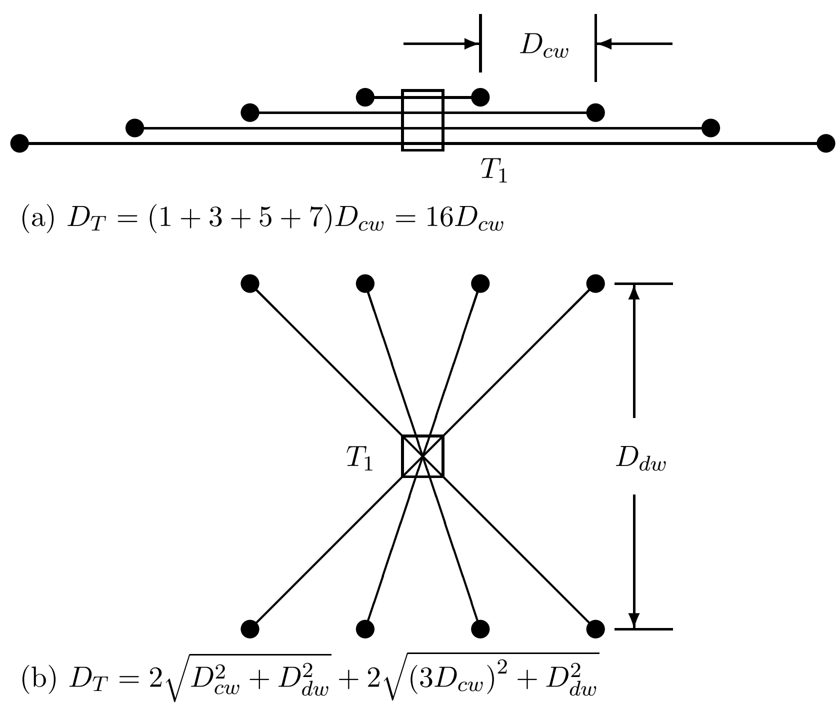


Figure 3: Trench lengths for low voltage wiring for 8 turbines in $1 \times 8$ and $2 \times 4$ configurations.

When the turbines are connected in a $2 \times 4$ configuration, the nearest turbines require a greater trench length while the most distant turbines require shorter trenches than the most distant turbines of the $1 \times 8$ configuration. Simple square roots are used to find the trench lengths, with the formula for this particular case shown in Fig. 3. No universal comparison can be made without knowing both $D_{cw}$ and $D_{dw}$, or at least their ratio. For the case where the downwind spacing is 2.5 times the crosswind spacing, the trench length for this configuration is $13.2D_{cw}$, an 18 percent reduction from the $16D_{cw}$ of the 1 by 8 configuration. This reduces both first cost and operating cost by reducing losses, so the $2 \times 4$ would be preferred over the

$1 \times 8$ for this $D_{dw}/D_{cw}$ ratio.

The $2 \times 4$ configuration also has the advantage of lowering the voltage drop from the most distant turbines, and also making the low voltage drop more nearly equal among all the turbines. The ampacity tables presented earlier deal only with heating effects and do not answer the question as to the acceptability of the voltage drop. Voltage drops will be considered in more detail in the next section.

The choice of low voltage configuration will also impact the distribution voltage circuit. This is illustrated in Fig. 4 for the case of 32 turbines in 4 rows of 8 turbines each. Four unit transformers $T_1$ are required in either case. The solid line shows the minimum trench length for the $1 \times 8$ configuration. There will be parallel trenches, with the cable serving as the return for the loop going through the transformer enclosure without physical connection. The dashed line shows the trench layout for the $2 \times 4$ configuration, with the arrows indicating a possible location for the transformer $T_2$. The bottom portion of the loop would actually be located close to the bottom row of turbines, rather than where it is drawn in the figure. The trench length for the $1 \times 8$ configuration is $6D_{dw}$, and $5D_{dw} + 8D_{cw}$ for the 2 by 4 configuration. Using the example of $D_{dw} = 2.5D_{cw}$, the $2 \times 4$ requires $20.5D_{cw}$ while the $1 \times 8$ requires $15D_{cw}$ of trench. Therefore the $1 \times 8$ is better in the distribution voltage trench and poorer in the low voltage trench requirements. It appears necessary to check several possible designs before concluding that one is superior to the others.

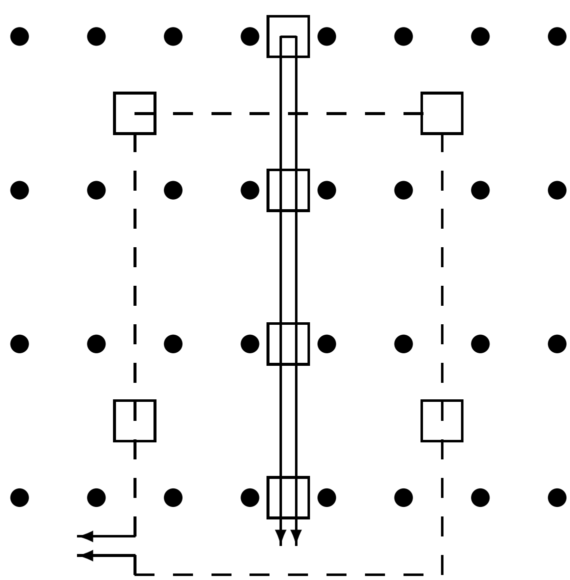

Figure 4: Trench lengths for distribution voltage wiring for 32 turbines in 4 rows, for both $1 \times 8$ and $2 \times 4$ low voltage configurations.

Distribution voltage trenches are shown which do not cross the low voltage trenches. This is not an absolute technical requirement, but doing it will certainly remove the hazard of low voltage cable crossing over high voltage cable.

After the trench lengths are determined, the circuit breaker $CB2$ must be selected. It is quite possible that a good design will result in a rated loop current of 500 A or less. When we go to the catalog to find a breaker with this rated current, however, we are surprised to find that the minimum rating is 1200 A, with only two other choices, 2000 and 3000 A. The reason for this is the strength requirements for withstanding large fault currents. Depending on the impedance of the source, a circuit breaker may be required to interrupt between 10,000 and 50,000 A. It takes a finite amount of time to detect the fault, send a signal to the breaker, mechanically move the contacts, and extinguish the arc, and during this time the contacts must withstand this fault current. Contacts large enough to withstand such fault currents are large enough to handle at least 1200 A on a continuous basis. The breaker can be operated on any value of current less than this, of course. Estimating prices for circuit breakers are shown in Table 9.6.

The transformer $T_2$ will step up the windfarm distribution voltage to the value necessary to tie into the utility's transmission network. Transformers of this size are not shelf items. Many options must be specified at the time of ordering, and then a specific price can be quoted. We shall present the basic procedure used by Westinghouse to illustrate the concept.

The list price for a Westinghouse three-phase transformer with rating 2500 kVA or larger is given by the formula

$$C = C_1 M_2 M_3 M_4 (1 + PA/100) + C_6 + C_7 \tag{8}$$

where $C_1$ is the base list price, $M_2$ is an efficiency multiplier, $M_3$ is an operating voltage multiplier, $M_4$ is a frequency multiplier, $PA$ are the percentage adders, $C_6$ is the cost of load tap changing equipment, and $C_7$ is the cost of various dollar adders. We shall briefly discuss each of these items.

Table 9.6. Cost of Three-phase circuit breakers.

| Voltage, kV | Current | Cost |
|---|---|---|
| 12.47 | 1200 | $12,000 |
| 34.5 | 1200 | 27,450 |
| 34.5 | 2000 | 29,640 |
| 69 | 1200 | 29,540 |
| 115 | 1200 | 62,310 |
| 115 | 2000 | 67,880 |
| 161 | 1200 | 85,465 |
| 161 | 2000 | 99,950 |
| 230 | 2000 | 119,815 |
| 345 | 2000 | 237,750 |

The base list price is determined either by a table lookup or by a formula. The formula used is

$$C_1 = 19800(\text{MVA})^{0.75} + 1.55(\text{BIL}_{\text{kV}})^{1.75} \tag{9}$$

where BIL refers to the Basic Impulse Level expressed in kV. It is a measure of the ability of the transformer to withstand high transient voltages without the insulation breaking down. A 69 kV transformer might have a BIL of 350 kV, for example.

The BIL for a nominal system voltage is shown in Table 9.7.

Table 9.7. Basic impulse levels.

| Nominal System Voltage, kV | Basic Impulse Level, kV |
|---|---|
| 15 | 110 |
| 34.5 | 200 |
| 69 | 350 |
| 115 | 450 |
| 138 | 550 |
| 161 | 650 |
| 230 | 750 |
| 345 | 850 |

The efficiency multiplier $M_2$ has to do with the tradeoff between capitol cost and operating cost of a transformer, as discussed earlier in the chapter. The cheapest transformer to build is the most expensive to operate. The total cost of owning a transformer for its lifetime, including both capitol and operating costs, will be minimum for a better transformer. Depending on the particular situation, a typical value for $M_2$ is 1.3.

The operating voltage multiplier $M_3$ reflects the extra cost of building a transformer with a non standard BIL. It will be unity for the standard transformer and does not exceed 1.1 for any case. We will assume it to be unity in our case.

The frequency multiplier $M_4$ is 1.125 for a 50 Hz transformer rather than the standard 60 Hz. This would be used only for windfarms in those countries where the frequency is 50 Hz.

The percent adders $PA$ are the additional percentage costs for such things as reducing the audible sound level, adding taps, changing the cooling system, and adding extra windings. We will assume that none of these extras are necessary for our system.

$C_6$ is the cost for load tap changing equipment, which can change the transformer ratio under load. It is necessary at some substations to keep the customer voltage within the proper range under all load conditions. Depending on the utility receiving power from the windfarm, it might be necessary in our situation, but we will ignore it for the present.

The dollar adders $C_7$ would be for built in current transformers, potential transformers, lightning arresters, and such items as relays, special paints, and special tests. This application will require current transformers, potential transformers, and lightning arresters. Other dollar adders could easily total $20,000. Rather than make the design any more detailed than it already is, we will assume a lump sum of $20,000 for these miscellaneous dollar adders (in addition to the current and potential transformers and arresters). The estimating costs for these devices are shown in Table 9.8.

Table 9.8. List costs of potential transformers, current transformers, and lightning arresters (before cost multiplier.

| Voltage, kV | Potential | Current | Arrester |
|---|---|---|---|
| 12.47 | 1660 | 1030 | 1430 |
| 34.5 | 5630 | 5690 | 2280 |
| 69 | 10,420 | 7750 | 4090 |
| 115 | 14,550 | 13,670 | 7450 |
| 161 | 24,100 | 21,680 | 11,590 |
| 230 | 26,970 | 33,700 | 17,570 |
| 345 | 43,820 | 46,840 | 31,860 |

*Example*

What is the list price of a three-phase, 20 MVA, 12.47/69 kV transformer, with an efficiency multiplier of 1.3, including three current and potential transformers and lightning arresters?

The base list price is, from Eq. 9,

$$C_1 = 19800(20)^{0.75} + 1.55(350)^{1.75} = \$231,150$$

The list price is, from Eq. 8,

$$C = 231,150(1.3) + 3(10,420 + 7750 + 4090) + 20000 = \$387,275$$

This price is then multiplied by a discount factor as quoted by the Westinghouse salesman. At the time of this writing, this factor is 0.51, which makes the actual selling price 387,275(0.51) = $197,510.

The transformer $T_2$ must then be connected to the utility grid by an overhead high voltage transmission line. This line may need to be several miles long to reach an existing line. The cost of the transmission line will also vary with the type of terrain, the necessary current capacity, and the local labor costs. In Kansas rough estimates for the total installed costs in 1991 dollars were as shown in Table 9.9.

Table 9.9. Overhead transmission line costs.

| | |
|---|---|
| 34.5 kV | $27,000/mile |
| 69 kV | 46,000/mile |
| 115 kV | 76,000/mile |
| 230 kV | 153,000/mile |
| 345 kV | 250,000/mile |

## 6 VOLTAGE DROP

The voltage drop in a conductor is simply $IZ$, where $I$ is the phasor current and $Z$ is the complex impedance. The current is known from the load requirements and the resistance is easily calculated or looked up in a table, such as Appendix C. The reactance term, on the other hand, is not as easy to obtain. The inductance of a wire increases as the distance to an adjacent wire (the return path) increases. For overhead transmission lines and for multiconductor cable (two or more conductors inside a plastic sheath) the distances to adjacent conductors are fixed, so tables can be prepared for such cases. Windfarms, however, will have individual conductors spaced at random in the bottom of trenches, so the exact value of reactance could only be obtained by measurement after the trench is backfilled. This is obviously not an acceptable solution to a design problem.

Rather than try to make an exact analysis, we will estimate the voltage drop for the windfarm situation from the voltage drop table for conductors in conduit, as published in the

American National Standard ANSI/IEEE Std 141-1986, affectionately known as the IEEE Red Book. A portion of the table for 600 V conductors is shown in Table 9.10. The table includes data for both copper and aluminum conductors, in conduits (the worst case). There will not be any magnetic materials in the trench, but the distribution of the conductors will cause the voltage drop to be slightly larger than the corresponding values for nonmagnetic conduit.

In using Table 9.10, the procedure is to find the voltage drop for 10,000 A·ft and multiply this value by the ratio of the actual number of ampere-feet to 10,000. The length used is the one way distance from the source to the load.

*Example*

A 250 kcmil aluminum conductor 480 V circuit is used to supply 300 A to a load 200 ft away. The power factor is 90 percent lagging. What is the voltage drop?

From Table 9.10, the voltage drop for 10,000 A·ft is 1.6 V. The actual number of A·ft is (200 ft)(300 A) = 60,000 A·ft. The total voltage drop from line to line is then

$$(60,000/10,000)(1.6) = 9.6\text{V}$$

This can be converted from a line-to-line value to a line-to-neutral value by dividing by $\sqrt{3}$ or multiplying by 0.577. The percentage drop is 9.6/480 = 0.02 or 2 percent. This would generally be quite acceptable.

Table 9.10. Voltage drop per 10,000 A·ft in magnetic conduit, 0.9 pf lag

| AWG kcmil | COPPER | ALUMINUM |
|---|---|---|
| 12 | 30 | 48 |
| 10 | 19 | 30 |
| 8 | 12 | 19 |
| 6 | 8.0 | 12 |
| 4 | 5.2 | 7.9 |
| 2 | 3.4 | 5.1 |
| 1 | 2.8 | 4.1 |
| 1/0 | 2.3 | 3.4 |
| 2/0 | 1.9 | 2.7 |
| 3/0 | 1.6 | 2.3 |
| 4/0 | 1.3 | 1.9 |
| 250 | 1.2 | 1.6 |
| 350 | 0.95 | 1.3 |
| 500 | 0.78 | 0.99 |
| 750 | 0.64 | 0.79 |
| 1000 | 0.57 | 0.69 |

*Example*

Calculate the voltage drop on a dc system where we have two 250 kcmil aluminum conductors carrying 300 A to a load 200 ft away. The input voltage is 480 V. What is the voltage drop and power loss?

From Table 2 in Appendix C, the resistance of 1000 ft of 250 kcmil aluminum conductor is 0.068 Ω. We have current flow through a total length of 400 ft (200 ft down and 200 ft back) with resistance

$$R = \frac{400}{1000}(0.068) = 0.0272 \ \Omega$$

The voltage drop is

$$V_{drop} = IR = 300(0.0272) = 8.16 \ \text{V}$$

The power loss in the line is

$$P_{loss} = I^2R = (300)^2(0.0272) = 2448 \ \text{W}$$

The voltage drop is less because of the lack of inductive reactance, but not substantially less. The drop due to resistance alone would not be a bad first estimate if Table 9.10 were not available.

# 7 LOSSES

Voltage drop ($IZ$) and resistive loss ($I^2R$) are closely related concepts, but present two different types of constraints. Voltage drop is a technical constraint. We want the voltage at the wall receptacle to be between 114 and 122 V, for example, so the light bulbs have the proper intensity and the electrical appliances work correctly. In the windfarm environment it would not be hard to design for a voltage drop up to 10%, so this is not a significant constraint. On the other hand, resistive loss is an economic constraint, at least for wire sizes adequate to carry the desire current. The economic goal of a windfarm design is to minimize the ratio of capitol cost to net energy production as measured at the windfarm boundary. The gross energy production (the total energy produced by the turbines before losses are considered) is a function of the skill of the turbine designer and of the wind resource at a particular site. Once the turbine and site have been selected, the windfarm designer still has to select wire sizes and other factors to minimize the cost per kWh delivered to the utility.

For example, a given turbine is rated at 220 A. The low voltage wire must have an ampacity of 1.15(220) = 253 A, which is met by AWG 3/0. A larger wire size would be selected for economic rather than technical reasons. A larger wire size increases the windfarm cost but, by reducing the losses, also increases the energy supplied to the utility. For the wire costs given earlier and for a typical windfarm layout, the cost per kWh hits its minimum at a wire size of around 350 kcmil. Beyond that point, the wire cost increases more rapidly while the energy saved becomes smaller, so the cost per kWh begins a slow increase.

The low voltage wire loss can be determined from Fig. 5, which shows a single turbine connected to a transformer $T_1$ by underground conductors in a trench of length $D_T$. All the low voltage wire in a windfarm carries approximately the same current, so the total loss can be found by using the total low voltage trench length. There are two possibilities, either single circuit or double circuit, shown as Fig. 5b and Fig. 5c. Each of the three conductors in the single circuit case will carry the full turbine current $I$. The additional ampacity of the double circuit case is obtained by simply paralleling two conductors for each phase. There are now six conductors in the trench, each carrying a current $I/2$.

The power dissipation in the single circuit case is

$$P_s = 3I^2 R_s \tag{10}$$

while the power dissipation in the double circuit case is

$$P_d = 6(I/2)^2 R_d = 1.5 I^2 R_d \tag{11}$$

where $R_s$ and $R_d$ are the resistances of a conductor of length $D_T$. It is tempting to assume that $P_d$ is smaller than $P_s$ because the multiplying factor is half as large (1.5 rather than 3). But it should be remembered that $R_d$ is larger because smaller wire is used in the double circuit case. In fact, the losses will be exactly the same if the conductor size in the double circuit case is half the size of the single circuit conductor. It does not make any difference in losses if the total conductor area of 500 kcmil, for example, is obtained from a single 500 kcmil conductor or from two conductors, each of 250 kcmil area.

*Example*

A wind turbine rated at 220 A is located 300 ft from its circuit breaker CB1 and transformer T1. Assume that the trench for a single circuit costs \$1/ft and \$2/ft for a double circuit. Wire costs for 600 V conductors are given in Table 9.5. What is the cost/ft for the single and double circuit cases and what is the power loss at rated current for each case?

As mentioned above, the wire must have a rating of 1.15(220) = 253 A. We see in Table 9.2 that 3/0 aluminum has a rating of 272 A in the single circuit case. Each of the individual conductors in the double circuit case must have a rating of 253/2 = 126.5 A. This is met by 2 AWG, rated at 151 A. The cost per ft for the single circuit case is

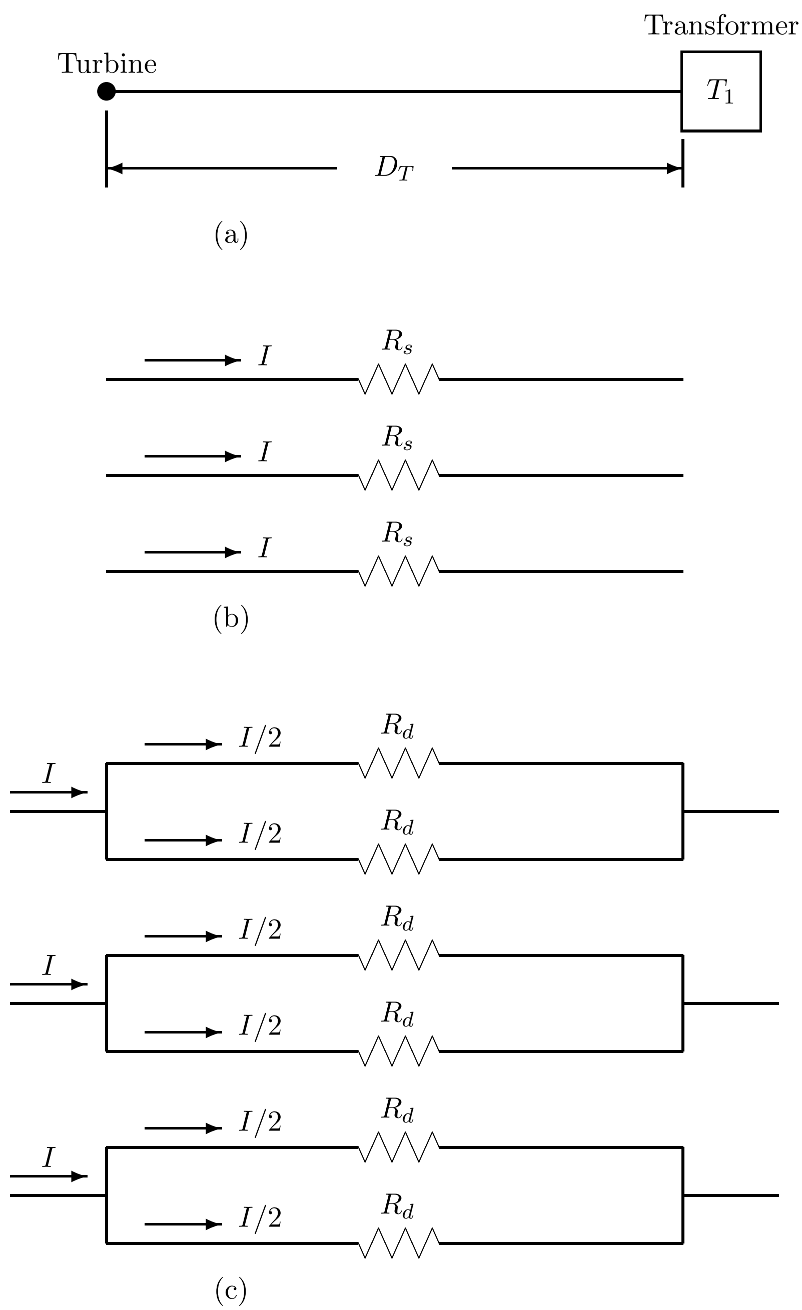


Figure 5: Loss Calculation in Low Voltage Cable

$$C_s = 4(\$0.363) + \$1 = \$2.452/\text{ft}$$

while for the double circuit case it is

$$C_d = 8(\$0.178) + \$2 = \$3.42/\text{ft}$$

Note that both cases includes a neutral of the same ampacity as the three phase conductors.

We now proceed to Table 2 of Appendix C to find the resistance of our conductors. We find that 2 AWG has a resistance of 0.2561 Ω per 1000 ft while 3/0 has a resistance of 0.1013 Ω per 1000 ft. The resistances $R_s$ and $R_d$ of Fig. 5 are therefore

$$R_s = (300/1000)(0.1013) = 0.03039 \ \ \Omega$$

$$R_d = (300/1000)(0.2561) = 0.07683 \ \ \Omega$$

The power losses at rated current are

$$P_s = 3(220)^2(0.03039) = 4413 \ \ \text{W}$$

$$P_d = 1.5(220)^2(0.07683) = 5578 \ \ \text{W}$$

In this particular case, the double circuit is both more expensive and more lossy than the single circuit. If a sufficiently large ampacity is required, then the double circuit will be less expensive. The losses for a double circuit will always be greater than the losses of a single circuit of the same ampacity.

We now need the yearly energy loss in the low voltage conductors before we can complete our economic analysis. We cannot just multiply the loss at rated current by 8760 hours per year because the turbines are operating at rated current only a small fraction of the year. From the wind speed duration curves and the curve of turbine power versus wind speed we can calculate the fraction of time that the turbine is at each power level. However, this does not give the full picture since the power factor of the generator decreases as power production decreases. This means that if a rated current of 220 A, for example, occurs at rated power, the current at half power will be greater than 220/2 = 110 A. A detailed analysis will require a histogram of current versus time for one year, which may be more trouble than it is worth.

A crude estimate of low voltage loss can be obtained by starting from the capacity factor CF for turbines at this site. A capacity factor of 0.2, for example, means that the yearly energy production of a turbine can be calculated by assuming the turbine is producing full power for 20% of the time and is off the remaining time, or is producing 20% power all the time. In the first case, the yearly energy loss would be

$$W_{s1} = (0.2)(8760)(3)(I)^2 R_s \tag{12}$$

and in the second case, if we assume the current drops to $0.3I$ for 20% power,

$$W_{s2} = (1.0)(8760)(3)(0.3I)^2 R_s = 0.45W_{s1} \tag{13}$$

$W_{s1}$ is an upper bound for conductor losses. Depending on the variation of current with power, $W_{s2}$ is a reasonable estimate for the lower bound of losses. An assumption of $0.6W_{s1}$ or $0.7W_{s1}$ should be adequate for most purposes.

A similar argument can be made for the load losses of transformer $T_1$. The current will be the same as in the low voltage conductors, and the resistance will just be that of the transformer windings. An estimate of $(0.6)(CF)(8760)P_{LL}$ should be quite acceptable.

The no load losses of $T_1$ can be found by multiplying the no load power from Table 1 by the number of hours per year that the transformer is energized. Significant amounts of energy can be saved by opening the circuit breakers CB2 during long periods of low winds. These circuit breakers are not intended for frequent cycling, but a few times each week should be acceptable.

The losses of the distribution voltage conductors can be determined in a manner similar to that of the low voltage conductors. Actually, the losses in these conductors will be much lower than the low voltage conductor losses and can be ignored without significant error. The reason for this is that the distribution voltage conductors must be sized for the worst case condition of one circuit breaker open and all the loop current flowing through the other one. In this case, the loop current increases from zero next to the open circuit breaker to rated at the operating circuit breaker. The average current in the loop would be approximately half the rated current, with losses on the order of one fourth the losses we would expect if the entire loop carried the same current. In normal operation, however, both circuit breakers CB2 will be operating, so the maximum current in the loop will be half the rated current. At some point around the midpoint of the loop, the current will actually be zero. The losses in this case will be on the order of one tenth the expected losses for a uniform current throughout the loop. This will usually be less than 0.5% of the energy produced by the windfarm, hence is not very significant.

## 8 PROTECTIVE RELAYS

The circuit breakers are operated by a variety of protective relays which sense various operating conditions that may be harmful to the utility, the windfarm, or to operating personnel. Some functions, such as overcurrent, would be common to all the circuit breakers. Others, such as a synchronism check relay, might only be located at one circuit breaker location. The relays need to be carefully coordinated so the windfarm operation will be both safe and economical. Several of the possible relays will be briefly discussed here.

Overcurrent relays are very important in preventing damage to equipment due to equipment failure or faults. They have two types of overcurrent operation. One is for moderate overcurrent conditions of perhaps five or six times rated current for a short period of time (a second or so). This could be experienced during normal operation, such as the starting of an induction motor, and should not cause the circuit breaker to open. If this current is sustained for several seconds, however, the circuit should be opened. A relay circuit involving the product of time and current is used, so that a larger overcurrent will cause relay operation in a shorter time.

The other operating mode is the so-called instantaneous trip mode. Under fault conditions, when conductors have shorted together, the current may be 20 times the rated current or more. This very large current is never a part of normal operation, so the relay is built to operate as quickly as possible under such conditions.

Overfrequency and underfrequency relays will operate when the windfarm is disconnected from the utility grid. The utility grid operates at a very precise 60 Hz in the U.S.A. so that any significant deviation from this frequency means the windfarm is not connected to the frequency controlled grid. It is possible that the utility lines could open at some distance from the windfarm, leaving some utility load attached to the windfarm. Depending on the load, the wind speed, and the presence of power factor correcting capacitors, wind driven induction generators could supply this load for some time, but at frequencies probably quite different from 60 Hz. This could result in damage to utility customer equipment and also in physical harm to linemen repairing the utility transmission system. Therefore the main circuit breaker to the windfarm must be opened when the frequency is outside some range (perhaps 59 to 61 Hz), and not reclosed until the utility lines again have 60 Hz present on them.

It is not obvious that all the circuit breakers need utility quality overfrequency and underfrequency relays connected to them. One set at the main transformer may be adequate, with perhaps some less expensive relays set for a wider frequency range at the individual turbines, as a backup for the main circuit breaker.

Overvoltage and undervoltage relays will probably also be required. If the windfarm is disconnected from the utility, both voltage and frequency will shift away from the proper values. It is conceivable that frequency would stay in the proper range while the voltage went either higher or lower than what is acceptable. It is also possible that a voltage regulator system would fail on the utility side, so that frequency is still controlled by the utility but the voltage is incorrect. Again, a sophisticated set of relays at the main circuit breaker and a crude set at the turbines may be all that is required.

Power directional relays indicate whether power is flowing from the utility to the windfarm or from the windfarm to the utility. The induction generators will automatically operate as motors in light wind conditions, driving the turbines as fans, a condition which obviously must be prevented for long term operation. However, reverse power may be acceptable or even necessary during some operating conditions, so considerable sophistication may be required. If the turbines need to be started by utility power, as in the case of Darrieus turbines, then reverse power will flow during the starting cycle. Also, depending on the length and energy requirements of the turbine shut-down and start-up cycles, it may be justified to allow reverse power flow during wind lulls if the average power flow over a 10 or 30 minute period is toward the utility.

Another relay which would be required for the main circuit breaker at least would be one that detects reverse phase or the loss of one phase of the three-phase system. Actual reversed phase sequence would be unlikely after the windfarm electrical system is once correctly wired, but the loss of one phase is not uncommon, caused either by a broken line or the failure of a circuit breaker to reclose properly. Induction generators would try to support the voltage on the lost phase, with possible heavy fault currents.

A synchronism check relay prevents a circuit breaker from closing if the windfarm generators are out of phase with the utility. It would not be required during normal startup conditions with induction generators since these would not have a voltage present at the time of connection to the utility. However, if the utility should have a circuit breaker opened elsewhere on the system, perhaps due to lightning, which recloses after a few tenths of a second, the induction generator voltages will not have had time to decay to zero, and will most probably be out of phase. The resulting high currents and torques could easily damage both the generators and the turbines. The safest approach would be to do a complete shutdown of the windfarm when utility power is lost for any reason, and then initiate a standard startup. With more experience, and fast acting solid state controls, it may be possible to add capacitance and local resistive load at the windfarm to maintain voltage, frequency, and phase so that automatic reclosing of the windfarm into the utility would be feasible.

Other relays may be considered for specific protection of devices. A differential relay may be used on the main transformer to detect differences between input and output, which would indicate an internal fault. It could also be used on the generators, but may be difficult to justify economically in the windfarm setting. A ground overcurrent relay may be used to detect large currents flowing in the ground connection of a wye connected transformer, which would indicate certain types of system failure. Other relays could be used as well.

# 9 WINDFARM COSTS

We have considered the costs of the electrical equipment necessary to connect wind turbines to the utility grid, hopefully in enough detail to illustrate the process. Prices of electrical equipment can change substantially over short periods of time, and labor costs vary with the part of the country, the remoteness of the site, and the site terrain, so the actual figures used for examples will not be accurate in most situations. One should always call suppliers and contractors to get current prices.

There are other costs associated with installing a windfarm. Somewhat arbitrarily, we have grouped these into the following categories:

1. Electrical
2. Turbine
3. Fixed
4. Auxiliary

We have just considered the electrical costs in detail. This includes the low voltage wire, the distribution voltage wire, trenches, transformers $T_1$ and $T_2$, and circuit breakers CB2 and CB3.

Turbine costs include the following:

1. Purchase price of the turbine
2. Shipping
3. Import duty (for imported turbines)
4. Import broker fee
5. Concrete and other foundation costs
6. Labor
7. Circuit Breaker CB1

Fixed costs are those costs which are not strongly sensitive to the size of the windfarm, such as buildings and legal documents. We include the following in this category:

1. *Permits*. These are required and granted by local government agencies.
2. *Zoning*. Agricultural land will probably need to be rezoned to industrial use (or other category) before a permit can be granted.
3. *Wind Study*. Wind speeds need to be measured at the proposed site for an appropriate amount of time (up to a year) before a decision is made to build a windfarm.
4. *Power Purchase Agreement*. This would include the engineering and legal fees incurred in writing an agreement with the utility buying the electricity produced by the windfarm.

5. *Engineering Design.* A Professional Engineer must perform a detailed design for the windfarm and prepare a set of plans which can be used for construction. This would include the electrical design plus the soil tests, earthwork, and footings necessary to long operation of the windfarm.

6. *Control Building.* Each windfarm will have a building or portion of a building to house the computers, meters, controls, and maintenance personnel. The computers (if not the maintenance personnel) will require this space to be clean and climate controlled.

7. *Maintenance Building.* This would be a building or portion of a building where maintenance and repair operations are conducted. It should be large enough to house the largest item which might be repaired. It may need an overhead crane to lift and move parts. This may be a final assembly building during construction, where tower pieces are connected together, the blades are bolted to the hub, etc.

8. *Visitor Center.* This might be a part of the Control Building or it might be a totally separate facility. Careful attention should be given to this requirement for the first few windfarms in a given part of the country so that visitors can be properly cared for.

9. *Meteorological Tower.* This would be a tower located near the Control Building with anemometers at several heights. Wind speed data would be used for monitoring wind turbine performance and such tasks as starting turbines after low wind conditions and stopping them in high wind conditions.

The Auxiliary costs are those costs related to construction, which vary with the size of the windfarm or the character of the turbines. They include:

1. *Land.* It will probably not be feasible to use the land in a windfarm for any purpose other than grazing, and that would probably not be worth the nuisance of keeping gates closed, so it will probably be necessary to purchase the land for the windfarm.

2. *Access Roads.* Gravel roads are needed within the site so the turbines can be repaired in wet weather. A road is also needed from the site to the nearest all weather road. This could be a substantial expense in remote or mountainous regions. It could be significant even in places like Kansas if the township or county road bridges were not adequate so several bridges needed to be built.

3. *Grading.* There may be earthwork necessary besides building roads and parking lots. Sharp peaks or gullies may affect the wind flow enough to justify some earth leveling activity.

4. *Vehicles.* A windfarm will probably require one or two pickup trucks and a larger truck for moving large components around the site.

5. *Crane.* Windfarms with turbines that tilt over on a hinged base will not require a crane, but a crane would be very desirable for turbines that do not tilt over. A crane can always be rented, but the extensive use of such a machine on a windfarm could easily justify its purchase.

6. *Fence.* A windfarm in grazing land would require a barbed wire fence to keep cattle out. Depending on population densities and insurance requirements, it may be necessary to build a fence to keep people out of the windfarm area. Such a fence would need to be at least six feet tall, of the chainlink type.

7. *Overhead Line.* The windfarm will need to be connected to the nearest utility transmission line by an overhead line.

Table 9.11 shows estimates used by Nordtank for a 10 MW windfarm, which can be used if no better figures are available.

Table 9.11. Nordtank cost estimates for a 10 MW windfarm.

| Item | Cost |
|---|---|
| Permits | $30,000 |
| Zoning | 15,000 |
| Wind Study | 17,000 |
| Engineering | 42,000 |
| Power Purchase Agreement | 30,000 |
| Control Building | 80,000 |

Table 9.12 shows estimates for other costs.

Table 9.12. Estimates of other costs for Kansas.

| | |
|---|---|
| Land. | About $400 per acre for grazing land and $800 per acre for farm land. This includes a premium over present costs which may be necessary to get the good sites. |
| Foundations. | Concrete costs between $40 and $50 per cubic yard delivered to the site. Installed cost, including steel, may be close to $100 per cubic yard. |
| Access Roads. | About $6 per linear foot for places where extensive grading is not required. Western Kansas is less expensive, perhaps $1 per linear foot. |
| Visitor Center. | $100,000 should be adequate. |
| Maintenance Building. | $150,000. |
| Meteorological Tower. | $6000 or more. |
| Fence. | $2/ft for barbed wire, $6/ft for 6 ft tall 9 gauge chain link plus $1/ft for 3 barbed wires on top. |
| Crane. | Winch and cable 50 ton $500,000 or hydraulic $600,000. Rental cost $150/hr or $4000/week. Rental includes operator but does not include travel. |
| Bulldozer. | Clearing brush $1500/acre, or $110/hr for D-8. |
| Labor. | Estimate at least $15/hour for skilled labor. |

# 10 PROBLEMS

1. An underground loop is being designed for a windfarm that will carry 8 MVA at a voltage of 13.2 kV line-to-line. Compare the installed costs of the loop for the one- and two-circuit cases.

2. A wind turbine is rated at 110 A, 480 V, three-phase, 91.5 kVA, and 80 kW. It is to be connected by single-circuit underground aluminum conductors to a transformer 300 ft away.

   (a) What is the minimum wire size according to Table 9.2?
   
   (b) What is the rated current of this wire?
   
   (c) What is the power loss in the three phase conductors between turbine and transformer under full load conditions, in watts and also as a fraction of the rated power?
   
   (d) What wire size would you select to reduce the fractional loss of the previous part to less that 2 percent?

3. A three-phase transformer rated at 750 kVA, 480/12470 V has no load losses at rated voltage of 1112 W and copper losses at rated current of 5184 W. What are the total transformer power losses when it is operating at 60 percent of rated current and 95 percent of rated voltage?

4. Vulcan Materials uses rectangular copper conductors 6 inches by 12 inches in cross section and a total circuit length of 400 ft to carry 15,000 A of direct current to a set of electrolysis cells. What is the power loss in 400 ft of this conductor, assuming the conductor temperature is $20^o$C? Use the techniques in Appendix C.

5. A wind turbine rated at 200 kVA, 480 V, three-phase, is located 500 ft from its step-up transformer and circuit breaker. Assume that the turbine operates at full power 10 percent of the time, half power 40 percent of the time, and is off the remaining 50 percent of the time.

   (a) What is the minimum wire size of aluminum underground cable, according to the National Electrical Code?

   (b) What is the voltage drop in the conductors, assuming a power factor of 0.9?

   (c) What is the yearly energy loss in the conductors *between* turbine and transformer.

6. An underground 12.47 kV loop carries 200 A in a three-conductor, single-circuit configuration. Full current flows 20 percent of the time and zero current the other 80 percent. Energy losses cost 5 cents/kWh, escalating at 3 percent per year. The wire is purchased on a 20 year note at 9 percent interest. Should you buy 1/0 AWG aluminum wire at $860/1000 ft or 4/0 AWG aluminum wire at $1500/1000 ft?

7. A wind turbine rated at 250 kVA, 480 V, three-phase, is connected by aluminum underground cable to a circuit breaker/starter and transformer located 700 feet away.

   (a) What size wire should be used, according to the NEC?

   (b) What is the rated current of this wire?

   (c) What NEMA size of circuit breaker/starter should be used?

   (d) Estimate the line-to-line voltage drop in volts for this installation when operating at rated kVA and 0.9 power factor lag.

8. An underground 12.47 kV loop is being designed to carry 10 MVA.

   (a) Assuming aluminum wire, is it more economical to use one circuit or two? Include trenching costs.

   (b) Is there any advantage to increasing the voltage from 12.47 kV to 13.8 kV? Explain.

# APPENDIX A: CONVERSION FACTORS

| To convert from | to | multiply by |
|---|---|---|
| acre | $ft^2$ | 43,560 |
| atmosphere | pascal | $1.01325 \times 10^5$ |
| barrel (oil, 42 gal) | $m^3$ | 0.15899 |
| Btu (mean) | joule(J) | 1056 |
| Btu/h | watt(W) | 0.293 |
| calorie (mean) | joule(J) | 4.190 |
| cm Hg ($0^o$C) | pascal | $1.333 \times 10^3$ |
| degree Celsius | kelvin(K) | $T_K = T_{^\circ C} + 273.15$ |
| degree Fahrenheit | degree Celsius | $T_{^\circ C} = (T_{^\circ F} - 32)/1.8$ |
| degree Fahrenheit | kelvin(K) | $T_K = (T_{^\circ F} + 459.67)/1.8$ |
| foot | meter | 0.3048 |
| $ft^3$ | gallon (US liquid) | 7.4805 |
| gallon (US liquid) | $m^3$ | 0.003785 |
| hp | watt(W) | 745.7 |
| in. Hg ($32^o$F) | pascal | $3.386 \times 10^3$ |
| in. of $H_2O$ ($39^o$F) | pascal | $2.491 \times 10^2$ |
| kelvin | degree Celsius | $T_{^\circ C} = T_K - 273.15$ |
| knot | mi/h | 1.151 |
| knot | km/h | 1.852 |
| knot | m/s | 0.5144 |
| kWh | Btu | 3410 |
| kWh | joule(J) | $3.6 \times 10^6$ |
| liter | $m^3$ | 0.001 |
| m/s | mi/h | 2.237 |
| m/s | knot | 1.944 |
| $m^3$ | gallon (US liquid) | 264.17 |
| $m^3$/s | cfs | 35.315 |
| $m^3$/s | gal/min | 15,850 |
| mile (statute) | meter | 1609 |
| mile (statute) | feet | 5280 |
| mile (nautical) | meter | 1852 |
| mi/h | feet/s | 1.467 |
| mi/h | km/h | 1.609 |
| mi/h | knot | 0.8690 |
| mi/h | m/s | 0.447 |
| N·m | pound-feet | 0.7376 |
| N·m | pound-inch | 8.8507 |
| psi | pascal | $6.895 \times 10^3$ |

# APPENDIX B
# ANSWERS TO SELECTED PROBLEMS

2.1 (a) $\rho = 1.146$ kg/m$^3$; (b) $\rho = 1.423$ kg/m$^3$

2.3 (a) $p = 92.5$ kPa; (b) $p = 83.5$ kPa; (c) $p = 59.3$ kPa

2.5 $T_g = 15^o$C

2.7 $\bar{u} = 8.773$ m/s, $\sigma^2 = 1.012$, $\sigma = 1.006$

2.10 (a) $\Gamma(1.8333) = 0.94066$; (b) $\Gamma(1.3571) = 0.89046$

2.13 711 hours/year between 8.5 and 9.5 m/s, 699 hours/year greater than 10 m/s, 0.0019 hours/year greater than 20 m/s.

2.15 (a) $\bar{u} = 11.18$ knots, $\sigma = 0.1262$; (b) 8.86 to 13.50 knots, one month outside; (c) from best month 10.89 to 17.71 knots, from worst month 6.88 to 11.18 knots; both intervals include the long-term monthly mean.

2.17 $u_W = 0.369 u_{DC} + 8.51$ knots, r = 0.476

2.18 (a) $u = 41.66$ m/s once every 20 years; (b) $u = 78.67$ m/s once every 500 years.

3.1 0–1.109, 1.109–1.328, 1.328–1.547, 56.672–57.000

3.2 1.28 s

3.4 6.44 m/s

4.1 1943 kW

4.2 15 m/s

4.4 4876 m$^2$, 78.79 m

4.6 (a) 9.82; (b) 22.44; (c) 0.273

4.8 (a) 0.264, 19,010 kWh; (b) 0.413, 29,770 kWh; (c) 0.576, 41,500 kWh

4.9 The 25-kW machine produces 48,180 kWh per year while the 60-kW machine produces 32,540 kWh per year.

4.11 3.5 inches

4.13 (a) $\theta = 1.921 \cos 0.262t$ rad; (b) 5.296 s; (c) Yes! Large currents flow during the out of phase condition.

5.3 $I = 83.33\underline{/-60^o}$, $Q = +17.32$ kvar

5.4 $S = 113.14\underline{/+45^o}$ kVA, pf = 0.707 lag

5.5 (a) $I_1 = 25\underline{/-53.13^o}$ A, $P = 3750$ W, $Q = 5000$ var, pf = 0.60 lag; (b) $E = 325.96\underline{/4.40^o}$;

(c) $P = 625$ W; (d) $I_c = 20\underline{/90^o}$ A, $I_1 = 15\underline{/0^o}$ A, pf = 1; (e) $E = 268.79\underline{/9.64^o}$, $P = 225$ W; (e) reduces reactive power requirement and reduces power line loss.

5.7 $I = 231.3\underline{/-25.84^o}$ A, $E = 4009.0\underline{/31.10^o}$, $\delta = 31.10^o$, $P = 962.9$ kW/phase, ohmic losses = 17.65 kW.

5.11 $X_{s,\text{pu,new}} = 6.01$

5.18 $R_a = 0.00479$ days/year or about 1 day in 209 years.

6.2 (a) $I_a = 12.83$ A; (b) $k_e = 0.383$; (c) $X_s = 4.91\ \Omega$; (d) 16 percent decrease.

7.2 The 14-ft-diameter propeller and 2.5-in.-diameter cylinder clearly meet the requirements. The 12-ft-diameter propeller and 2-in.-diameter cylinder will probably be quite satisfactory at a lower cost.

7.4 (a) $n_s = 350$; (b) $P_m = 19{,}260$ W = 25.83 hp.

7.5 $h_2 = 416$ ft, $Q_2 = 113$ gal/min, $P_{m2} = 12.66$ kW

8.1 $862

8.3 13 units

8.5 $P_v = \$44.88$. You should buy the cover.

8.7 $P_{v,X} = \$12{,}275.92$, $P_{v,Y} = \$12{,}551.84$. You should buy machine X.

# APPENDIX C: WIRE SIZES

The resistance of a long, straight conductor of uniform cross section is given by the expression

$$R = \rho \frac{\ell}{A} \qquad (C.1)$$

where $R$ is the resistance in ohms, $\ell$ is the length of the conductor, $A$ is the cross-sectional area of the conductor, and $\rho$ is the resistivity. In the SI system, length is in meters and area is in $m^2$, so $\rho$ is obviously given in ohm-meters. This expression is quite straightforward to use, as shown in the following example.

*Example.* What is the resistance of a square copper conductor with resistivity 1.724 $\times 10^{-8}$ ohm-meters, cross-section 0.5 × 0.5 cm, and a length of 100 m?

$$R = \rho \frac{\ell}{A} = 1.724 \times 10^{-8} \frac{100}{(0.5 \times 10^{-2})(0.5 \times 10^{-2})} = 0.06896 \ \Omega$$

Most wire used in the United States is based on the English system, and probably will be for years to come, so it is important for engineers to also be familiar with this system. The unit for resistivity is *ohm circular mils per foot.* This measure of area is quite interesting because it is perhaps the only *circular* measure in existence. Other measures are square (or rectangular). That is, we think of 10 square meters as the area of a rectangle, say 2 meters wide by 5 meters long. The area of a circle of diameter $d$ is $(\pi/4)d^2$ expressed in square measure. The presence of the transcendental number $\pi$ means that the area of circles will always be rounded off to some arbitrary number of digits, and that we can never have both the diameter and the area accurately expressed with two or three significant digits as long as we describe circles with square measure.

The alternative, of course, is to define a circular measure for circular areas, as shown in Fig. C.1. The unit of diameter size used for wires is the *mil*, where 1 mil = 0.001 inch. The area of any circular wire in circular mils is equal to the square of its diameter in mils.

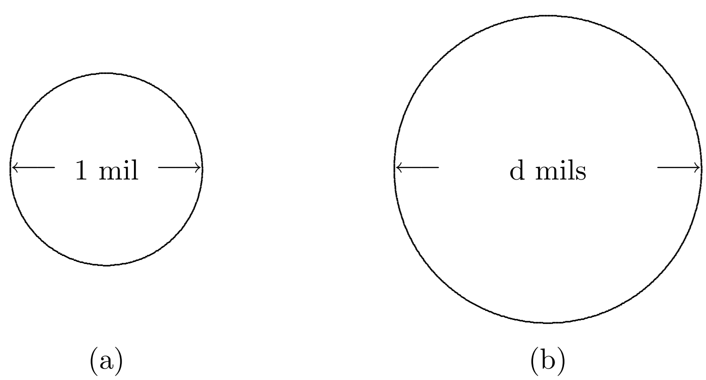


Figure C.1: Circular areas

Area of (a) = $\pi d^2/4 = (\pi/4)$square mils = 1 circular mil.

Area of (b) in circular mils = $(d \text{ in mils})^2$

Area of (b) in square mils = $(\pi/4)(d \text{ in mils})^2$

Number of square mils = $(\pi/4)\times$ number of circular mils

*Example.* What is the resistance of a copper wire 500 feet long having a diameter of 0.1 inch, if the resistivity is 10.37 ohm circular mils per foot?

The diameter of the wire is 100 mils (0.1 inch × 1000 mils/inch) and its area in circular mils is $d^2$, or $10^4$ circular mils. Substitution of these values in Eqn. 1 gives

$$R = \rho\frac{\ell}{A} = 10.37\frac{500}{10^4} = 0.5185\ \Omega$$

If we have to find the resistance of a rectangular conductor, we simply find the area in square mils and multiply by $4/\pi$ to get the corresponding number of circular mils.

*Example.* What is the resistance of 1000 feet of a copper conductor 0.1 × 0.2 inch in cross section, if $\rho = 10.37$ ohm circular mils per foot?

The cross section of the conductor is $100 \times 200 = 2 \times 10^4$ square mils. Converting to circular measure gives $(4/\pi)(2 \times 10^4)$ circular mils.

$$R = \rho\frac{\ell}{A} = 10.37\frac{1000}{(4/\pi)(2 \times 10^4)} = 0.4075\ \Omega$$

Resistivity for some common metals is given in Table C.1.

Table C.1. Resistivity $\rho$ at $20^o$C.
Selected from CRC Handbook of Tables
for Applied Engineering Science

| Material | Ohm-meters | | Ohm circular mils per foot | $\alpha$ Temp. coefficient |
|---|---|---|---|---|
| Aluminum wire | 2.82 | $\times 10^{-8}$ | 17.0 | 0.0039 |
| Brass | 7.0 | $\times 10^{-8}$ | 42.1 | 0.002 |
| Constantan | 49 | $\times 10^{-8}$ | 295 | 0.0001 |
| Copper wire | 1.724 | $\times 10^{-8}$ | 10.37 | 0.00393 |
| Gold | 2.35 | $\times 10^{-8}$ | 14.1 | 0.004 |
| Iron (pure) | 9.7 | $\times 10^{-8}$ | 58.4 | 0.00651 |
| Lead | 20.6 | $\times 10^{-8}$ | 124 | 0.00336 |
| Manganin | 44 | $\times 10^{-8}$ | 265 | 0.00001 |
| Mercury | 98.4 | $\times 10^{-8}$ | 592 | 0.00089 |
| Nichrome | 100 | $\times 10^{-8}$ | 602 | 0.004 |
| Nickel | 6.85 | $\times 10^{-8}$ | 41.2 | 0.0069 |
| Platinum (pure) | 10.5 | $\times 10^{-8}$ | 63.2 | 0.00393 |
| Silver | 1.59 | $\times 10^{-8}$ | 9.57 | 0.0041 |
| Tungsten | 5.65 | $\times 10^{-8}$ | 34.0 | 0.0046 |

The last column in Table C.1 shows the temperature coefficient of resistance, $\alpha$, which is the rate at which the resistance changes with temperature. In the case of metals, the change in resistance is positive; that is, the resistance increases with the rise in temperature. This change is very small for special alloys such as Manganin (composed of copper, manganese, and nickel). There are other materials, such as carbon, electrolytes, gaseous arcs, and ceramic materials, that possess a negative temperature coefficient, which means that the resistance decreases with the rise in temperature. The usual explanation for this phenomenon is that the electron current carriers in a metal experience more collisions in a thermally excited lattice, thus increasing the resistance. On the other hand, a rise in temperature in electrolytes and conducting gases results in the presence of more ions serving as carriers, thus tending to increase the current for a given potential difference, which is a decrease in resistance.

The temperature coefficients change somewhat with temperature, but these values in Table C.1 can be considered reasonably accurate over the temperature range of $-50^o$C to $100^o$C, which includes most cases of interest.

If the resistance of a wire is $R_1$ at temperature $T_1$, the resistance $R_2$ at temperature $T_2$ is given by

$$R_2 = R_1[1 + \alpha(T_2 - T_1)] \qquad (C.2)$$

*Example*

If the resistance of a coil of copper wire is 10 Ω at $20^o$C, what is the resistance at $50^o$C?

$$R_2 = 10[1 + 0.00393(50 - 20)] = 11.18 \ \ \Omega$$

The resistance has increased almost 12% with a $30^o$C increase in temperature. This shows that if precise values of electrical losses are required, one must use the actual temperature of the wire in calculating the resistance.

Only two metals are widely used as electrical conductors, copper and aluminum, so we will focus our attention on them. Conductors are made in many different sizes to meet needs for a given current carrying ability. If the diameter is 460 mils (0.46 inch) or smaller, the size is specified by a number called the American Wire Gauge (AWG). If the diameter is 500 mils or larger, the size is specified by the wire area expressed in thousands of circular mils, kcmil. A partial list of wire sizes is given in Table C.2, along with the diameter, area, and resistance per 1000 ft at a temperature of $20^o$C. The odd sizes are omitted for wires of 3 gauge through 29 gauge, since they are rarely used. The very small sizes are also omitted since their fineness makes them difficult to handle.

If intermediate values are needed, one can use the fact that the areas of two adjacent wire gauges are always in a constant ratio with each other, for the AWG portion of the table. For example, the ratio of areas of 4/0 and 3/0 wires is 211.6/167.8 = 1.261, and likewise for all the other adjacent sizes. For wires that are two gauge sizes apart, like 6 gauge and 4 gauge, the ratio is $41.74/26.25 = 1.590 = 1.261^2$. A span of 10 gauge numbers yields a change of area of $(1.261)^{10} = 10.166$ or approximately a factor of 10. The resistance is inversely proportional to area, so if the resistance of a 10 gauge copper wire is about 1 Ω per 1000 ft, then the resistance of a 20 gauge wire will be about 10 Ω per 1000 ft.

The selection of a value of 1.261 for the ratio between areas of adjacent gauge sizes means that the potential benefit of having diameters expressed in integers has been lost, except for the 250 and 1000 kcmil conductors. It could have been done in a manner similar to resistor sizes, where each standard value is about 10 % larger than the previous size, but rounded off to two digits. But it is too late to make such a choice now, so we must learn to live with the values given in the table.

There are two different constraints which must be considered in selecting a wire size. First, the $I^2R$ loss in the wire must not result in a temperature rise in the wire that will damage the insulation. Second, the voltage drop in the wire must not excessively lower the load voltage. We will illustrate the second constraint with a short example.

*Example*

The new well at your country home is 400 ft from your house. The 120-V single-phase induction motor driving the pump draws 30 A of starting current and 10 A of running current. The starting current flows only for a few seconds at most, so is not a factor in determining the wire temperature. You are told that 12 gauge copper wire is rated for 20 A service in residential wiring. This is twice the running current for this situation, which seems like an ample safely margin for thermal considerations. But you want to check the voltage drop also. The current has to flow to the well and back to the house, so the total length of conductor is 2(400) = 800 ft. The resistance from Table C.2 is

$$R = \frac{800}{1000} 1.588 = 1.270 \;\; \Omega$$

The voltage drop while the starting current is flowing is

$$V_{\text{drop}} = IR = 30(1.27) = 38.1 \;\; \text{V}$$

The voltage available to the pump motor is only 120 - 38.1 = 81.9 V during the starting interval. Single-phase motors do not have very good starting characteristics, and may not start under load if the terminal voltage is less than about 90% of rated, or 108 V for the 120 V system. The proposed wire size is too small.

We see that selecting wire sizes based on thermal considerations alone may easily lead to situations where performance is poor due to voltage drop. In general, we have two choices in such situations. We can increase the voltage rating or we can increase the wire size (or both). A 240 V pump motor costs about the same as a 120 V motor, but draws only half the current for the same power. Insulation on most 12 gauge wire is rated at 600 V, so that is not a factor. Assuming the new starting current to be 15 A for the new motor, the voltage drop would be 19 V, which is less than 10% of the 240 V rating. Therefore 12 gauge wire would probably work for the 240 V case where it would not work for the 120 V situation.

It should be mentioned that the above analysis is not completely accurate since it ignores the inductance in the wire. This increases the impedance and the voltage drop, so the analysis using only resistance is somewhat optimistic.

*Example.* Suppose that we are forced to use the 120 V motor in the above example and that we want to select a wire size such the voltage drop during starting will be 10 V. The maximum resistance for the round trip would be

$$R_{max} = \frac{V}{I} = \frac{10}{30} = 0.333\Omega/800\text{ft} = 0.417\Omega/1000\text{ft}$$

The smallest conductor that has a resistance less than 0.417 Ω/ 1000 ft is 6 gauge, according to Table C.2. We need four times the volume of copper to meet the voltage drop requirement as we need to meet the thermal requirement.

It is obvious from the table that copper is the better conductor per unit area. However, the specific gravity of aluminum is 2.70 and copper has a specific gravity of 8.96, so aluminum is the better conductor per unit mass. Copper tends to cost more per kg than aluminum, so if there were no other factors, aluminum would always be the conductor of choice. There are two factors that keep aluminum from this status. One is that aluminum oxide is not a conductor while copper oxide is. Copper conductors need no protection from the atmosphere at joints and splices, therefore. The second factor is that aluminum tends to cold flow under pressure. That is, when a screw is tightened onto an aluminum conductor, the aluminum tends to flow away from the high pressure point over a period of months or years so that the conductor becomes loose. The exposed aluminum forms a nonconducting layer of aluminum oxide so we have a high impedance connection. Current flowing through the poor connection heats up the surroundings and has been known to start fires. This fire hazard has caused virtually all household wiring to be made of copper.

On the other hand, overhead and underground wiring outside of buildings tends to be mostly aluminum for cost reasons. Connections can be made of special compression fittings that both prevent cold flow and protect the joint from the atmosphere. If the connection is properly made, aluminum conductors are just as reliable as copper.

Table C.2 Wire Size and Resistance
(Adapted from Kloeffler and Sitz, Basic Theory in Electrical Engineering, Macmillan, 1955)

| Size AWG or kcmil | Diameter mils | Area kcmil | Ohms per 1000 ft at 20$^o$C copper | Ohms per 1000 ft at 20$^o$C aluminum |
|---|---|---|---|---|
| 30 | 10.03 | 0.1005 | 103.2 | 169.2 |
| 28 | 12.64 | 0.1598 | 64.90 | 106.4 |
| 26 | 15.94 | 0.2541 | 40.81 | 69.90 |
| 24 | 20.10 | 0.4040 | 25.67 | 42.08 |
| 22 | 25.35 | 0.6424 | 16.14 | 26.46 |
| 20 | 31.96 | 1.022 | 10.15 | 16.63 |
| 18 | 40.30 | 1.624 | 6.385 | 10.47 |
| 16 | 50.82 | 2.583 | 4.016 | 6.581 |
| 14 | 64.08 | 4.107 | 2.525 | 4.139 |
| 12 | 80.81 | 6.530 | 1.588 | 2.603 |
| 10 | 101.9 | 10.38 | 0.9989 | 1.638 |
| 8 | 128.5 | 16.51 | 0.6282 | 1.030 |
| 6 | 162.0 | 26.25 | 0.3951 | 0.6476 |
| 4 | 204.3 | 41.74 | 0.2485 | 0.4073 |
| 2 | 257.6 | 66.37 | 0.1563 | 0.2561 |
| 1 | 289.3 | 83.69 | 0.1239 | 0.2031 |
| 1/0 | 324.9 | 105.5 | 0.09827 | 0.1611 |
| 2/0 | 364.8 | 133.1 | 0.07793 | 0.1277 |
| 3/0 | 409.6 | 167.8 | 0.06180 | 0.1013 |
| 4/0 | 460.0 | 211.6 | 0.04901 | 0.08034 |
| 250 | 500.0 | 250 | 0.04148 | 0.06800 |
| 350 | 591.6 | 350 | 0.02963 | 0.04857 |
| 500 | 707.1 | 500 | 0.02074 | 0.03400 |
| 750 | 866.0 | 750 | 0.01383 | 0.02267 |
| 1000 | 1000 | 1000 | 0.01037 | 0.01700 |

## APPENDIX D: STREAMS AND WATERWAYS

Wind turbines need to be installed on high ground rather than low ground. The low ground, where water flows, has many names, which can vary with region of the country and with landowners within a region. The following dictionary definitions should be helpful in discussing land features. The definitions are from the Random House Unabridged, Second Edition.

*arroyo*: (Chiefly in Southwest U.S.) a small steep-sided watercourse or gulch with a nearly flat floor: usually dry except after heavy rains.

*brook*: a small natural stream of fresh water.

*canyon*: a deep valley with steep sides, often with a stream flowing through it.

*coulee*: (Chiefly Western U.S. and Western Canada) a deep ravine or gulch, usually dry, that has been formed by running water.

*creek*: (U.S., Canada, and Australia) a stream smaller than a river.

*ditch*: a long, narrow excavation made in the ground by digging, as for draining or irrigating land; trench.

*draw*: (definition 65a.) a small natural drainageway with a shallow bed; gully. b. the dry bed of a stream. c. (Chiefly Western U.S.) a coulee, ravine.

*gorge*: 1. a narrow cleft with steep, rocky walls, esp. one through which a stream runs. 2. a small canyon.

*gully*: a small valley or ravine originally worn away by running water and serving as a drainageway after prolonged heavy rains.

*gulch*: a deep, narrow ravine, esp. one marking the course of a stream or torrent.

*ravine*: a narrow steep-sided valley commonly eroded by running water.

*rill*: a small rivulet or brook.

*river*: a natural stream of water of fairly large size flowing in a definite course or channel.

*slough, slew, slue*: (Northern U.S. and Canada) a marshy or reedy pool, pond, inlet, backwater, or the like.

*swale*: 1. a low place in a tract of land. 2. a valleylike intersection of two slopes in a piece of land.

*valley*: 1. an elongated depression between uplands, hills, or mountains, esp. one following the course of a stream. 2. an extensive, more or less flat, and relatively low region drained by a great river system. 3. any depression or hollow resembling a valley.

*watercourse*: 1. a steam of water, as a river or brook. 2. the bed of a stream that flows only seasonally. 3. a natural channel conveying water. 4. a channel or canal made for the conveyance of water.

*waterway*: a river, canel, or other body of water serving as a route or way of travel or transport.

A second definition for *waterway* that is not in the unabridged dictionary is "natural or constructed channel covered with an erosion-resistant grass, that transports surface runoff to a suitable discharge point at a nonerosive rate." The agricultural concept of a waterway is an area that can be driven across by a four wheel drive vehicle in dry weather. It is conceivable that a wind turbine could be located in a waterway, although a few feet away on ground a few inches higher would be a wise choice. There is no reason for a technician to be standing in water while working on a turbine after a heavy rain.

The general size progression of terms would be rill, gully, ravine, draw, and canyon. A rill in a plowed field is a small eroded channel that can be smoothed out by plowing across it. If it gets wide and deep enough that it cannot be farmed across or driven across, then it is called a gully. A ravine is a large gully, which may be difficult to even walk across. In Eastern Kansas, ravines usually have brush in the bottom. The word draw may be used as a synonym for gully or ravine, but often implies an eroded area that is wider and shallower. An eroded area two feet deep and one hundred feet wide would be a draw, while one four feet deep and six feet wide would be a gully.

Canyon refers to a large channel, with no limit on size. This term is rarely used in Kansas, but is common to the states west of Kansas. The term *rill* is a technical term used by people who have studied agriculture. The other terms are commonly known and used by most rural Kansans.

When the emphasis is on the water rather than the results of the water flowing, the progression of size goes as brook, creek, and river. Stream may be used as a generic term. Water flow is continuous during years of normal rainfall. One needs a bridge to cross a brook, creek, or river. Brook is seldom used in Kansas. It may be that people think of a brook as a flow of clear water in the mountains, with trout swimming. A creek then would be a flow of muddy water with catfish in it. A creek in Eastern Kansas usually has trees growing on both sides of it. If water flow is not continuous, then it is called an *intermittent creek*.

The terms such as creek and river are relative in nature. A river is a large creek, but the water flow in a river in Western Kansas may be smaller than the water flow in a creek in Eastern Kansas.

The word *valley* is often used with a modifier, such as river valley or mountain valley. A river valley may be several miles wide, usually with fertile farm land, extending to hills or bluffs on either side. A mountain valley is probably smaller, but a relatively flat region with perhaps a small brook flowing through the center. There are no mountains in Kansas, but there is upland (as opposed to lowland or river bottom land), so perhaps the corresponding term is "upland valley".