6

Capacitor Application

Capacitors provide tremendous benefits to distribution system performance. Most noticeably, capacitors reduce losses, free up capacity, and reduce voltage drop:

- *Losses; Capacity* — By canceling the reactive power to motors and other loads with low power factor, capacitors decrease the line current. Reduced current frees up capacity; the same circuit can serve more load. Reduced current also significantly lowers the I^2R line losses.
- *Voltage drop* — Capacitors provide a voltage boost, which cancels part of the drop caused by system loads. Switched capacitors can regulate voltage on a circuit.

If applied properly and controlled, capacitors can significantly improve the performance of distribution circuits. But if not properly applied or controlled, the reactive power from capacitor banks can create losses and high voltages. The greatest danger of overvoltages occurs under light load. Good planning helps ensure that capacitors are sited properly. More sophisticated controllers (like two-way radios with monitoring) reduce the risk of improperly controlling capacitors, compared to simple controllers (like a time clock).

Capacitors work their magic by storing energy. Capacitors are simple devices: two metal plates sandwiched around an insulating dielectric. When charged to a given voltage, opposing charges fill the plates on either side of the dielectric. The strong attraction of the charges across the very short distance separating them makes a tank of energy. Capacitors oppose changes in voltage; it takes time to fill up the plates with charge, and once charged, it takes time to discharge the voltage.

On ac power systems, capacitors do not store their energy very long — just one-half cycle. Each half cycle, a capacitor charges up and then discharges its stored energy back into the system. The net real power transfer is zero. Capacitors provide power just when reactive loads need it. Just when a motor with low power factor needs power from the system, the capacitor is there to provide it. Then in the next half cycle, the motor releases its excess energy, and the capacitor is there to absorb it. Capacitors and reactive loads

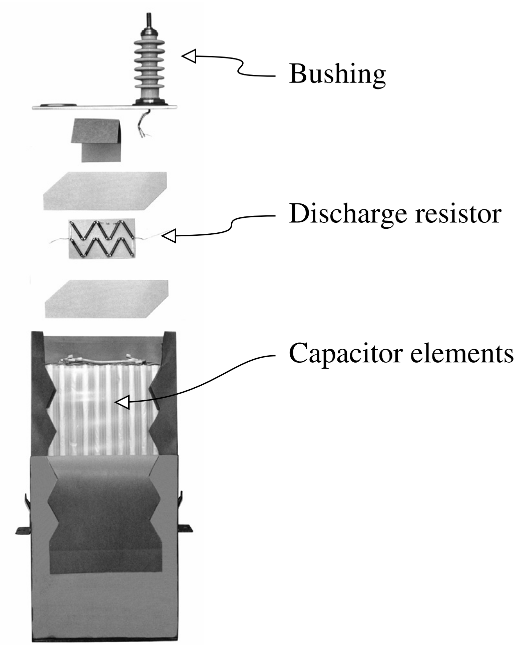

FIGURE 6.1
Capacitor components. (From General Electric Company. With permission.)

exchange this reactive power back and forth. This benefits the system because that reactive power (and extra current) does not have to be transmitted from the generators all the way through many transformers and many miles of lines; the capacitors can provide the reactive power locally. This frees up the lines to carry real power, power that actually does work.

Capacitor units are made of series and parallel combinations of capacitor packs or elements put together as shown in Figure 6.1. Capacitor elements have sheets of polypropylene film, less than one mil thick, sandwiched between aluminum foil sheets. Capacitor dielectrics must withstand on the order of 2000 V/mil (78 kV/mm). No other medium-voltage equipment has such high voltage stress. An underground cable for a 12.47-kV system has insulation that is at least 0.175 in. (4.4 mm) thick. A capacitor on the same system has an insulation separation of only 0.004 in. (0.1 mm).

Utilities often install substation capacitors and capacitors at points on distribution feeders. Most feeder capacitor banks are pole mounted, the least expensive way to install distribution capacitors. Pole-mounted capacitors normally provide 300 to 3600 kvar at each installation. Many capacitors are switched, either based on a local controller or from a centralized controller through a communication medium. A line capacitor installation has the capacitor units as well as other components, possibly including arresters, fuses, a control power transformer, switches, and a controller (see Figure 6.2 for an example).

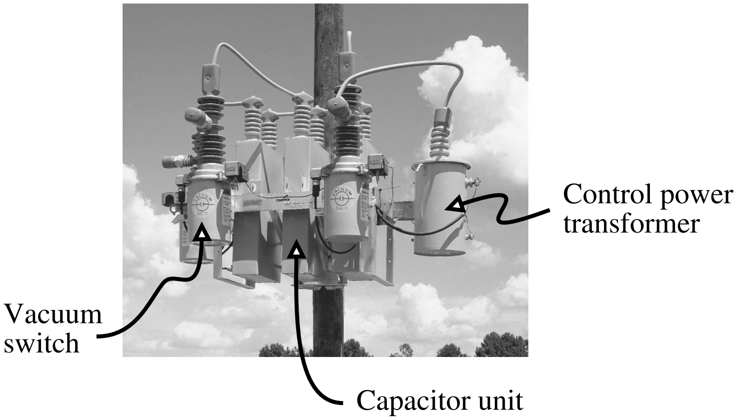

FIGURE 6.2
Overhead line capacitor installation. (From Cooper Power Systems, Inc. With permission.)

While most capacitors are pole mounted, some manufacturers provide padmounted capacitors. As more circuits are put underground, the need for padmounted capacitors will grow. Padmounted capacitors contain capacitor cans, switches, and fusing in a deadfront package following standard padmounted-enclosure integrity requirements (ANSI C57.12.28-1998). These units are much larger than padmounted transformers, so they must be sited more carefully to avoid complaints due to aesthetics. The biggest obstacles are cost and aesthetics. The main complaint is that padmounted capacitors are large. Customers complain about the intrusion and the aesthetics of such a large structure (see Figure 6.3).

FIGURE 6.3
Example padmounted capacitor. (From Northeast Power Systems, Inc. With permission.)

TABLE 6.1

Substation vs. Feeder Capacitors

Advantages	Disadvantages
Feeder Capacitors	
Reduces line losses	More difficult to control reliably
Reduces voltage drop along the feeder	Size and placement important
Frees up feeder capacity	
Lower cost	
Substation Capacitors	
Better control	No reduction in line losses
Best placement if leading vars are needed for system voltage support	No reduction in feeder voltage drop
	Higher cost

Substation capacitors are normally offered as open-air racks. Normally elevated to reduce the hazard, individual capacitor units are stacked in rows to provide large quantities of reactive power. All equipment is exposed. Stack racks require a large substation footprint and are normally engineered for the given substation. Manufacturers also offer metal-enclosed capacitors, where capacitors, switches, and fuses (normally current-limiting) are all enclosed in a metal housing.

Substation capacitors and feeder capacitors both have their uses. Feeder capacitors are closer to the loads — capacitors closer to loads more effectively release capacity, improve voltage profiles, and reduce line losses. This is especially true on long feeders that have considerable line losses and voltage drop. Table 6.1 highlights some of the differences between feeder and station capacitors. Substation capacitors are better when more precise control is needed. System operators can easily control substation capacitors wired into a SCADA system to dispatch vars as needed. Modern communication and control technologies applied to feeder capacitors have reduced this advantage. Operators can control feeder banks with communications just like station banks, although some utilities have found the reliability of switched feeder banks to be less than desired, and the best times for switching in vars needed by the system may not correspond to the best time to switch the capacitor in for the circuit it is located on.

Substation capacitors may also be desirable if a leading power factor is needed for voltage support. If the power factor is leading, moving this capacitor out on the feeder increases losses. Substation capacitors cost more than feeder capacitors. This may seem surprising, but we must individually engineer station capacitors, and the space they take up in a station is often valuable real estate. Pole-mounted capacitor installations are more standardized.

Utilities normally apply capacitors on three-phase sections. Applications on single-phase lines are done but less common. Application of three-phase banks downstream of single-phase protectors is normally not done because of ferroresonance concerns. Most three-phase banks are connected grounded-wye on four-wire multigrounded circuits. Some are connected in floating wye. On three-wire circuits, banks are normally connected as a floating wye.

Most utilities also include arresters and fuses on capacitor installations. Arresters protect capacitor banks from lightning-overvoltages. Fuses isolate failed capacitor units from the system and clear the fault before the capacitor fails violently. In high fault-current areas, utilities may use current-limiting fuses. Switched capacitor units normally have oil or vacuum switches in addition to a controller. Depending on the type of control, the installation may include a control power transformer for power and voltage sensing and possibly a current sensor. Because a capacitor bank has a number of components, capacitors normally are not applied on poles with other equipment.

Properly applied capacitors return their investment very quickly. Capacitors save significant amounts of money in reduced losses. In some cases, reduced loadings and extra capacity can also delay building more distribution infrastructure.

6.1 Capacitor Ratings

Capacitor units rated from 50 to over 500 kvar are available; Table 6.2 shows common capacitor unit ratings. A capacitor's rated kvar is the kvar at rated voltage. Three-phase capacitor banks are normally referred to by the total kvar on all three phases. Distribution feeder banks normally have one or two or (more rarely) three units per phase. Many common size banks only have one capacitor unit per phase.

IEEE Std. 18 defines standards for capacitors and provides application guidelines. Capacitors should not be applied when any of the following limits are exceeded (IEEE Std. 18-2002):

- 135% of nameplate kvar
- 110% of rated rms voltage, and crest voltage not exceeding $1.2\sqrt{2}$ of rated rms voltage, including harmonics but excluding transients
- 135% of nominal rms current based on rated kvar and rated voltage

Capacitor dielectrics must withstand high voltage stresses during normal operation — on the order of 2000 V/mil. Capacitors are designed to withstand overvoltages for short periods of time. IEEE Std. 18-1992 allows up to 300 power-frequency overvoltages within the time durations in Table 6.3 (without transients or harmonic content). New capacitors are tested with at least a 10-sec overvoltage, either a dc-test voltage of 4.3 times rated rms or an ac voltage of twice the rated rms voltage (IEEE Std. 18-2002).

TABLE 6.2

Common Capacitor Unit Ratings

Volts, rms (Terminal-to-Terminal)	kvar	Number of Phases	BIL, kV
216	5, 7 1/2, 13 1/3, 20, and 25	1 and 3	30
240	2.5, 5, 7 1/2, 10, 15, 20, 25, and 50	1 and 3	30
480, 600	5, 10, 15, 20, 25, 35, 50, 60, and 100	1 and 3	30
2400	50, 100, 150, 200, 300, and 400	1 and 3	75, 95, 125, 150, and 200
2770	50, 100, 150, 200, 300, 400, and 500	1 and 3	75, 95, 125, 150, and 200
4160, 4800	50, 100, 150, 200, 300, 400, 500, 600, 700, and 800	1 and 3	75, 95, 125, 150, and 200
6640, 7200, 7620, 7960, 8320, 9540, 9960, 11,400, 12,470, 13,280, 13,800, 14,400	50, 100, 150, 200, 300, 400, 500, 600, 700, and 800	1	95, 125, 150, and 200
15,125	50, 100, 150, 200, 300, 400, 500, 600, 700, and 800	1	125, 150, and 200
19,920	100, 150, 200, 300, 400, 500, 600, 700, and 800	1	125, 150, and 200
20,800, 21,600, 22,800, 23,800, 24,940	100, 150, 200, 300, 400, 500, 600, 700, and 800	1	150 and 200

Source: IEEE Std. 18-2002. Copyright 2002 IEEE. All rights reserved.

TABLE 6.3

Maximum Permissible Power-Frequency Voltages

Duration	Maximum Permissible Voltage (multiplying factor to be applied to rated voltage rms)
6 cycles	2.20
15 cycles	2.00
1 sec	1.70
15 sec	1.40
1 min	1.30
30 min	1.25
Continuous	1.10

Note: This is not in IEEE Std. 18-2002 but it will be addressed in IEEE's updated capacitor application guide.

Source: ANSI/IEEE Std. 18-1992. Copyright 1993 IEEE. All rights reserved.

Capacitors should withstand various peak voltage and current transients; the allowable peak depends on the number of transients expected per year (see Table 6.4).

The capacitance of a unit in microfarads is

TABLE 6.4

Expected Transient Overcurrent and Overvoltage Capability

Probable Number of Transients per year	Permissible Peak Transient Current (multiplying factor to be applied to rated rms current)	Permissible Peak Transient Voltage (multiplying factor to be applied to rated rms voltage)
4	1500	5.0
40	1150	4.0
400	800	3.4
4000	400	2.9

Note: This is not in IEEE Std. 18-2002, but it will be addressed in IEEE's updated capacitor application guide.

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$$C_{uF} = \frac{2.65 Q_{kvar}}{V_{kV}^2}$$

where
V_{kV} = capacitor voltage rating, kV
Q_{kvar} = unit reactive power rating, kvar

Capacitors are made within a given tolerance. The IEEE standard allows reactive power to range between 100 and 110% when applied at rated sinusoidal voltage and frequency (at 25°C case and internal temperature) (IEEE Std. 18-2002). Older units were allowed to range up to 115% (ANSI/IEEE Std. 18-1992). Therefore, the capacitance also must be between 100 and 110% of the value calculated at rated kvar and voltage. In practice, most units are from +0.5 to +4.0%, and a given batch is normally very uniform.

Capacitor losses are typically on the order of 0.07 to 0.15 W/kvar at nominal frequency. Losses include resistive losses in the foil, dielectric losses, and losses in the internal discharge resistor.

Capacitors must have an internal resistor that discharges a capacitor to 50 V or less within 5 min when the capacitor is charged to the peak of its rated voltage $(\sqrt{2}V_{rms})$. This resistor is the major component of losses within a capacitor. The resistor must be low enough such that the *RC* time constant causes it to decay in 300 sec as

$$\frac{50}{\sqrt{2}V} \le e^{-300/RC}$$

where
V = capacitor voltage rating, V
R = discharge resistance, Ω
C = capacitance, F

TABLE 6.5

Maximum Ambient Temperatures for Capacitor Application

Mounting Arrangement	Ambient Air Temperature (°C) 4-h Average[a]
Isolated capacitor	46
Single row of capacitors	46
Multiple rows and tiers of capacitors	40
Metal-enclosed or -housed equipments	40

[a] The arithmetic average of the four consecutive highest hourly readings during the hottest day expected at that location.

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So, the discharge resistor must continually dissipate at least the following power in watts:

$$P_{watts} = -\frac{Q_{kvar}}{113.2}\ln\left(\frac{35.36}{V}\right)$$

where Q_{kvar} is the capacitor rating (single or three phase). For 7.2-kV capacitors, the lower bound on losses is 0.047 W/kvar.

Some utilities use a shorting bar across the terminals of capacitors during shipping and in storage. The standard recommends waiting for 5 min to allow the capacitor to discharge through the internal resistor.

Capacitors have very low losses, so they run very cool. But capacitors are very sensitive to temperature and are rated for lower temperatures than other power system equipment such as cables or transformers. Capacitors do not have load cycles like transformers; they are always at full load. Also, capacitors are designed to operate at high dielectric stresses, so they have less margin for degraded insulation. Standards specify an upper limit for application of 40 or 46°C depending on arrangement (see Table 6.5). These limits assume unrestricted ventilation and direct sunlight. At the lower end, IEEE standard 18 specifies that capacitors shall be able to operate continuously in a –40°C ambient.

6.2 Released Capacity

In addition to reducing losses and improving voltage, capacitors release capacity. Improving the power factor increases the amount of real-power load the circuit can supply. Using capacitors to supply reactive power reduces the amount of current in the line, so a line of a given ampacity can

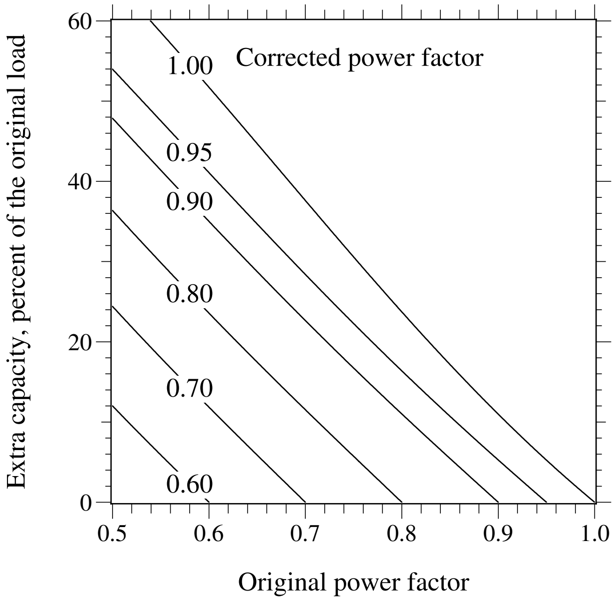

FIGURE 6.4
Released capacity with improved power factor.

carry more load. Figure 6.4 shows that capacitors release significant capacity, especially if the original power factor is low. Figure 6.5 shows another way to view the extra capacity, as a function of the size of capacitor added.

6.3 Voltage Support

Capacitors are constant-impedance devices. At higher voltages, capacitors draw more current and produce more reactive power as

$$I = I_{rated} V_{pu} \quad \text{and} \quad Q_{kvar} = Q_{rated} V_{pu}^{\;2}$$

where V_{pu} is the voltage in per unit of the capacitor's voltage rating. Capacitors applied at voltages other than their rating provide vars in proportion to the per-unit voltage squared.

Capacitors provide almost a fixed voltage rise. The reactive current through the system impedance causes a voltage rise in percent of

$$V_{rise} = \frac{Q_{kvar} X_L}{10\, V_{kV,l\text{-}l}^2}$$

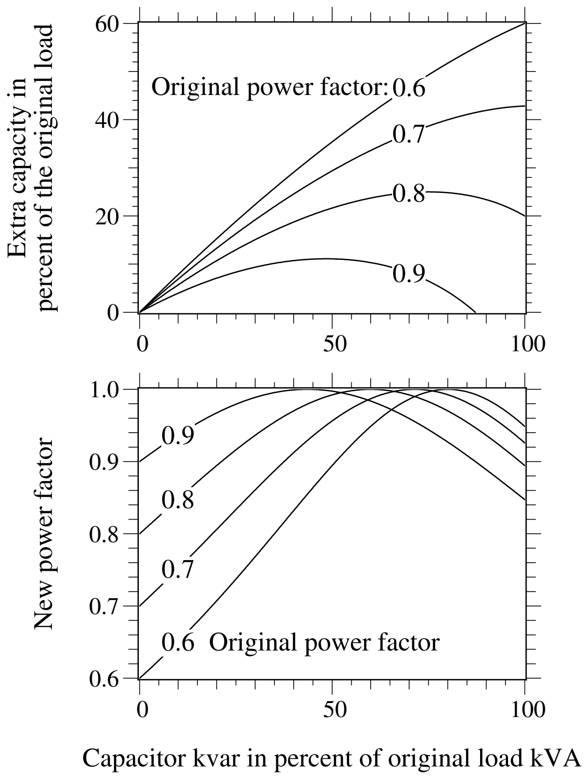

FIGURE 6.5
Extra capacity as a function of capacitor size.

where

X_L = positive-sequence system impedance from the source to the capacitor, Ω

$V_{kV,\,l\text{-}l}$ = line-to-line system voltage, kV

Q_{kvar} = three-phase bank rating, kvar

While this equation is very good for most applications, it is not exactly right because the capacitive current changes in proportion to voltage. At a higher operating voltage, a capacitor creates more voltage rise than the equation predicts.

Since the amount of voltage rise is dependent on the impedance upstream of the bank, to get the voltage boost along the entire circuit, put the capacitor at the end of the circuit. The best location for voltage support depends on where the voltage support is needed. Figure 6.6 shows how a capacitor changes the voltage profile along a circuit. Unlike a regulator, a capacitor changes the voltage profile upstream of the bank.

Table 6.6 shows the percentage voltage rise from capacitors for common conductors at different voltages. This table excludes the station transformer

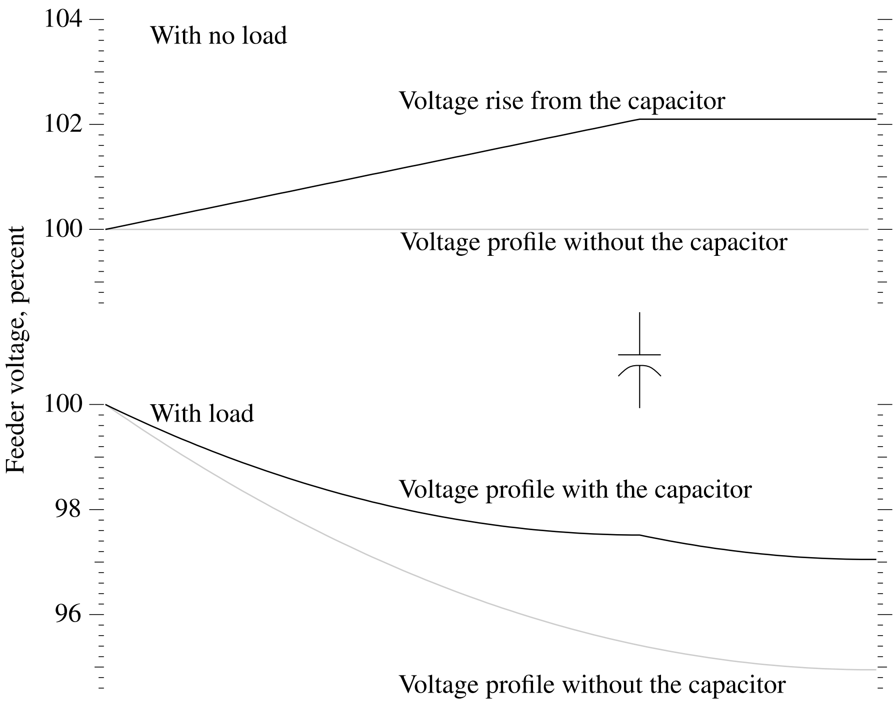

FIGURE 6.6
Voltage profiles after addition of a capacitor bank. (Copyright © 2002. Electric Power Research Institute. 1001691. *Improved Reliability of Switched Capacitor Banks and Capacitor Technology.* Reprinted with permission.)

TABLE 6.6
Percent Voltage Rise for Various Conductors and Voltage Levels

		Percent Voltage Rise per Mile with 100 kvar per Phase			
		Line-to-Line System Voltage, kV			
Conductor Size	X_L **Ω/mi**	**4.8**	**12.47**	**24.9**	**34.5**
4	0.792	1.031	0.153	0.038	0.020
2	0.764	0.995	0.147	0.037	0.019
1/0	0.736	0.958	0.142	0.036	0.019
4/0	0.694	0.903	0.134	0.034	0.017
350	0.656	0.854	0.127	0.032	0.017
500	0.635	0.826	0.122	0.031	0.016
750	0.608	0.791	0.117	0.029	0.015

Note: Impedance are for all-aluminum conductors with GMD=4.8 ft.

impedance but still provides a useful approximation. Inductance does not change much with conductor size; the voltage change stays the same over a wide range of conductor sizes. For 15-kV class systems, capacitors increase the voltage by about 0.12% per mi per 100 kvar per phase.

On switched capacitor banks, the voltage change constrains the size of banks at some locations. Normally, utilities limit the voltage change to 3 to 4%. On a 12.47-kV circuit, a three-phase 1200-kvar bank boosts the voltage 4% at about 8 mi from the substation. To keep within a 4% limit, 1200-kvar banks must only be used within the first 8 mi of the station.

6.4 Reducing Line Losses

One of the main benefits of applying capacitors is that they can reduce distribution line losses. Losses come from current through the resistance of conductors. Some of that current transmits real power, but some flows to supply reactive power. Reactive power provides magnetizing for motors and other inductive loads. Reactive power does not spin kWh meters and performs no useful work, but it must be supplied. Using capacitors to supply reactive power reduces the amount of current in the line. Since line losses are a function of the current squared, I^2R, reducing reactive power flow on lines significantly reduces losses.

Engineers widely use the "2/3 rule" for sizing and placing capacitors to optimally reduce losses. Neagle and Samson (1956) developed a capacitor placement approach for uniformly distributed lines and showed that the optimal capacitor location is the point on the circuit where the reactive power flow equals half of the capacitor var rating. From this, they developed the 2/3 rule for selecting and placing capacitors. For a uniformly distributed load, the optimal size capacitor is 2/3 of the var requirements of the circuit. The optimal placement of this capacitor is 2/3 of the distance from the substation to the end of the line. For this optimal placement for a uniformly distributed load, the substation source provides vars for the first 1/3 of the circuit, and the capacitor provides vars for the last 2/3 of the circuit (see Figure 6.7).

A generalization of the 2/3 rule for applying n capacitors to a circuit is to size each one to $2/(2n+1)$ of the circuit var requirements. Apply them equally spaced, starting at a distance of $2/(2n+1)$ of the total line length from the substation and adding the rest of the units at intervals of $2/(2n+1)$ of the total line length. The total vars supplied by the capacitors is $2n/(2n+1)$ of the circuit's var requirements. So to apply three capacitors, size each to 2/7 of the total vars needed, and locate them at per unit distances of 2/7, 4/7, and 6/7 of the line length from the substation.

Grainger and Lee (1981) provide an optimal yet simple method for placing fixed capacitors on a circuit with any load profile, not just a uniformly

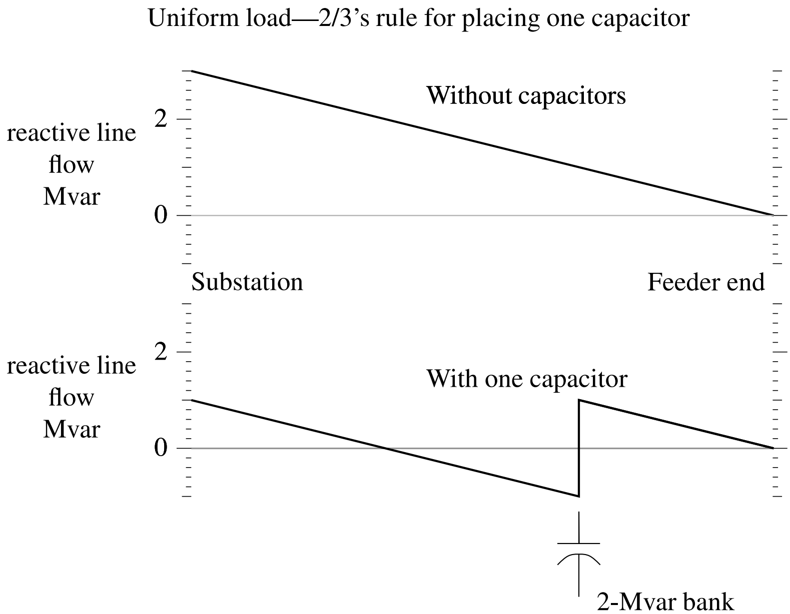

FIGURE 6.7
Optimal capacitor loss reduction using the two-thirds rule. (Copyright © 2002. Electric Power Research Institute. 1001691. *Improved Reliability of Switched Capacitor Banks and Capacitor Technology.* Reprinted with permission.)

distributed load. With the Grainger/Lee method, we use the reactive load profile of a circuit to place capacitors. The basic idea is again to locate banks at points on the circuit where the reactive power equals one half of the capacitor var rating. With this 1/2-*kvar rule*, the capacitor supplies half of its vars downstream, and half are sent upstream. The basic steps of this approach are:

1. *Pick a size* — Choose a standard size capacitor. Common sizes range from 300 to 1200 kvar, with some sized up to 2400 kvar. If the bank size is 2/3 of the feeder requirement, we only need one bank. If the size is 1/6 of the feeder requirement, we need five capacitor banks.
2. *Locate the first bank* — Start from the end of the circuit. Locate the first bank at the point on the circuit where var flows on the line are equal to half of the capacitor var rating.
3. *Locate subsequent banks* — After a bank is placed, reevaluate the var profile. Move upstream until the next point where the var flow equals half of the capacitor rating. Continue placing banks in this manner until no more locations meet the criteria.

There is no reason we have to stick with the same size of banks. We could place a 300-kvar bank where the var flow equals 150 kvar, then apply a 600-

kvar bank where the var flow equals 300 kvar, and finally apply a 450-kvar bank where the var flow equals 225 kvar. Normally, it is more efficient to use standardized bank sizes, but different size banks at different portions of the feeder might help with voltage profiles.

The 1/2-kvar method works for any section of line. If a line has major branches, we can apply capacitors along the branches using the same method. Start at the end, move upstream, and apply capacitors at points where the line's kvar flow equals half of the kvar rating of the capacitor. It also works for lines that already have capacitors (it does not optimize the placement of all of the banks, but it optimizes placement of new banks). For large industrial loads, the best location is often going to be right at the load.

Figure 6.8 shows the optimal placement of 1200-kvar banks on an example circuit. Since the end of the circuit has reactive load above the 600-kvar threshold for sizing 1200-kvar banks, we apply the first capacitor at the end

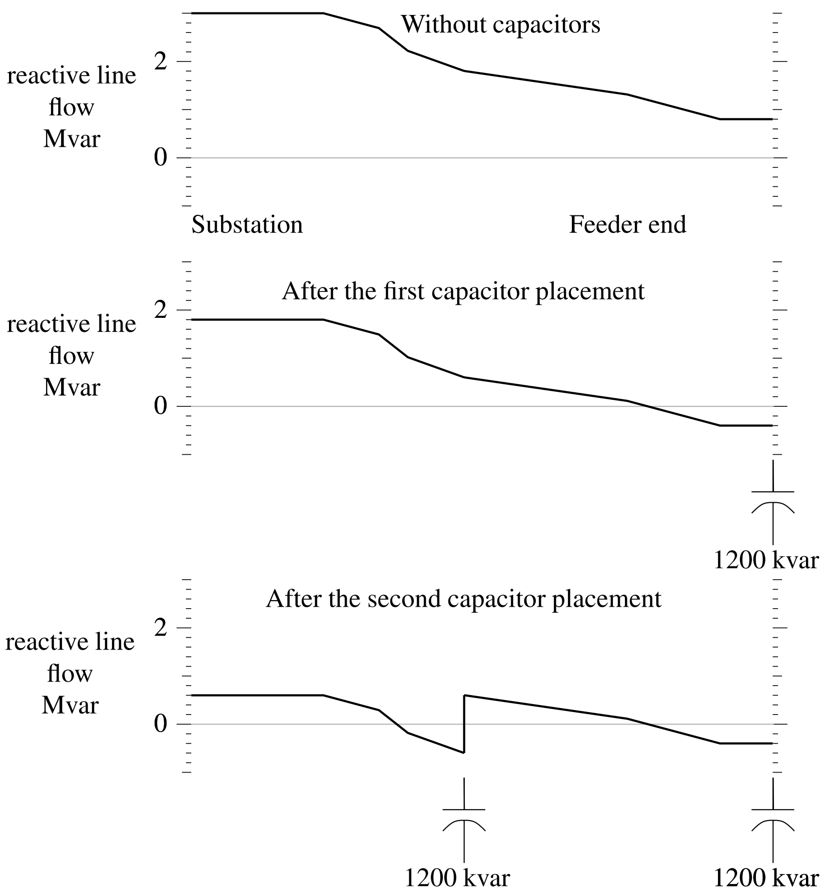

FIGURE 6.8
Placement of 1200-kvar banks using the 1/2-kvar method.

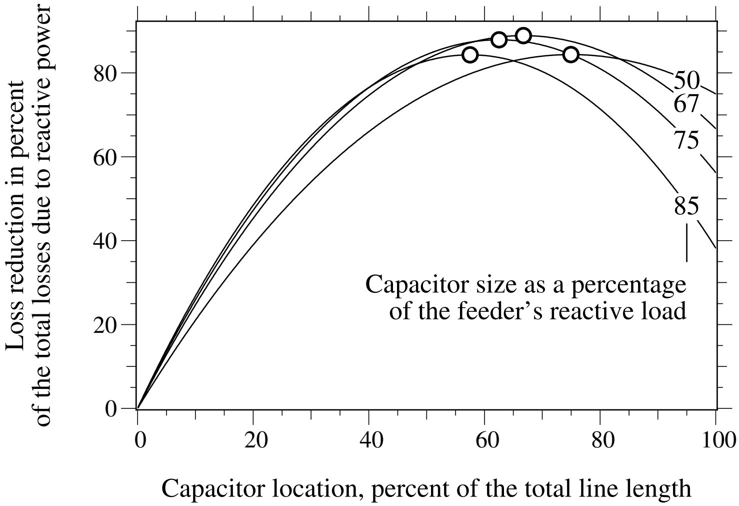

FIGURE 6.9
Sensitivity to losses of sizing and placing one capacitor on a circuit with a uniform load. (The circles mark the optimum location for each of the sizes shown.)

of the circuit. (The circuit at the end of the line could be one large customer or branches off the main line.) The second bank goes near the middle. The circuit has an express feeder near the start. Another 1200-kvar bank could go in just after the express feeder, but that does not buy us anything. The two capacitors total 2400 kvar, and the feeder load is 3000 kvar. We really need another 600-kvar capacitor to zero out the var flow before it gets to the express feeder.

Fortunately, capacitor placement and sizing does not have to be exact. Quite good loss reduction occurs even if sizing and placement are not exactly optimum. Figure 6.9 shows the loss reduction for one fixed capacitor on a circuit with a uniform load. The 2/3 rule specifies that the optimum distance is 2/3 of the distance from the substation and 2/3 of the circuit's var requirement. As long as the size and location are somewhat close (within 10%), the not-quite-optimal capacitor placement provides almost as much loss reduction as the optimal placement.

Consider the voltage impacts of capacitors. Under light load, check that the capacitors have not raised the voltages above allowable standards. If voltage limits are exceeded, reduce the size of the capacitor banks or the number of capacitor banks until voltage limits are not exceeded. If additional loss reduction is desired, consider switched banks as discussed below.

6.4.1 Energy Losses

Use the average reactive loading profile to optimally size and place capacitors for energy losses. If we use the peak-load case, the 1/2-kvar method optimizes losses during the peak load. If we have a load-flow case with the average reactive load, the 1/2-kvar method or the 2/3 rule optimizes energy losses. This leads to more separation between banks and less kvars applied than if we optimize for peak losses.

If an average system case is not available, then we can estimate it by scaling the peak load case by the reactive load factor, *RLF*:

$$RLF = \frac{\text{Average kvar Demand}}{\text{Peak kvar Demand}}$$

The reactive load factor is similar to the traditional load factor except that it only considers the reactive portion of the load. If we have no information on the reactive load factor, use the total load factor. Normally, the reactive load factor is higher than the total load factor. Figure 6.10 shows an example of power profiles; the real power (kW) fluctuates significantly more than the reactive power (kvar).

6.5 Switched Banks

Switched banks provide benefits under the following situations:

- *More loss reduction* — As the reactive loading on the circuit changes, we reduce losses by switching banks on and off to track these changes.
- *Voltage limits* — If optimally applied banks under the average loading scenario cause excessive voltage under light load, then use switched banks.

In addition, automated capacitors — those with communications — have the flexibility to also use distribution vars for transmission support.

Fixed banks are relatively easy to site and size optimally. Switched banks are more difficult. Optimally sizing capacitors, placing them, and deciding when to switch them are difficult tasks. Several software packages are available that can optimize this solution. This is an intensely studied area, and technical literature documents several approaches (among these Carlisle and El-Keib, 2000; Grainger and Civanlar, 1985; Shyh, 2000).

To place switched capacitors using the 1/2-kvar method, again place the banks at the location where the line kvar equals half the bank rating. But instead of using the average reactive load profile (the rule for fixed banks), use the average reactive flow during the time the capacitor is on. With time-switched banks and information on load profiles (or typical load profiles),

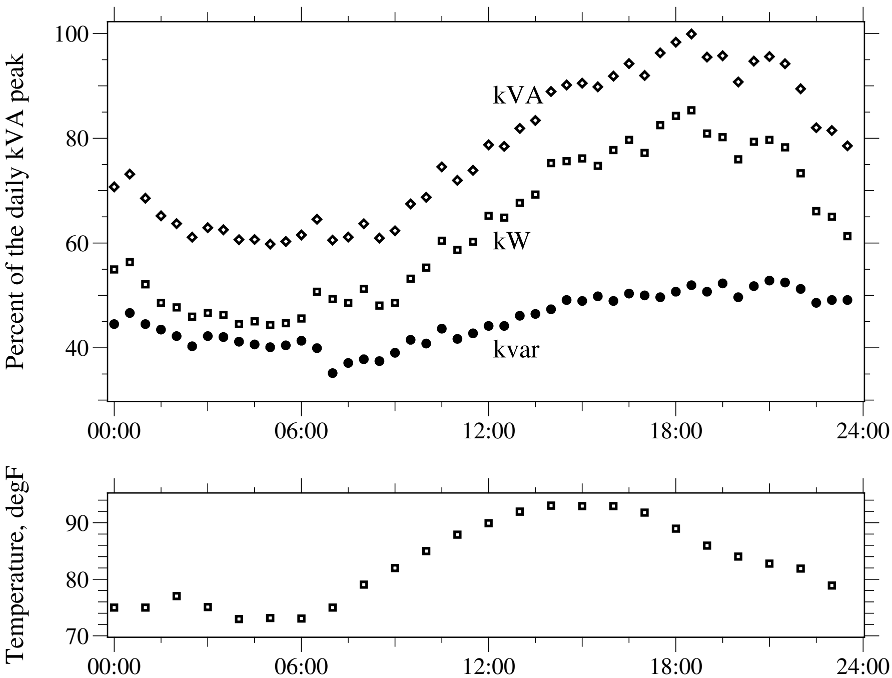

FIGURE 6.10
Example of real and reactive power profiles on a residential feeder on a peak summer day with 95% air conditioning. (Data from East Central Oklahoma Electric Cooperative, Inc. [RUS 1724D-112, 2001].)

we can pick the on time and the off time and determine the proper sizing based on the average reactive flow between the on and off times. Or, we can place a bank and pick the on and off times such that the average reactive line flow while the bank is switched on equals half of the bank rating. In these cases, we have specified the size and either the placement or switching time. To more generally optimize — including sizing, placement, number of banks, and switching time — we must use a computer, which iterates to find a solution [see Lee and Grainger (1981) for one example].

Combinations of fixed and switched banks are more difficult. The following approach is not optimal but gives reasonable results. Apply fixed banks to the circuit with the 1/2-kvar rule based on the light-load case. Check voltages. If there are undervoltages, increase the size of capacitors, use more capacitor banks, or add regulators. Now, look for locations suitable for switched banks. Again, use the average reactive line flows for the time when the capacitor is on (with the already-placed fixed capacitors in the circuit model). When applying switched capacitors, check the light-load case for possible overvoltages, and check the peak-load case for undervoltages.

6.6 Local Controls

Several options for controls are available for capacitor banks:

- *Time clock* — The simplest scheme: the controller switches capacitors on and off based on the time of day. The on time and the off time are programmable. Modern controllers allow settings for weekends and holidays. This control is the cheapest but also the most susceptible to energizing the capacitor at the wrong time (due to loads being different from those expected, to holidays or other unexpected light periods, and especially to mistakenly set or inaccurate clocks). Time clock control is predictable; capacitors switch on and off at known times and the controller limits the number of switching operations (one energization and one deenergization per day).
- *Temperature* — Another simple control; the controller switches the capacitor bank on or off depending on temperature. Normally these might be set to turn the capacitors on in the range of 85 and 90°F and turn them off at temperatures somewhere between 75 and 80°F.
- *Voltage* — The capacitor switches on and off, based on voltage. The user provides the threshold minimum and maximum voltages as well as time delays and bandwidths to prevent excessive operations. Voltage control is most appropriate when the primary role of a capacitor is voltage support and regulation.
- *Vars* — The capacitor uses var measurements to determine switching. This is the most accurate method of ensuring that the capacitor is on at the appropriate times for maximum reduction of losses.
- *Power factor* — Similar to var control, the controller switches capacitors on and off based on the measured power factor. This is rarely used by utilities.
- *Current* — The capacitor switches on and off based on the line current (as measured downstream of the capacitor). While not as effective as var control, current control does engage the capacitor during heavy loads, which usually corresponds to the highest needs for vars.

Many controllers offer many or all of these possibilities. Many are usable in combination; turn capacitors on for low voltage or for high temperature.

Var, power factor, voltage, or current controllers require voltage or current sensing or both. To minimize cost and complexity, controllers often switch all three phases using sensors on just one phase. A control power transformer is often also used to sense voltage. While unusual, Alabama Power switches each phase independently depending on the var requirements of each phase (Clark, 2001); this optimizes loss reduction and helps reduce unbalance. Because capacitor structures are rather busy, some utilities like to use voltage and/or current-sensing insulators. Meter-grade accuracy is not needed for controlling capacitors.

To coordinate more than one capacitor with switched var controls, set the most-distant unit to have the shortest time delay. Increase the time delay on successive units progressing back to the substation. This leaves the unit closest to the substation with the longest time delay. The most distant unit switches first. Upstream units see the change and do not need to respond. This strategy is the opposite of that used for coordinating multiple line voltage regulators.

For var-controlled banks, locate the current sensor on the source (substation) side of the bank. Then, the controller can detect the reactive power change when the capacitor switches. To properly calculate vars, the wiring for the CT and PT must provide correct polarities to the controller.

One manufacturer provides the following rules of thumb for setting var control trip and close settings (Fisher Pierce, 2000):

- Close setpoint: 2/3 × capacitor bank size (in kvar), lagging.
- Trip setpoint: Close set point – 1.25 × bank size, will be leading. (This assumes that the CT is on the source side of the bank.)

For a 600-kvar bank application, this yields

Close setpoint: $2/3 \times 600 = +400$ kvar (lagging)

Trip setpoint: $400 - 1.25 \times 600 = -350$ kvar (leading)

For this example, the unit trips when the load kvar drops below +250 kvar (lagging). This effectively gives a bandwidth wide enough (+400 to +250 kvar) to prevent excessive switching operations in most cases.

Voltage-controlled capacitor banks have bandwidths. Normally, we want the bandwidth to be at least 1.5 times the expected voltage change due to the capacitor bank. Ensure that the bandwidth is at least 3 or 4 V (on a 120-V scale). Set the trip setting below the normal light-load voltage (or the bank will never switch off).

If a switched capacitor is located on a circuit that can be operated from either direction, make sure the controller mode can handle operation with power flow in either direction. Time-of-day, temperature, and voltage control are not affected by reverse power flow; var, current, and power factor control are affected. Some controllers can sense reverse power and shift control modes. One model provides several options if it detects reverse power: switch to voltage mode, calculate var control while accounting for the effect of the capacitor bank, inhibit switching, trip and lock out the bank, or close and hold the bank in. If a circuit has distributed generation, we do not want to shift modes based on reverse power flow; the controller should shift modes only for a change in direction to the system source.

Capacitor controllers normally have counters to record the number of operations. The counters help identify when to perform maintenance and can identify control-setting problems. For installations that are excessively switching, modify control settings, time delays, or bandwidths to reduce switching. Some controllers can limit the number of switch operations within a given time period to reduce wear on capacitor switches.

Voltage control provides extra safety to prevent capacitors from causing overvoltages. Some controllers offer types of voltage override control; the primary control may be current, vars, temperature, or time of day, but the controller trips the bank if it detects excessive voltage. A controller may also restrain from switching in if the extra voltage rise from the bank would push the voltage above a given limit.

6.7 Automated Controls

Riding the tide of lower-cost wireless communication technologies, many utilities have automated capacitor banks. Many of the cost reductions and feature improvements in communication systems have resulted from the proliferation of cellular phones, pagers, and other wireless technologies used by consumers and by industry. Controlling capacitors requires little bandwidth, so high-speed connections are unnecessary. This technology changes quickly. The most common communications systems for distribution line capacitors are 900-MHz radio systems, pager systems, cellular phone systems, cellular telemetric systems, and VHF radio. Some of the common features of each are

- *900-MHz radio* — Very common. Several spread-spectrum data radios are available that cover 902–928 MHz applications. A private network requires an infrastructure of transmission towers.
- *Pager systems* — Mostly one-way, but some two-way, communications. Pagers offer inexpensive communications options, especially for infrequent usage. One-way communication coverage is widespread; two-way coverage is more limited (clustered around major cities). Many of the commercial paging networks are suitable for capacitor switching applications.
- *Cellular phone systems* — These use one of the cellular networks to provide two-way communications. Many vendors offer cellular modems for use with several cellular networks. Coverage is typically very good.
- *Cellular telemetric systems* — These use the unused data component of cellular signals that are licensed on existing cellular networks. They allow only very small messages to be sent — enough, though,

to perform basic capacitor automation needs. Coverage is typically very good, the same as regular cellular coverage.

- *VHF radio* — Inexpensive one-way communications are possible with VHF radio communication. VHF radio bands are available for telemetry uses such as this. Another option is a simulcast FM signal that uses extra bandwidth available in the commercial FM band.

Standard communication protocols help ease the building of automated infrastructures. Equipment and databases are more easily interfaced with standard protocols. Common communication protocols used today for SCADA applications and utility control systems include DNP3, IEC 870, and Modbus.

DNP 3.0 (Distributed Network Protocol) is the most widely used standard protocol for capacitor controllers (DNP Users Group, 2000). It originated in the electric industry in America with Harris Distributed Automation Products and was based on drafts of the IEC870-5 SCADA protocol standards (now known as IEC 60870-5). DNP supports master–slave and peer-to-peer communication architectures. The protocol allows extensions while still providing interoperability. Data objects can be added to the protocol without affecting the way that devices interoperate. DNP3 was designed for transmitting data acquisition information and control commands from one computer to another. (It is not a general purpose protocol for hypertext, multimedia, or huge files.)

One-way or two-way — we can remotely control capacitors either way. Two-way communication has several advantages:

- *Feedback* — A local controller can confirm that a capacitor switched on or off successfully. Utilities can use the feedback from two-way communications to dispatch crews to fix capacitor banks with blown fuses, stuck switches, misoperating controllers, or other problems.
- *Voltage/var information* — Local information on line var flows and line voltages allows the control to more optimally switch capacitor banks to reduce losses and keep voltages within limits.
- *Load flows* — Voltage, current, and power flow information from pole-mounted capacitor banks can be used to update and verify load-flow models of a system. The information can also help when tracking down customer voltage, stray voltage, or other power quality problems. Loading data helps utilities monitor load growth and plan for future upgrades. One utility even uses capacitor controllers to capture fault location information helping crews to locate faults.

When a controller only has one-way communications, a local voltage override control feature is often used. The controller blocks energizing a capacitor bank if doing so would push the voltage over limits set by the user.

Several schemes and combinations of schemes are used to control capacitors remotely:

- *Operator dispatch* — Most schemes allow operators to dispatch distribution capacitors. This feature is one of the key reasons utilities automate capacitor banks. Operators can dispatch distribution capacitors just like large station banks. If vars are needed for transmission support, large numbers of distribution banks can be switched on. This control scheme is usually used in conjunction with other controls.
- *Time scheduling* — Capacitors can be remotely switched, based on the time of day and possibly the season or temperature. While this may seem like an expensive time control, it still allows operators to override the schedule and dispatch vars as needed.
- *Substation var measurement* — A common way to control feeder capacitors is to dispatch based on var/power factor measurements in the substation. If a feeder has three capacitor banks, they are switched on or off in some specified order based on the power factor on the feeder measured in the substation.
- *Others* — More advanced (and complicated) algorithms can dispatch capacitors based on a combination of local var measurements and voltage measurements along with substation var measurements.

6.8 Reliability

Several problems contribute to the overall reliability or unreliability of capacitor banks. In a detailed analysis of Kansas City Power & Light's automated capacitor banks, Goeckeler (1999) reported that blown fuses are KCP&L's biggest problem, but several other problems exist (Table 6.7). Their automa-

TABLE 6.7

Maintenance Needs Identified by Kansas City Power & Light's Capacitor Automation System Based on Two Years of Data

Problem	Annual Percent Failures
Primary fuse to capacitor blown (nuisance fuse operation)	9.1
Failed oil switches	8.1
Hardware accidentally set to "Local" or "Manual"	4.2
Defective capacitor unit	3.5
Miscellaneous	2.4
Control power transformer	1.5
TOTAL	28.8

Source: Goeckeler, C., "Progressive Capacitor Automation Yields Economic and Practical Benefits at KCPL," *Utility Automation*, October 1999.

tion with two-way communications allowed them to readily identify bank failures. The failure rates in Table 6.7 are high, much higher than most distribution equipment. Capacitor banks are complicated; they have a lot of equipment to fail; yet, failure rates should be significantly better than this.

An EPRI survey on capacitor reliability found wide differences in utilities' experience with capacitors (EPRI 1001691, 2002). Roughly one-third of survey responses found feeder capacitors "very good," another one-third found them "typical of line equipment," and the final third found them "problematic." The survey along with follow-up contacts highlighted several issues:

- *Misoperation of capacitor fuses* — Many utilities have operations of fuses where the capacitor bank is unharmed. This can unbalance circuit voltages and reduce the number of capacitors available for var support. Review fusing practices to reduce this problem.
- *Controllers* — Controllers were found "problematic" by a significant number of utilities. Some utilities had problems with switches and with the controllers themselves.
- *Lightning and faults* — In high-lightning areas, controllers can fail from lightning. Controllers are quite exposed to lightning and power-supply overvoltages during faults. Review surge protection practices and powering and grounding of controllers.
- *Human element* — Many controllers are set up incorrectly. Some controllers are hard to program. And, field crews often do not have the skills or proper attitudes toward capacitors and their controls. At some utilities, crews often manually switch off nearby capacitors (and often forget to turn them back on after finishing their work). To reduce these problems, properly train crews and drive home the need to have capacitors available when needed.

6.9 Failure Modes and Case Ruptures

Capacitors can fail in two modes:

- *Low current, progressive failure* — The dielectric fails in one of the elements within the capacitor (see Figure 6.11). With one element shorted, the remaining elements in the series string have increased voltage and higher current (because the total capacitive impedance is lower). With more stress, another element may short out. Failures can cascade until the whole string shorts out. In this scenario, the current builds up slowly as elements successively fail.

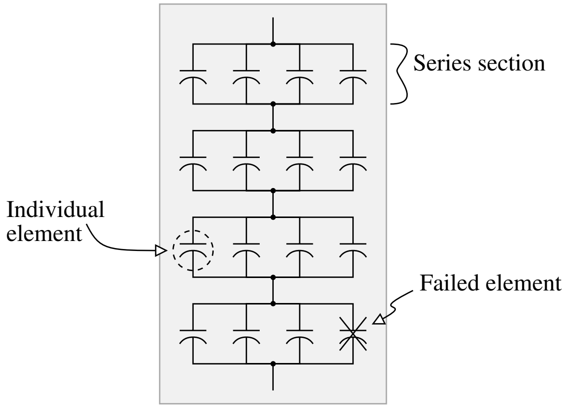

FIGURE 6.11
Capacitor unit with a failed element.

- *High current* — A low-impedance failure develops across the capacitor terminals or from a phase terminal to ground. A broken connector could cause such a fault.

Most failures are progressive. Sudden jumps to high current are rare. To detect progressive failures quickly, fusing must be very sensitive. Film-foil capacitors have few case ruptures — much less than older paper units. An EPRI survey of utilities (EPRI 1001691, 2002) found that film-foil capacitor ruptures were rare to nonexistent. This contrasts sharply with paper capacitors, where Newcomb (1980) reported that film/paper capacitors ruptured in 25% of failures.

Paper and paper-film capacitors have an insulating layer of paper between sheets of foil. When a breakdown in a pack occurs, the arc burns the paper and generates gas. In progressive failures, even though the current is only somewhat higher than normal load current, the sustained arcing can create enough gas to rupture the enclosure. Before 1975, capacitors predominantly used polychlorinated biphenyls (PCB) as the insulating liquid. Environmental regulations on PCB greatly increased the costs of cleanup if these units ruptured (U.S. Environmental Protection Agency 40 CFR Part 761 Polychlorinated Biphenyls (PCBs) Manufacturing, Processing, Distribution in Commerce, and Use Prohibitions). The environmental issues and safety concerns led utilities to tighten up capacitor fusing.

In modern film-foil capacitors, sheets of polypropylene film dielectric separate layers of aluminum foil. When the dielectric breaks down, the heat from the arc melts the film; the film draws back; and the aluminum sheets weld together. With a solid weld, a single element can fail and not create any gas (the current is still relatively low). In film-foil capacitors, the progressive failure mode is much less likely to rupture the case. When all of the packs in series fail, high current flows through the capacitor. This can generate enough heat and gas to rupture the capacitor if it is not cleared quickly.

Figure 6.12 shows capacitor-rupture curves from several sources. Most case-rupture curves are based on tests of prefailed capacitors. The capacitors are failed by applying excessive voltage until the whole capacitor is broken down. The failed capacitor is then subjected to a high-current short-circuit

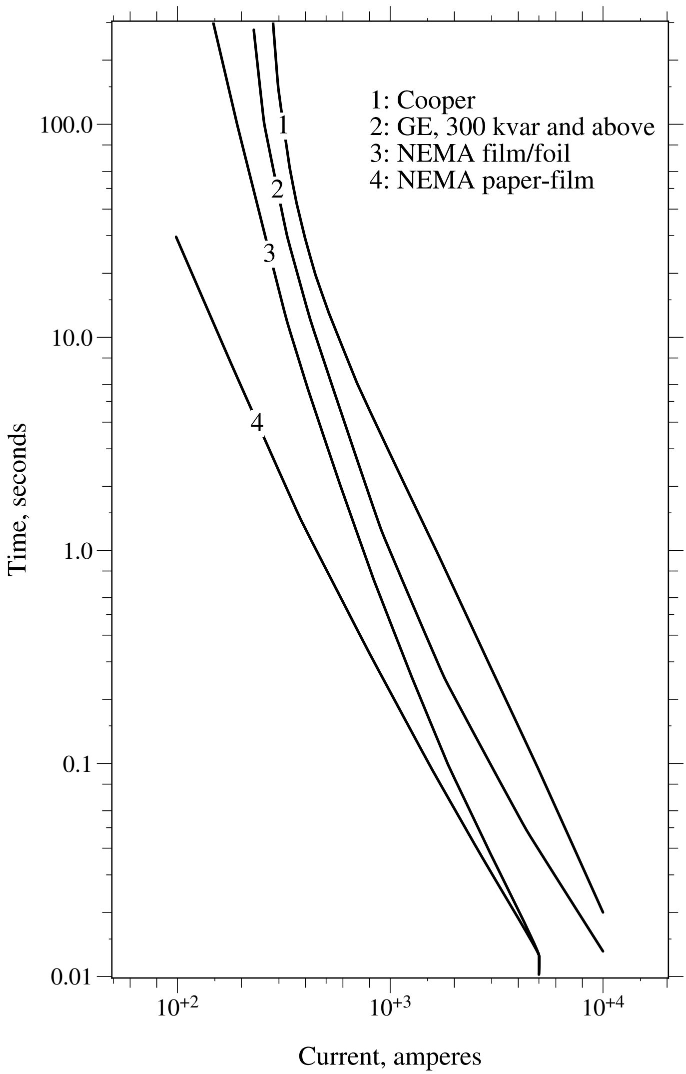

FIGURE 6.12
Capacitor rupture curves. (Data from [ANSI/IEEE Std. 18-1992; Cooper Power Systems, 1990; General Electric, 2001].)

source of known amperage for a given time. Several such samples are tested to develop a case-rupture curve.

The case-rupture curves do not represent all failure modes. Such curves do not show the performance during the most common failures: low-current and progressive element failures (before all elements are punctured). Although, thankfully, rare, high-current faults more severe than those tested for the rupture curves are possible. An arc through the insulating dielectric fluid can generate considerable pressure. Pratt et al. (1977) performed tests on film/foil capacitor units with arc lengths up to 3 in. (7.6 cm) in length. They chose 3 in. as the maximum realistic arc length in a capacitor as the gap spacing between internal series section terminals. Under these conditions, they damaged or ruptured several units for currents and times well below the capacitor rupture curves in Figure 6.12.

Also consider other equipment at a capacitor bank installation. Capacitor switches, especially oil switches, are vulnerable to violent failure. This type of failure has not received nearly the attention that capacitor ruptures or distribution transformer failures have. Potential transformers, current transformers, controller power-supply transformers, and arresters: these too can fail violently. Any failure in which an arc develops inside a small enclosure can rupture or explode. In areas with high fault current, consider applying current-limiting fuses. These will help protect against violent failures of capacitor units, switches, and other accessories in areas with high fault current.

When one element fails and shorts out, the other series sections have higher voltage, and they draw more current. Capacitor packs are designed with a polypropylene film layer less than one mil thick (0.001 in. or 0.025 mm), which is designed to hold a voltage of 2000 V. Table 6.8 shows the number of series sections for several capacitors as reported by Thomas (1990). More recent designs could have even fewer groups. One manufacturer uses three series sections for 7.2 to 7.96 kV units and six series sections for 12.47 to 14.4 kV units. As series sections fail, the remaining elements must hold increasing voltage, and the capacitor draws more current in the same proportion. Figure

TABLE 6.8

Number of Series Sections in Different Voltage Ratings

	Manufacturer		
Unit Voltage, V	**A**	**B**	**C**
2,400	2	2	2
7,200	4	4	4
7,620	5	5	4
13,280	8	8	7
13,800	8	8	—
14,400	8	8	8

Source: Thomas, E. S., "Determination of Neutral Trip Settings for Distribution Capacitor Banks," IEEE Rural Electric Power Conference, 1990. With permission. ©1990 IEEE.

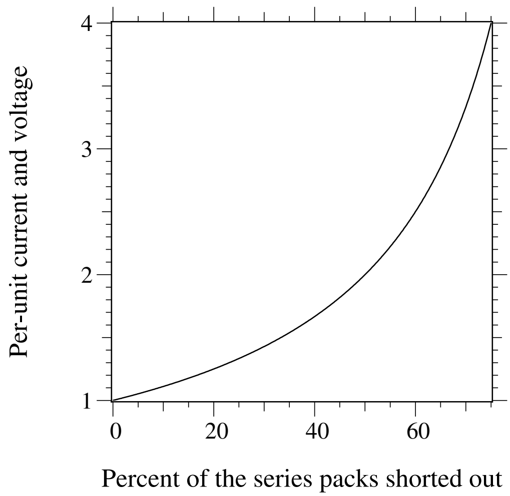

FIGURE 6.13
Per-unit current drawn by a failing bank depending on the portion of the bank that is failed (assuming an infinite bus). This is also the per-unit voltage applied on the series sections still remaining.

6.13 shows the effect on the per-unit current drawn by a failing unit and the per-unit voltage on the remaining series sections.

If a capacitor bank has multiple units on one phase and all units are protected by one fuse (group fusing), the total bank current should be considered. Consider a bank with two capacitor units. If one unit loses half of its series sections, that unit will draw twice its nominal current. The group — the two units together — will draw 1.5 times the nominal bank load. (This is the current that the fuse sees.)

6.10 Fusing and Protection

The main purpose of the fuse on a capacitor bank is to clear a fault if a capacitor unit or any of the accessories fail. The fuse must clear the fault quickly to prevent any of the equipment from failing violently. Ruptures of capacitors have historically been problematic, so fusing is normally tight. Fuses must be sized to withstand normal currents, including harmonics.

A significant number of utilities have problems with nuisance fuse operations on capacitor banks. A fuse is blown, but the capacitors themselves are still functional. These blown fuses may stay on the system for quite some time before they are noticed (see Figure 6.14). Capacitors with blown fuses increase voltage unbalance, can increase stray voltages, and increase losses. Even if the capacitor controller identifies blown fuses, replacement adds extra maintenance that crews must do.

FIGURE 6.14
Capacitor bank with a blown fuse. (Copyright © 2002. Electric Power Research Institute. 1001691. *Improved Reliability of Switched Capacitor Banks and Capacitor Technology.* Reprinted with permission.)

IEEE guides suggest selecting a fuse capable of handling 1.25 to 1.35 times the nominal capacitor current (IEEE Std. C37.48-1997); a 1.35 factor is most common. Three factors can contribute to higher than expected current:

- *Overvoltage* — Capacitive current increases linearly with voltage, and the reactive vars increase as the square of the voltage. When estimating maximum currents, an upper voltage limit of 110% is normally assumed.
- *Harmonics* — Capacitors can act as a sink for harmonics. This can increase the peak and the rms of the current through the capacitor. Additionally, grounded three-phase banks absorb zero-sequence harmonics from the system.
- *Capacitor tolerance* — Capacitors were allowed to have a tolerance to +15% above their rating (which would increase the current by 15%).

Most fusing practices are based on fusing as tightly as possible to prevent case rupture. So, the overload capability of fuse links is included in fuse sizing. This effectively allows a tighter fusing ratio. K and T tin links can be overloaded to 150%, so for these links with a 1.35 safety factor, the smallest size fuse that can be used is

$$I_{min} = \frac{1.35 I_1}{1.5} = 0.9 I_1$$

where
I_{min} = minimum fuse rating, A
I_1 = capacitor bank current, A

Table 6.9 shows one manufacturer's recommendations based on this tight-fusing approach.

With this tight-fusing strategy, fuses must be used consistently. If silver links are used instead of tin links, the silver fuses can blow from expected levels of current because silver links have no overload capability.

Prior to the 1970s, a fusing factor of 1.65 was more common. Due to concerns about case ruptures and PCBs, the industry went to tighter fusing factors, 1.35 being the most common. Because of the good performance of all-film capacitors and problems with nuisance fuse operations, consider a

TABLE 6.9

Fusing Recommendations for ANSI Tin Links from One Manufacturer

3-Phase Bank	System Line-to-Line Voltage, kV							
kvar	4.2	4.8	12.5	13.2	13.8	22.9	24.9	34.5
Recommended Fuse Link								
150	20T	20T	8T	6T	6T			
300	40K	40K	15T	12T	12T	8T	8T	5T
450	65K	50K	20T	20T	20T	10T	10T	8T
600	80K	65K	25T	25T	25T	15T	15T	10T
900		100K	40K	40K	40K	20T	20T	15T
1200			50K	50K	50K	30T	25T	20T
1800			80K	80K	80K	40K	40K	30K
2400			100K	100K	100K	65K	50K	40K
Fusing Ratio for the Recommended Link (Link Rating/Nominal Current)								
150	0.96	1.11	1.15	0.91	0.96			
300	0.96	1.11	1.08	0.91	0.96	1.06	1.15	1.00
450	1.04	0.92	0.96	1.02	1.06	0.88	0.96	1.06
600	0.96	0.90	0.90	0.95	1.00	0.99	1.08	1.00
900		0.92	0.96	1.02	1.06	0.88	0.96	1.00
1200			0.90	0.95	1.00	0.99	0.90	1.00
1800			0.96	1.02	1.06	0.88	0.96	1.00
2400			0.90	0.95	1.00	1.07	0.90	1.00

Note: This is not the manufacturer's most up-to-date fusing recommendation. It is provided mainly as an example of a commonly applied fusing criteria for capacitors.

Source: Cooper Power Systems, *Electrical Distribution — System Protection*, 3rd ed., 1990.

looser fusing factor, possibly returning to the 1.65 factor. Slower fuses should also have fewer nuisance fuse operations.

Capacitors are rated to withstand 180% of rated rms current, including fundamental and harmonic currents. Fusing is normally not based on this limit, and is normally much tighter than this, usually from 125 to 165% of rated rms current. Occasionally, fuses in excess of 180% are used. In severe harmonic environments (usually in commercial or industrial applications), normally fuses blow before capacitors fail, but sometimes capacitors fail before the fuse operates. This depends on the fusing strategy.

If a capacitor bank has a blown fuse, crews should test the capacitors before re-fusing. A handheld digital capacitance meter is the most common approach and is accurate. Good multimeters also can measure a capacitance high enough to measure the capacitance on medium-voltage units. There is a chance that capacitance-testers may miss some internal failures requiring high voltage to break down the insulation at the failure. Measuring the capacitance on all three phases helps identify units that may have partial failures. Partial failures show up as a change in capacitance. In a partial failure, one of several series capacitor packs short out; the remaining packs appear as a lower impedance (higher capacitance). As with any equipment about to be energized, crews should visually check the condition of the capacitor unit and make sure there are no bulges, burn marks, or other signs that the unit may have suffered damage.

Some utilities have problems with nuisance fuse operations on distribution transformers. Some of the causes of capacitor fuse operations could be the same as transformer fuse operations, but some differences are apparent:

- Capacitor fuses see almost continuous full load (when the capacitor is switched in).
- Capacitor fuses tend to be bigger. The most common transformer sizes are 25 and 50 kVA, usually with less than a 15 A fuse. Typical capacitor sizes are 300 to 1200 kvar with 15 to 65 A fuses.
- Both have inrush; a capacitor's is quicker.
- Transformers have secondary faults and core saturation that can contribute to nuisance fuse operations; capacitors have neither.

Some possible causes of nuisance fuse operations are

- *Lightning* — Capacitors are a low impedance to the high-frequency lightning surge, so they naturally attract lightning current, which can blow the fuse. Smaller, faster fuses are most prone to lightning. Given that the standard rule of thumb that a fuse at least as big as a 20K or a 15T should prevent nuisance operations, it is hard to see how lightning itself could cause a significant number of fuse operations (as most capacitor bank fuses are larger than this).

- *Outrush to nearby faults* — If a capacitor dumps its stored charge into a nearby fault, the fuse can blow. Capacitor banks also have inrush every time they are switched in, but this is well below the melt point of the fuse.
- *Severe harmonics* — Harmonics increase the current through the fuse.
- *Animal or other bushing faults* — A fault across a bushing due to an animal, contamination on the bushing, or tree contact can blow a fuse. By the time anyone notices the blown fuse, the squirrel or branch has disappeared. Use animal guards and covered jumpers to reduce these.
- *Mechanical damage and deterioration* — Corrosion and vibration can weaken fuse links. On fuse links collected from the field on transformers, Ontario Hydro found that 3% had broken strain wires (CEA 288 D 747, 1998). Another 15% had braids that were brittle and had broken strands. Larger fuses used in capacitors should not have as much of a problem.
- *Installation errors* — Fuses are more likely to blow if crews put in the wrong size fuse or wrong type fuse or do not properly tighten the braid on the fuse.

Outrush is highlighted as a possible failure mode that has been neglected by the industry. Outrush is sometimes considered for station banks to calculate the probability of a fuse operation from a failure of an adjacent parallel unit. But for distribution fuses, nearby faults have not been considered in regard to the effects on fuse operations.

The energy input into the fuse during outrush depends on the line resistance between the capacitor and the fault (see Figure 6.15). The capacitor has stored energy; when the fault occurs, the capacitor discharges its energy into the resistance between the capacitor and the fault. Closer faults cause more energy to go into the fuse. The I^2t that the fuse suffers during outrush to a line-to-ground fault is

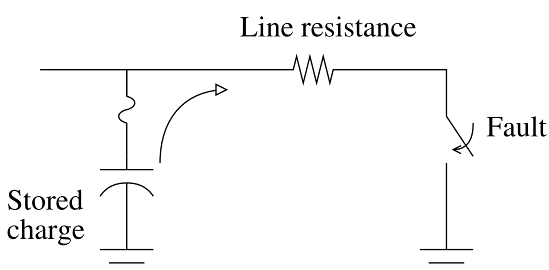

FIGURE 6.15
Outrush from a capacitor to a nearby fault.

$$I^2t = \frac{\frac{1}{2}CV_{pk}^2}{R} = \frac{2.65Q_{kvar}}{R}V_{pu}^2$$

where

C = capacitance of one unit, μF
V_{pk} = peak voltage on the capacitor at the instant of the fault, kV
R = resistance between the capacitor and the fault, Ω
Q_{kvar} = single-phase reactive power, kvar
V_{pu} = voltage at the instant of the fault in per unit of the capacitor's rated voltage

Table 6.10 shows several sources of fuse operations and the I^2t that they generate for a 900-kvar bank at 12.47 kV. The nominal load current is 41.7 A. Utilities commonly use 40 or 50-A fuses for this bank. The table shows the minimum melt I^2t of common fuses. Outrush to nearby faults produces high enough energy to blow common fuses, especially the K links. Of the other possible causes of fuse operation, none are particularly high except for a lightning first stroke. The lightning data is misleading because much of the first stroke will go elsewhere — usually, the line flashes over, and much of the lightning current diverts to the fault.

Use Figure 6.16 to find outrush I^2t for other cases. Two factors make outrush worse:

- *Higher system voltages* — The outrush I^2t stays the same with increases in voltage for the same size capacitor bank. The line impedance stays the same for different voltages. But higher-voltage capac-

TABLE 6.10

Comparison of I^2t of Events that Might Blow a Fuse to the Capability of Common Fuses for a Three-Phase, 900-kvar Bank at 12.47 kV (I_{load} = 41.7 A)

Source	I^2t, A^2-sec
Lightning, median 1st stroke	57,000
Lightning, median subsequent stroke	5,500
Inrush at nominal voltage (I_{SC}=5 kA, X/R=8)	4,455
Inrush at 105% voltage	4,911
Outrush to a fault 500-ft away (500-kcmil AAC)	20,280
Outrush to a fault 250-ft away (500-kcmil AAC)	40,560
Outrush to a fault 250-ft away with an arc restrike[a]	162,240
40K fuse, minimum melt I^2t	36,200
50K fuse, minimum melt I^2t	58,700
40T fuse, minimum melt I^2t	107,000

[a] Assumes that the arc transient leaves a voltage of 2 per unit on the capacitor before the arc restrikes.

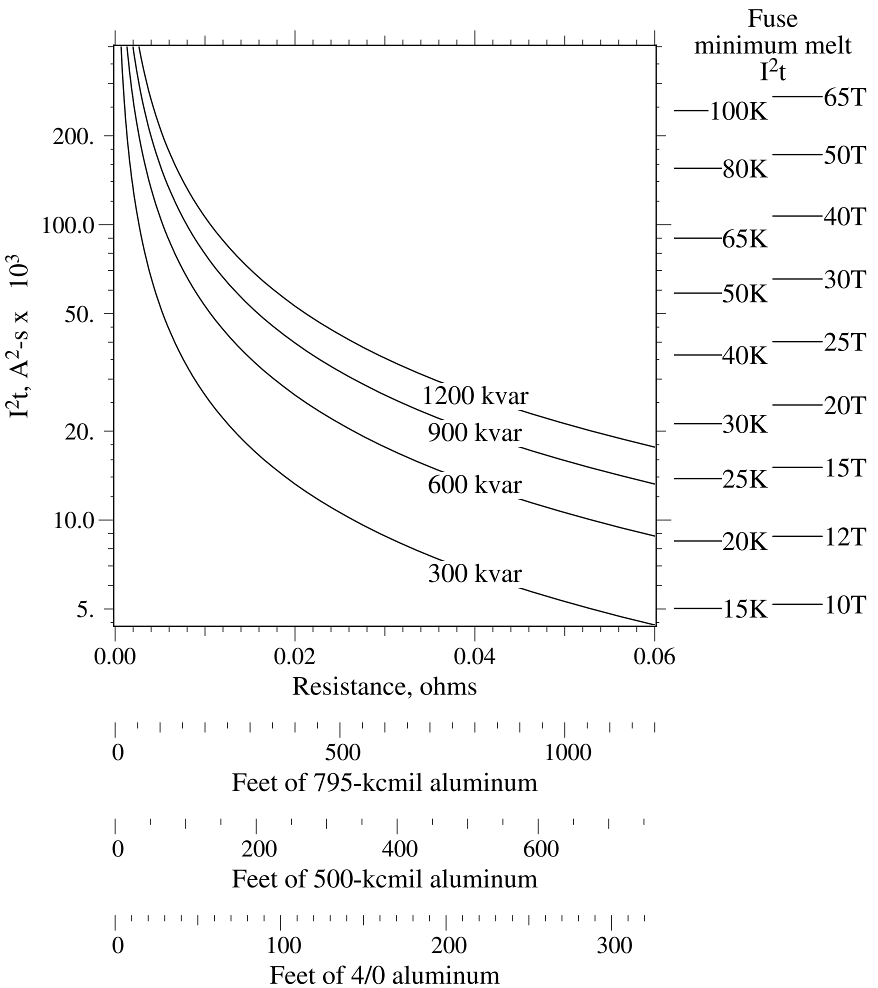

FIGURE 6.16
Outrush as a function of the resistance to the fault for various size capacitor banks (the sizes given are three-phase kvar; the resistance is the resistance around the loop, out and back; the distances are to the fault).

itor banks use smaller fuses, with less I^2t capability. So, a 25-kV capacitor installation is more likely to have nuisance fuse operations than a 12.5-kV system.

- *Larger conductors* — Lower resistance.

Consider a 1200-kvar bank with 500-kcmil conductors. At 12.47 kV (I_{load} = 55.6 A) with a 65K fuse, the fuse exceeds its minimum melt I^2t for faults up to 150 ft away. At 24.94 kV (I_{load} = 27.8 A) with a 30K fuse, the fuse may melt for faults up to 650 ft away. At 34.5 kV (I_{load} = 20.1 A) with a 25 K fuse, the location is off of the chart (it is about 950 ft). Note that the distance scales in Figure 6.16 do not include two important resistances: the capacitor's internal resistance and the fuse's resistance. Both will help reduce the I^2t. Also, the minimum melt I^2t values of the fuses in Figure 6.16 are the 60-Hz values. For high-frequency currents like an outrush discharge, the minimum melt I^2t of expulsion fuses is 30 to 70% of the 60-Hz I^2t (Burrage, 1981).

As an estimate of how much outrush contributes to nuisance fuse operations, consider a 900-kvar bank at 12.47 kV with 40K fuses. We will estimate that the fuse may blow or be severely damaged for faults within 250 ft (76 m). Using a typical fault rate on distribution lines of 90 faults/100 mi/year (56 faults/100 km/year), faults within 250 ft (75 m) of a capacitor occur at the rate of 0.085 per year. This translates into 8.5% fuse operations per capacitor bank per year, a substantial number.

The stored energy on the fault depends on the timing of the fault relative to the point on the voltage wave. Unfortunately, most faults occur at or near the peak of the sinusoid.

Several system scenarios could make individual instances worse; most are situations that leave more than normal voltage on the capacitor before it discharges into the fault:

- *Regulation overvoltages* — Voltages above nominal increase the outrush energy by the voltage squared.
- *Voltage swells* — If a line-to-ground fault on one phase causes a voltage swell on another and the fault jumps to the "swelled" phase, higher-than-normal outrush flows through the fuse.
- *Arc restrikes* — If a nearby arc is not solid but sputters, arc restrikes, much like restrikes of switches, can impress more voltage on the capacitor and subject the fuse to more energy, possibly much larger voltage depending on the severity. (I know of no evidence that this occurs regularly; most arcs are solid, and the system stays faulted once the arc bridges the gap.)
- *Lightning* — A nearby lightning strike to the line can charge up the capacitor (and start the fuse heating). In most cases, the lightning will cause a nearby flashover, and the capacitor's charge will dump right back through the fuse.
- *Multiple-phase faults* — Line-to-line and three-phase faults are more severe for two reasons: the voltage is higher, and the resistance is lower. For example, on a line-to-line fault, the voltage is the line-to-line voltage, and the resistance is the resistance of the phase wires (rather than the resistance of a phase wire and the neutral in series).

These estimates are conservative in that they do not consider skin effects, which have considerable effect at high frequencies. Skin effects increase the conductor's resistance. The transients oscillate in the single-digit kilohertz range. At these frequencies, conductor resistance increases by a factor of two to three. On the negative side, the fuse element is impacted by skin effects, too — higher frequency transients cause the fuse to melt more quickly.

Capacitors also have inrush every time they are energized. Inrush into grounded banks has a peak current (IEEE Std. 1036-1992) of

$$I_{pk} = 1.41\sqrt{I_{SC} I_1}$$

where

I_{pk} = peak value of inrush current, A
I_{SC} = available three-phase fault current, A
I_1 = capacitor bank current, A

The energy into a fuse from inrush is normally very small. It subjects the capacitor fuse to an I^2t (in A^2-s) (Brown, 1979) of

$$I^2 t = 2.65\sqrt{1+k^2}\, I_{SC} I_1 / 1000$$

where

k = X/R ratio at the bank location

Inrush is much worse if a capacitor is switching into a system with a nearby capacitor. The outrush from the already-energized bank dumps into the capacitor coming on line. Fuses at both banks see this transient. In substation applications, this *back-to-back* switching is a major design consideration, often requiring insertion of reactors between banks. For distribution feeder capacitors, the design constraints are not as large. A few hundred feet of separation is enough to prevent inrush/outrush problems. For back-to-back switching, the I^2t is almost the same as that for outrush:

$$I^2 t = \frac{\frac{1}{2} C V_{pk}^2}{R} = \frac{2.65 Q_{kvar}}{R} V_{pu}^2$$

The only difference is that the capacitance is the series combination of the two capacitances: $C = C_1 C_2 / (C_1 + C_2)$, and $Q_{kvar} = Q_1 Q_2 / (Q_1 + Q_2)$. For the same size banks, $C = C_1/2$, and $Q_{kvar} = Q_1/2$. Figure 6.16 applies if we double the kvar values on the curves. In most situations, maintaining a separation of 500 ft between capacitor banks prevents fuse operations from this inrush/outrush. Separate capacitor banks by 500 ft (150 m) on 15-kV class circuits to avoid inrush problems. Large capacitor banks on higher voltage distribution systems may require modestly larger separations.

Preventing case ruptures is a primary goal of fusing. The fuse should clear before capacitor cases fail. Figure 6.17 shows capacitor rupture curves compared against fuse clearing curves. The graph shows that there is considerable margin between fuse curves and rupture curves. Consider a 12.47-kV, 900-kvar bank of three 300-kvar units, which has a nominal current of 41.7 A. Utilities commonly use a 40 or 50 K fuse for this bank. Larger fuses for this bank are possible, while still maintaining levels below case rupture curves. An EPRI survey found that case ruptures on modern film-foil capacitors are rare (EPRI 1001691, 2002). This gives us confidence that we can loosen fusing practices without having rupture problems.

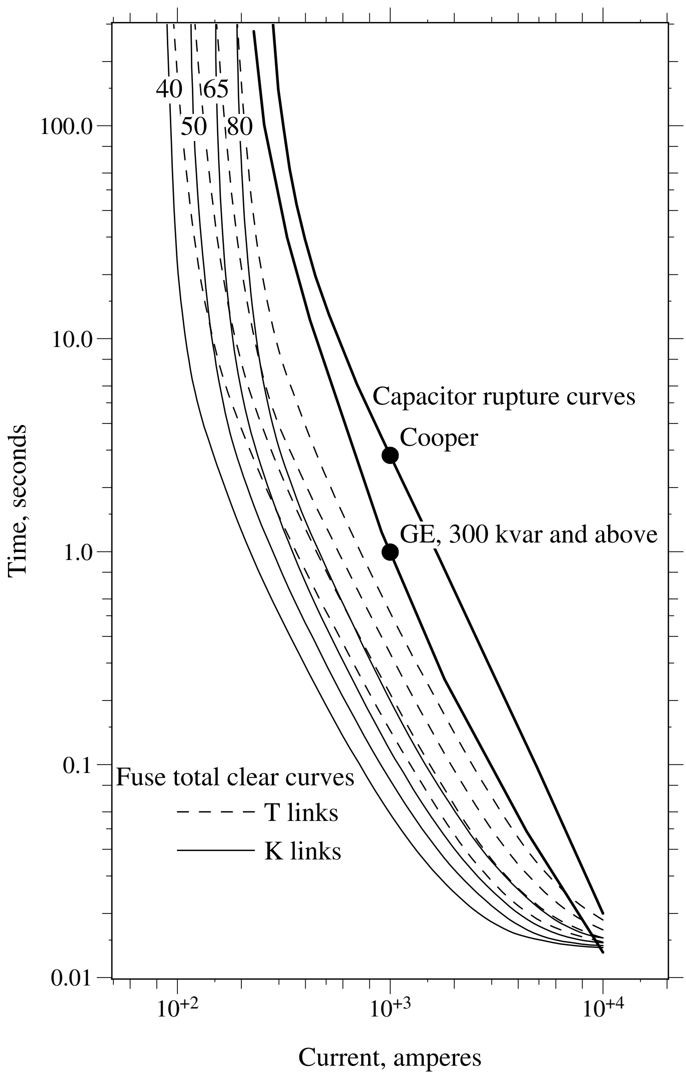

FIGURE 6.17
Fuse curves with capacitor rupture curves.

In areas of high fault current, current-limiting fuses provide extra safety. Either a backup current-limiting fuse in series with an expulsion link or a full-range current-limiting fuse is an appropriate protection scheme in high fault-current areas. While it may seem that expulsion fuses provide adequate protection even to 8 kA (depending on which rupture curve we use), current-limiting fuses provide protection for those less frequent faults with longer internal arcs. They also provide protection against failures in the capacitor switches and other capacitor-bank accessories. Utilities that apply current-limiting fuses on capacitors normally do so for areas with fault currents above 3 to 5 kA.

With backup current-limiting fuses, it is important that crews check the backup fuse whenever the expulsion link operates. On transformers, crews can get away with replacing the expulsion link. If the transformer still does not have voltage, they will quickly know that they have to replace the backup link. But, on capacitors, there is no quick indication that the backup-fuse has operated. Crews must check the voltage on the cutout to see if the backup fuse is operational; or crews should check the capacitor neutral current after replacing the expulsion link to make sure it is close to zero (if all three phases are operational, the balanced currents cancel in the neutral). In addition to not fixing the problem, failing to replace a blown backup fuse could cause future problems. The backup fuse is not designed to hold system voltage continuously — they are not an insulator. Eventually, they will track and arc over.

Because of utility problems with nuisance fuse operations, some loosening of fusing practices is in order. For most of the possible causes of nuisance-fuse operations, increasing the fuse size will decrease the number of false operations. Going to a slower fuse, especially, helps with outrush and other fast transients. If you have nuisance fuse operation problems, consider using T links and/or increase the fuse size one or two sizes. Treat these recommendations as tentative; as of this writing, these fusing issues are the subject of ongoing EPRI research, which should provide more definitive recommendations.

Neutral monitoring (Figure 6.18) is another protection feature that some capacitor controllers offer. Neutral monitoring can detect several problems:

- *Blown fuse* — When one capacitor fuse blows, the neutral current jumps to a value equal to the phase current.
- *Failing capacitor unit* — As a capacitor fails, internal groups of series packs short out. Prior to complete failure, the unit will draw more current than normal. Figure 6.19 shows how the neutral current changes when a certain portion of the capacitor shorts out. Capacitors rated from 7.2 to 7.96 kV normally have three or four series sections, so failure of one element causes neutral currents of 25% (for four in series) or 34% (for three in series) of the phase current.

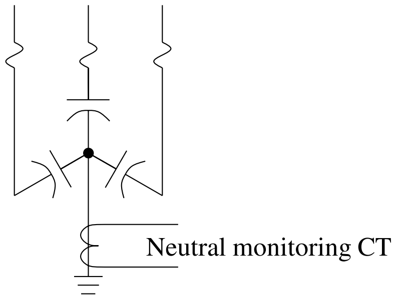

FIGURE 6.18
Neutral monitoring of a capacitor bank.

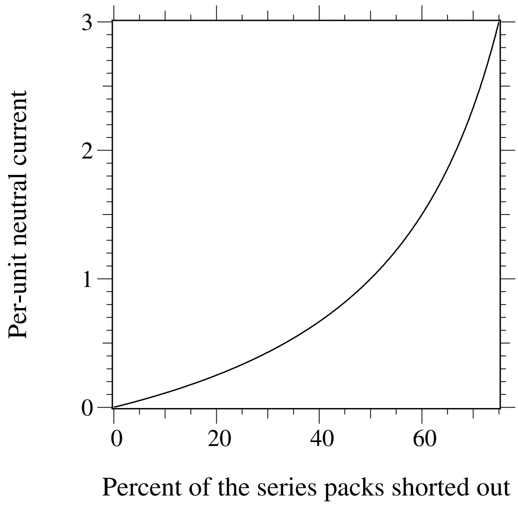

FIGURE 6.19
Neutral current drawn by a failing grounded-wye bank depending on the portion of the bank that is failed (the neutral current is in per-unit of the nominal capacitor current).

Failure of more than half of the series sections causes more than the capacitor's rated current in the neutral.

- *High harmonic current* — Excessive neutral current may also indicate high harmonic currents.

Neutral monitoring is common in substation banks, and many controllers for switched pole-mounted banks have neutral-monitoring capability. Neutral-current monitors for fixed banks are also available, either with a local warning light or a wireless link to a centralized location.

Neutral monitoring can help reduce operations and maintenance by eliminating regular capacitor patrols and field checks. Quicker replacement of blown fuses also reduces the time that excessive unbalance is present (and the extra losses and possibility of stray voltage). This can lead to more reliable var regulation, and even reduce the number of capacitor banks needed.

6.11 Grounding

Three-phase capacitors can be grounded in a wye configuration or ungrounded, either in a floating-wye or a delta. For multigrounded distribution systems, a grounded-wye capacitor bank offers advantages and disadvantages:

- *Unit failure and fault current* — If a unit fails, the faulted phase draws full fault current. This allows the fuse to blow quickly, but requires fuses to be rated for the full fault current.
- *Harmonics* — The grounded-wye bank can attract zero-sequence harmonics (balanced 3rd, 9th, 15th, …). This problem is often found in telephone interference cases.

Advantages and disadvantages of the floating-wye, ungrounded banks include

- *Unit failure* — The collapse of voltage across a failed unit pulls the floating neutral to phase voltage. Now, the neutral shift stresses the remaining capacitors with line-to-line voltage, 173% of the capacitor's rating.
- *Fault current* — When one unit fails, the circuit does not draw full fault current — it is a high-impedance fault. This is an advantage in some capacitor applications.
- *Harmonics* — Less chance of harmonic problems because the ungrounded, zero-sequence harmonics (balanced 3rd, 9th, 15th, …) cannot flow to ground through the capacitor.

The response of the floating-wye configuration deserves more analysis. During a progressive failure, when one series section shorts out, the shift of the neutral relieves the voltage stress on the remaining series sections. In the example in Figure 6.20, for a floating-wye bank with half of the series sections shorted, the line-to-neutral voltage becomes 0.75 per unit. The remaining elements normally see 50% of the line-to-neutral voltage, but now they see 75% (1.5 per unit, so the current is also 1.5 times normal). The reduction in voltage stress due to the neutral shift prolongs the failure — not what we want. The excess heating at the failure point increases the risk of gas generation and case rupture. When one element fails, we really want the fuse (or other protection) to trip quickly. The neutral shift also increases the voltage stress on the units on the other phases.

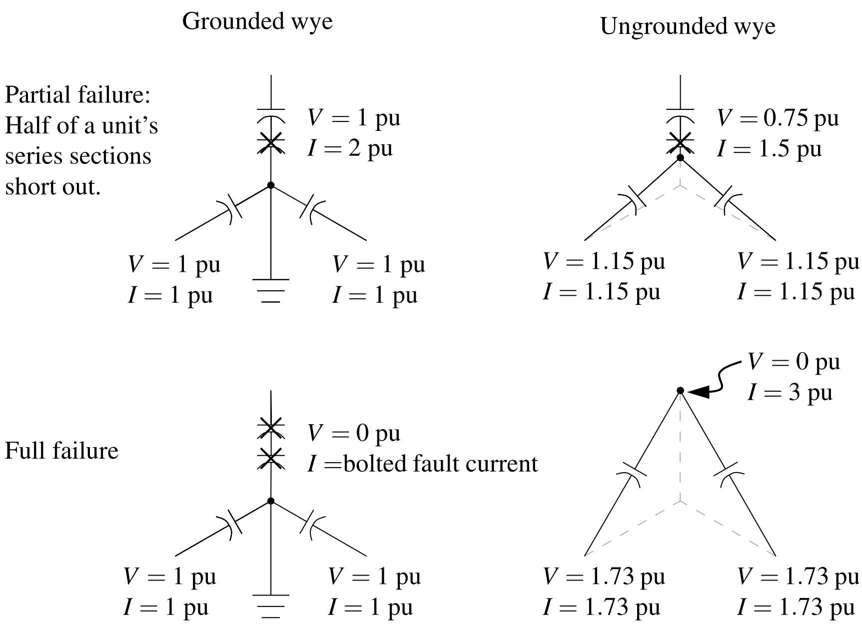

FIGURE 6.20
Comparison of grounded-wye and ungrounded-wye banks during a partial and full failure of one unit. (Copyright © 2002. Electric Power Research Institute. 1001691. *Improved Reliability of Switched Capacitor Banks and Capacitor Technology.* Reprinted with permission.)

Floating-wye configurations are best applied with neutral detection — a potential transformer measuring voltage between the floating neutral and ground can detect a failure of one unit. When one unit fails, a relay monitoring the neutral PT should trip the capacitor's oil or vacuum switch (obviously, this only works on switched banks).

Standard utility practice is to ground banks on multigrounded systems. Over 80% of the respondents to an EPRI survey used grounded-wye capacitor connections (EPRI 1001691, 2002). On three-wire systems, utilities use both ungrounded-wye and delta configurations.

Most utilities use two-bushing capacitors, even though most also use a grounded neutral. Having two bushings allows crews to convert capacitor banks to a floating neutral configuration if telephone interference is a problem.

Utilities universally ground capacitor cases on pole-mounted capacitors (even though it is not strictly required by the National Electrical Safety Code [IEEE C2-1997]). In rare cases, banks with single-bushing capacitors are floated when it becomes necessary to convert a bank to a floating-wye. Avoid this if possible.

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