5

Voltage Regulation

One of a utility's core responsibilities is to deliver voltage to customers within a suitable range, so utilities must regulate the voltage. On distribution circuits, voltage drops due to current flowing through the line impedances. Primary and secondary voltage drop can be allocated as necessary along the circuit to provide end users with suitable voltage. Voltage regulators — in the substation or on feeders — can adjust primary voltage. This chapter discusses voltage regulators and regulation standards and techniques.

5.1 Voltage Standards

Most regulatory bodies and most utilities in America follow the ANSI voltage standards (ANSI C84.1-1995). This standard specifies acceptable operational ranges at two locations on electric power systems:

- *Service voltage* — The service voltage is the point where the electrical systems of the supplier and the user are interconnected. This is normally at the meter. Maintaining acceptable voltage at the service entrance is the *utility's* responsibility.
- *Utilization voltage* — The voltage at the line terminals of utilization equipment. This voltage is the *facility's* responsibility. Equipment manufacturers should design equipment which operates satisfactorily within the given limits.

The standard allows for some voltage drop within a facility, so service voltage requirements are tighter than utilization requirements.

The standard also defines two ranges of voltage:

- *Range A* — Most service voltages are within these limits, and utilities should design electric systems to provide service voltages within

TABLE 5.1

ANSI C84.1 Voltage Ranges for 120 V

	Service Voltage		Utilization Voltage	
	Minimum	**Maximum**	**Minimum**	**Maximum**
Range A	114 (–5%)	126 (+5%)	110 (–8.3%)	125 (+4.2%)
Range B	110 (–8.3%)	127 (+5.8%)	106 (–11.7%)	127 (+5.8%)

these limits. As the standard says, voltage excursions "should be infrequent."

- *Range B* — These requirements are more relaxed than Range A limits. According to the standard: "Although such conditions are a part of practical operations, they shall be limited in extent, frequency, and duration. When they occur, corrective measures shall be undertaken within a reasonable time to improve voltages to meet Range A requirements." Utilization equipment should give acceptable performance when operating within the Range B utilization limits, "insofar as practical" according to the standard.

These limits only apply to sustained voltage levels and not to momentary excursions, sags, switching surges, or short-duration interruptions.

Table 5.1 shows the most important limits, the limits on low-voltage systems. The table is given on a 120-V base; it applies at 120 V but also to any low-voltage system up to and including 600 V. The main target for utilities is the Range A service voltage, 114 to 126 V.

ANSI C84.1 defines three voltage classes: low voltage (1 kV or less), medium voltage (greater than 1 kV and less than 100 kV), and high voltage (greater than or equal to 100 kV). Within these classes, ANSI provides standard nominal system voltages along with the voltage ranges. A more detailed summary of the ANSI voltages is shown in Table 5.2 and Table 5.3.

For low-voltage classes, two nominal voltages are given — one for the electric system and a second, somewhat lower, nominal for the utilization equipment (for low-voltage motors and controls; other utilization equipment may have different nominal voltages). In addition, the standard gives common nameplate voltage ratings of equipment as well as information on what nominal system voltages the equipment is applicable to. As the standard points out, there are many inconsistencies between equipment voltage ratings and system nominal voltages.

For medium-voltage systems, ANSI C84.1 gives tighter limits for Ranges A and B. Range A is –2.5 to +5%, and Range B is –5 to +5.8%. However, most utilities do not follow these as limits for their primary distribution systems (utilities use the ANSI service voltage guidelines and set their primary voltage limits to meet the service voltage guidelines based on their practices). The three-wire voltages of 4,160, 6,900, and 13,800 V are mainly suited for industrial customers with large motors. Industrial facilities use motors on these systems with ratings of 4,000, 6,600, and 13,200 V, respectively.

TABLE 5.2

ANSI Standard Nominal System Voltages and Voltage Ranges for
Low-Voltage Systems

		Range A			Range B		
		Maximum	Minimum		Maximum	Minimum	
Nominal System Voltage	Nominal Utilization Voltage	Utilization and Service Voltage[a]	Service Voltage	Utilization Voltage	Utilization and Service Voltage	Service Voltage	Utilization Voltage
Two Wire, Single Phase							
120	115	126	114	110	127	110	106
Three Wire, Single Phase							
120/240	**115/230**	**126/252**	**114/228**	**110/220**	**127/254**	**110/220**	**106/212**
Four Wire, Three Phase							
208Y/120	**200**	**218/126**	**197/114**	**191/110**	**220/127**	**191/110**	**184/106**
240/120	**230/115**	**252/126**	**228/114**	**220/110**	**254/127**	**220/110**	**212/106**
480Y/277	**460**	**504/291**	**456/263**	**440/254**	**508/293**	**440/254**	**424/245**
Three Wire, Three Phase							
240	230	252	228	220	254	220	212
480	**460**	**504**	**456**	**440**	**508**	**440**	**424**
600	575	630	570	550	635	550	530

Note: Bold entries show preferred system voltages.

[a] The maximum utilization voltage for Range A is 125 V or the equivalent (+4.2%) for other nominal voltages through 600 V.

Improper voltage regulation can cause many problems for end users. Sustained overvoltages or undervoltages can cause the following end-use impacts:

- *Improper or less-efficient equipment operation* — For example, lights may give incorrect illumination or a machine may run fast or slow.
- *Tripping of sensitive loads* — For example, an uninterruptible power supply (UPS) may revert to battery storage during high or low voltage. This may drain the UPS batteries and cause an outage to critical equipment.

In addition, undervoltages can cause

- *Overheating of induction motors* — For lower voltage, an induction motor draws higher current. Operating at 90% of nominal, the full-load current is 10 to 50% higher, and the temperature rises by 10 to 15%. With less voltage, the motor has reduced motor starting torque.

TABLE 5.3

ANSI Standard Nominal System Voltages and Voltage Ranges for Medium-Voltage Systems

	Range A			Range B		
	Maximum	**Minimum**		**Maximum**	**Minimum**	
Nominal System Voltage	**Utilization and Service Voltage**	**Service Voltage**	**Utilization Voltage**	**Utilization and Service Voltage**	**Service Voltage**	**Utilization Voltage**
Four Wire, Three Phase						
4160Y/2400	4370/2520	4050/2340	3740/2160	4400/2540	3950/2280	3600/2080
8320Y/4800	8730/5040	8110/4680		8800/5080	7900/4560	
12000Y/6930	12600/7270	11700/6760		12700/7330	11400/6580	
12470Y/7200	**13090/7560**	**12160/7020**		**13200/7620**	**11850/6840**	
13200Y/7620	**13860/8000**	**12870/7430**		**13970/8070**	**12504/7240**	
13800Y/7970	14490/8370	13460/7770		14520/8380	13110/7570	
20780Y/1200	21820/12600	20260/11700		22000/12700	19740/11400	
22860Y/13200	24000/13860	22290/12870		24200/13970	21720/12540	
24940Y/14400	**26190/15120**	**24320/14040**		**26400/15240**	**23690/13680**	
34500Y/19920	**36230/20920**	**33640/19420**		**36510/21080**	**32780/18930**	
Three Wire, Three Phase						
2400	2520	2340	2160	2540	2280	2080
4160	**4370**	**4050**	**3740**	**4400**	**3950**	**3600**
4800	5040	4680	4320	5080	4560	4160
6900	7240	6730	6210	7260	6560	5940
13800	**14490**	**13460**	**12420**	**14520**	**13110**	**11880**
23000	24150	22430		24340	21850	
34500	36230	33640		36510	32780	

Notes: Bold entries show preferred system voltages. Some utilization voltages are blank because utilization equipment normally does not operate directly at these voltages.

Also, overvoltages can cause

- *Equipment damage or failure* — Equipment can suffer insulation damage. Incandescent light bulbs wear out much faster at higher voltages.
- *Higher no-load losses in transformers* — Magnetizing currents are higher at higher voltages.

5.2 Voltage Drop

We can approximate the voltage drop along a circuit as

$$V_{drop} = |V_s| - |V_r| \approx I_R \cdot R + I_X \cdot X$$

where
$\quad V_{drop}$ = voltage drop along the feeder, V
$\qquad R$ = line resistance, Ω
$\qquad X$ = line reactance, Ω
$\qquad I_R$ = line current due to real power flow (in phase with the voltage), A
$\qquad I_X$ = line current due to reactive power flow (90° out of phase with the voltage), A

In terms of the load power factor, *pf*, the real and reactive line currents are

$$I_R = I \cdot pf = I \cos\theta$$

$$I_X = I \cdot qf = I \sin\theta = I \sin(\cos^{-1}(pf))$$

where
$\quad I$ = magnitude of the line current, A
$\quad pf$ = load power factor
$\quad qf$ = load reactive power factor = $\sin(\cos^{-1}(pf))$
$\quad \theta$ = angle between the voltage and the current

While just an approximation, Brice (1982) showed that $I_R \cdot R + I_X \cdot X$ is quite accurate for most distribution situations. The largest error occurs under heavy current and leading power factor. The approximation has an error less than 1% for an angle between the sending and receiving end voltages up to 8° (which is unlikely on a distribution circuit). Most distribution programs use the full complex phasor calculations, so the error is mainly a consideration for hand calculations.

This approximation highlights two important aspects about voltage drop:

- *Resistive load* — At high power factors, the voltage drop strongly depends on the resistance of the conductors. At a power factor of 0.95, the reactive power factor (*qf*) is 0.31; so even though the resistance is normally smaller than the reactance, the resistance plays a major role.

- *Reactive load* — At moderate to low power factors, the voltage drop depends mainly on the reactance of the conductors. At a power factor of 0.8, the reactive power factor is 0.6, and because the reactance is usually larger than the resistance, the reactive load causes most of the voltage drop. Poor power factor significantly increases voltage drop.

Voltage drop is higher with lower voltage distribution systems, poor power factor, single-phase circuits, and unbalanced circuits. The main ways to reduce voltage drop are to:

- Increase power factor (add capacitors)
- Reconductor with a larger size

- Balance circuits
- Convert single-phase sections to three-phase sections
- Reduce load
- Reduce length

In many cases, we can live with significant voltage drop as long as we have enough voltage regulation equipment to adjust for the voltage drop on the circuit.

5.3   Regulation Techniques

Distribution utilities have several ways to control steady-state voltage. The most popular regulation methods include:

- Substation load tap-changing transformers (LTCs)
- Substation feeder or bus voltage regulators
- Line voltage regulators
- Fixed and switched capacitors

Most utilities use LTCs to regulate the substation bus and supplementary feeder regulators and/or switched capacitor banks where needed.

Taps on distribution transformers are another tool to provide proper voltage to customers. Distribution transformers are available with and without no-load taps (meaning the taps are to be changed without load) with standard taps of ±2.5 and ±5%. Utilities can use this feature to provide a fixed boost for customers on a circuit with low primary voltage. This also allows the primary voltage to go lower than most utilities would normally allow. Remember, the service entrance voltage is most important. Most distribution transformers are sold without taps, so this practice is not widespread. It also requires consistency; an area of low primary voltage may have several transformers to adjust — if one is left out, the customers fed by that transformer could receive low voltage.

5.3.1   Voltage Drop Allocation and Primary Voltage Limits

Most utilities use the ANSI C84.1 ranges for the service entrance, 114 to 126 V. How they control voltage and allocate voltage drop varies. Consider the voltage profile along the circuit in Figure 5.1. The substation LTC or bus regulator controls the voltage at the source. Voltage drops along the primary line, the distribution transformer, and the secondary. We must consider the customers at the start and end of the circuit:
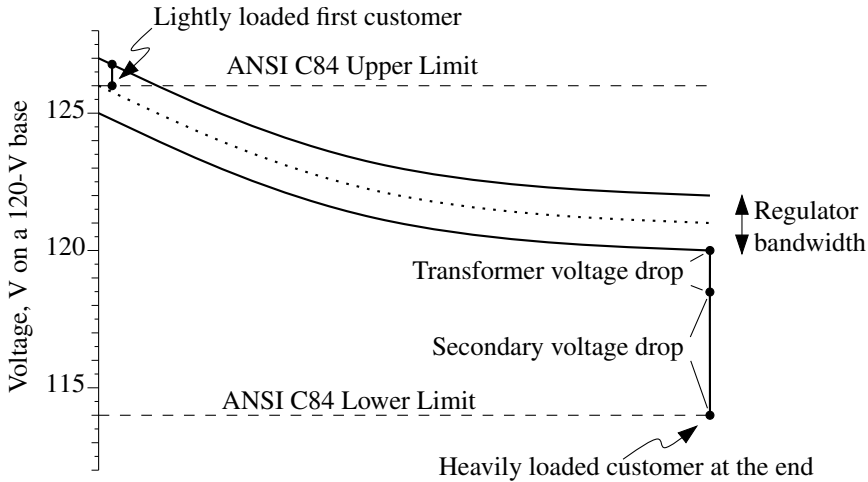
FIGURE 5.1
Voltage drop along a radial circuit with no capacitors or line regulators.

- *End — Heavily loaded —* Low voltages are a concern, so we consider a heavily loaded transformer and secondary. The allocation across the secondary depends on the utility's design practices as far as allowable secondary lengths and conductor sizes are concerned.
- *Source — Lightly loaded —* Near the source, we can operate the primary above 126 V, but we must ensure that the first customer does not have overvoltages when that customer is lightly loaded. Commonly, utilities assume that the secondary and transformer drop to this lightly loaded customer is 1 V. With that, the upper primary voltage limit is 127 V.

In the voltage drop along the primary, we must consider the regulator bandwidth (and bandwidths for capacitors if they are switched based on voltage). Voltage regulators allow the voltage to deviate by half the bandwidth in either direction. So, if we have a 2-V bandwidth and a desired range of 7 V of primary drop, subtracting the 2-V bandwidth only leaves 5 V of actual drop (see Figure 5.1). Likewise, if we choose 127 V as our upper limit on the primary, our maximum set voltage is 126 V with a 2-V regulator bandwidth.

Normally, utilities use standardized practices to allocate voltage drop. Deviations from the standard are possible but often not worth the effort.

If we have an express feeder at the start of a circuit, we can regulate the voltage much higher than 126 V as long as the voltage drops enough by the time the circuit reaches the first customer.

Primary voltage allocation affects secondary allocation and vice versa. A rural utility may have to allow a wide primary voltage range to run long

TABLE 5.4

Primary Voltage Ranges at Several Utilities

Service Area Type	Minimum	Maximum	Percent Range
Dense urban area	120	127	5.4
Dense urban area	117	126	7.5
Urban/suburban	114	126	10.0
Urban/suburban	115	125	8.3
Urban/suburban			
No conservation reduction	119	126	5.8
With conservation reduction	119	123	3.3
Multi-state area	117	126	7.5
Multi-state area			
Urban standard	123	127	3.3
Rural standard	119	127	6.6
Suburban and rural	113	125	10.0
Suburban and rural			
Urban standard	116	125	7.5
Rural standard	112	125	10.8
Urban and rural	115	127	10.0
Rural, mountainous	116	126	8.3
Rural, mountainous	113	127	11.7

Source: Willis, H. L., *Power Distribution Planning Reference Book*, Marcel Dekker, New York, 1997b, with additional utilities added.

circuits, which leaves little voltage drop left for the transformer and secondary. Since rural loads are typically each fed by their own transformer, rural utilities can run the primary almost right to the service entrance. Using low-impedance distribution transformers and larger-than-usual transformers also helps reduce the voltage drop beyond the primary. For the secondary conductors, triplex instead of open wire and larger size conductors help reduce secondary drop. Utilities that allow less primary voltage drop can run longer secondaries.

Utility practices on voltage limits on the primary range widely, as shown in Table 5.4. The upper range is more consistent — most are from 125 to 127 V — unless the utility uses voltage reduction (for energy conservation or peak shaving). The lower range is more variable, anywhere from 112 to 123 V. Obviously, the utility that uses a 112-V lower limit is not required to abide by the ANSI C84.1 limits.

5.3.2 Load Flow Models

Load flows provide voltage profiles that help when planning new distribution circuits, adding customers, and tracking down and fixing voltage problems. Most distribution load-flow programs offer a function to plot the voltage as a function of distance from the source.

We can model a distribution circuit at many levels of detail. Many utilities are modeling more of their systems in more detail. For most load flows,

utilities normally just model the primary. Modeling the secondary is occasionally useful for modeling specific problems at a customer. We can still have very good models with simplifications. Modeling long laterals or branches is normally a good idea, but we can lump most laterals together as a load where they tie into the main line. Modeling each transformer as a load is rarely worth the effort; we can combine loads together and maintain accuracy with some common sense. Most mainline circuits can be accurately modeled if broken into 10 to 20 sections with load lumped with each section. Of course, accurate models of capacitors and line regulators are a good idea.

Correctly modeling load phasing provides a better voltage profile on each phase. Unbalanced loads cause more voltage drop because of:

- *Higher loop impedance* — The impedance seen by unbalanced loads, the loop impedance including the zero-sequence impedance, is higher than the positive-sequence impedance seen by balanced loads.
- *Higher current on the loaded phases* — If the current splits unevenly by phases, the more heavily loaded phases see more voltage drop.

Utilities often do not keep accurate phasing information, but it helps improve load-flow results. We do not need the phasing on every transformer, but we will have better accuracy if we know the phasing of large single-phase taps.

Of the data entered into the load flow model, the load allocation is the trickiest. Most commonly, loads are entered in proportion to the transformer kVA. If a circuit has a peak load equal to the sum of the kVA of all of the connected transformers divided by 2.5, then each load is modeled as the given transformer size in kVA divided by 2.5. Incorporating metering data is another more sophisticated way to allocate load. If a utility has a transformer load management system or other system that ties metered kilowatt-hour usage to a transformer to estimate loadings, feeding this data to the load flow can yield a more precise result. In most cases, all of the loads are given the same power factor, usually what is measured at the substation. Additional measurements could be used to fine-tune the allocation of power factor. Some utilities also assign power factor by customer class.

Most distribution load flow programs offer several load types, normally constant power, constant current, and constant impedance:

- *Constant power load* — The real and reactive power stays constant as the voltage changes. As voltage decreases, this load draws more current, which increases the voltage drop. A constant power model is good for induction motors.
- *Constant current load* — The current stays constant as the voltage changes, and the power increases with voltage. As voltage decreases, the current draw stays the same, so the voltage drop does not change.

TABLE 5.5

Load Modeling Approximations Recommended by Willis (1997a)

Feeder Type	Percent Constant Power	Percent Constant Impedance
Residential and commercial, summer peaking	67	33
Residential and commercial, winter peaking	40	60
Urban	50	50
Industrial	100	0
Developing countries	25	75

Source: Willis, H. L., "Characteristics of Distribution Loads," in *Electrical Transmission and Distribution Reference Book.* Raleigh, NC, ABB Power T&D Company, 1997.

- *Constant impedance load* — The impedance is constant as the voltage changes, and the power increases as the square of the voltage. As voltage decreases, the current draw drops off linearly; so the voltage drop decreases. The constant impedance model is good for incandescent lights and other resistive loads.

Normally, we can model most circuits as something like 40 to 60% constant power and 40 to 60% constant impedance (see Table 5.5 for one set of recommendations). Modeling all loads as constant current is a good approximation for many circuits. Modeling all loads as constant power is conservative for voltage drop.

5.3.3 Voltage Problems

Voltage complaints (normally undervoltages) are regular trouble calls for utilities. Some are easy to fix; others are not. First, check the secondary. Before tackling the primary, confirm that the voltage problem is not isolated to the customers on the secondary. If secondary voltage drop is occurring, check loadings, make sure the transformer is not overloaded, and check for a loose secondary neutral.

If the problem is on the primary, some things to look for include:

- *Excessive unbalance* — Balancing currents helps reduce voltage drop.
- *Capacitors* — Look for blown fuses, incorrect time clock settings, other incorrect control settings, or switch malfunctions.
- *Regulators* — Check settings. See if more aggressive settings can improve the voltage profile enough: a higher set voltage, more line drop compensation, and/or a tighter bandwidth.

These problems are relatively easy to fix. If it is not these, and if there is too much load for the given amount of impedance, we will have to add equipment to fix the problem. Measure the primary voltage (and if possible the loadings) at several points along the circuit. An easy way to measure the

primary voltage is to find a lightly loaded distribution transformer and measure the secondary voltage. Measure the power factor at the substation. A poor power factor greatly increases the voltage drop.

Load flows are a good tool to try out different options to improve voltage on a circuit. If possible, match voltage profiles with measurements on the circuit. Measurements provide a good sanity check. Try to measure during peak load conditions. Regulator and capacitor controllers can provide extra information if they have data logging capability. Normally, we allocate the load for the model equally by transformer kVA. This may not always be right, and measurements can help "tweak" the model. A load flow can help determine the best course of action. Where do we need a supplementary line regulator? How many? Can fixed capacitors do the job? Do we need switched capacitors? Circuits with poor power factor are the best candidates for capacitors as they will help reduce line losses as well as improve voltage.

In addition to extra regulating equipment, consider other options. Sometimes, we can move one or more circuit sections to a different feeder to reduce the loading on the circuit. If transformers have taps, investigate changing the transformer taps. Though it is expensive, we can also build new circuits, upgrade to a higher voltage, or reconductor.

5.3.4   Voltage Reduction

Utilities can use voltage adjustments as a way to manage system load. Voltage reduction can reduce energy consumption and/or reduce peak demand. Several studies have shown roughly a linear response relationship between voltage and energy use — a 1% reduction in voltage reduces energy usage by 1% (or just under 1%, depending on the study). Kirshner and Giorsetto (1984) analyzed trials of conservation voltage reduction (CVR) at several utilities. While results varied significantly, most test circuits had energy savings of between 0.5 and 1% for each 1% voltage reduction. Their regression analysis of the feeders found that residential energy savings were 0.76% for each 1% reduction in voltage, while commercial and industrial loads had reductions of 0.99% and 0.41% (but the correlations between load class and energy reduction were fairly small).

Voltage reduction works best with resistive loads because the power drawn by a resistive load decreases with the voltage squared. Lighting and resistive heating loads are the dominant resistive loads; these are not ideal resistive loads. For example, the power on incandescent lights varies as the voltage to the power of about 1.6, which is not quite to the power of 2 but close. Residential and commercial loads have higher percentages of resistive load. For water heaters and other devices that regulate to a temperature, reducing voltage does not reduce overall energy usage; the devices just run more often.

Voltage reduction to reduce demand has even more impact than that on energy reduction. The most reduction occurs right when the voltage is reduced, and then some of the reduction is lost as some loads keep running

longer than normal to compensate for lower voltage. For example, Priess and Warnock (1978) found that during a 4-h, 5% voltage reduction, the demand on one typical residential circuit dropped by 4% initially and diminished to a 3% drop by the end of the 4-h period.

Voltage reduction works best on short feeders — those that do not have much voltage drop. On these, we can control reduction just through adjustments of the station LTC regulator settings. It is straightforward to set up a system where operators can change the station set voltage through SCADA. On longer circuits, we need extra measures. Some strategies include:

- *Extra regulators* — Extra regulators can help flatten the voltage profile along the circuit. Each regulator is set with a set voltage and compensation settings appropriate for a tighter voltage range. This approach is most appropriate for energy conservation. Controlling the regulators to provide peak shaving is difficult; the communications and controls add significantly to the cost.

- *Feeder capacitors* — The vars injected by capacitors help flatten the voltage profile and allow a lower set voltage on the station LTC. On many circuits, just fixed capacitors can flatten the profile enough to reduce the station set voltage. McCarthy (2000) reported how Georgia Power used this strategy to reduce peak loads by 500 kW on circuits averaging approximately 18 MW.

- *Tighter bandwidth* — With a smaller regulator bandwidth, the voltage spread on the circuit is smaller. A smaller bandwidth requires more frequent regulator or LTC maintenance (the regulator changes taps more often) but not drastic differences. Kirshner (1990) reported that reducing the bandwidth from 3 to 1.5 V doubled the number of regulator tap changes.

- *Aggressive line drop compensation* — An aggressive line-drop compensation scheme can try to keep the voltage at the low end (say, at 114 V) for the last customer at all times. The set voltage in the station may be 115 to 117 V, depending on the circuit voltage profile. Aggressive compensation boosts the voltage during heavy loads, while trying to keep voltages low at the ends of circuits. During light loads, the station voltage may drop to well under 120 V. This strategy helps the least at heavy load periods, so it is more useful for energy conservation than for peak shaving. Aggressive compensation makes low voltages more likely at the end of circuits. If any of the planning assumptions are wrong, especially power factor and load placement, customers at the end of circuits can have low voltages.

- *Others* — Other voltage profile improvement options help when implementing a voltage reduction program, although some of these options, such as reconductoring, undergrounding, load balancing, and increasing primary voltage levels, are quite expensive.

Boost connection   Buck connection
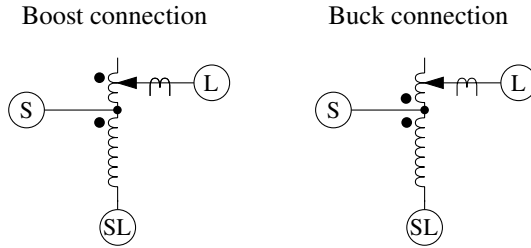
FIGURE 5.2
ANSI type A single-phase regulator, meaning taps on the load bushing.

5.4 Regulators

Voltage regulators are autotransformers with automatically adjusting taps. Commonly, regulators provide a range from –10 to +10% with 32 steps. Each step is 5/8%, which is 0.75 V on a 120-V scale.

A single-phase regulator has three bushings: the source (S), the load (L), and the source-load (SL). The series winding is between S and L. Figure 5.2 shows a straight regulator (ANSI type A) with the taps on the load side. An ANSI type B, the inverted design, has the taps on the source bushing. The regulator controller measures current with a CT at the L bushing and measures the voltage with a PT between L and SL. Regulators have a reversing switch that can flip the series winding around to change back and forth between the boost and the buck connection.

Regulators are rated on current (IEEE Std. C57.15-1999). Regulators also have a kVA rating which is the two-winding transformer rating and not the load-carrying capability. A regulator at 7.62 kV line to ground with a ±10% range and a load current rating of 100 A has a kVA rating of 0.1(7.62 kV)(100A) = 76 kVA. The load-carrying capability is ten times the regulator's kVA rating.

By reducing the range of regulation, we can extend the rating of the regulator. Reducing the range from ±10 to ±5% increases the rating by 60% (see Figure 5.3).

The impedance is the two-winding impedance times a base value about ten times as large. Because the impedance is so small, we can normally neglect it.

Three-phase regulators, often used in stations, are used on wye or delta systems. A three-phase regulator controls all three phases simultaneously. These are normally larger units. The normal connection internally is a wye connection with the neutral point floating.

Commonly, utilities use single-phase units, even for regulating three-phase circuits. We can connect single-phase regulators in several ways [see Figure 5.4 and (Bishop et al., 1996)]:
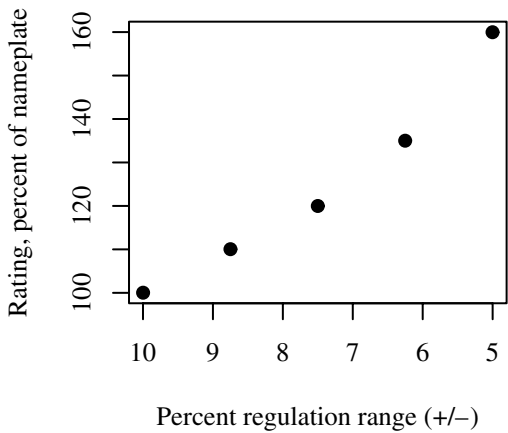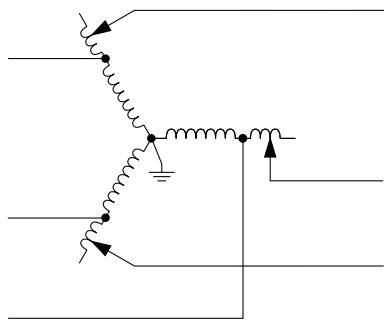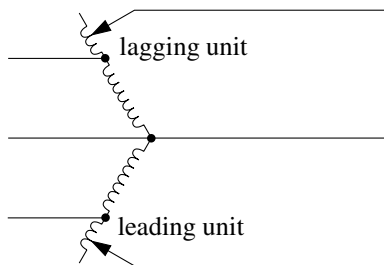
FIGURE 5.3
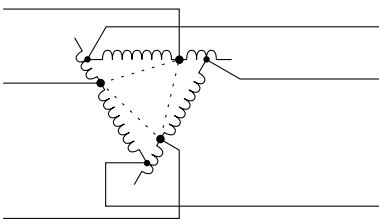Increased regulator ratings with reduced regulation range.

FIGURE 5.4
Three-phase regulator connections.

- *Line to neutral* — On four-wire systems, three-phase circuits normally have three single-phase regulators connected line to neutral. Line-to-neutral connections are also appropriate for single-phase and two-phase circuits. Each regulator independently controls voltage, which helps control voltage unbalance as well as steady-state voltage.
- *Open delta* — Only two single-phase regulators are needed, each connected phase to phase.
- *Closed delta* — Three regulators are connected phase to phase. Using the closed delta extends the regulation range by 50%, from ±10 to ±15%.

In both of the delta connections, the regulators see a current phase-shifted relative to the voltage. In the leading connection with unity power factor loads, the line current through the regulator leads the line-to-line voltage by 30°. The lagging connection has the current reversed: for a unit power factor load, the line current lags the line-to-line voltage by 30°. In the open-delta configuration, one of the units is leading and the other is lagging. In the closed-delta arrangement, all three units are either leading or all three are lagging. Although uncommon, both of the delta connections can be applied on four-wire systems.

Regulators have a voltage regulating relay that controls tap changes. This relay has three basic settings that control tap changes (see Figure 5.5):

- *Set voltage* — Also called the set point or bandcenter, the set voltage is the desired output of the regulator.
- *Bandwidth* — Voltage regulator controls monitor the difference between the measured voltage and the set voltage. Only when the difference exceeds one half of the bandwidth will a tap change start. Use a bandwidth of at least two times the step size, 1.5 V for ±10%, 32-step regulators. Settings of 2 and 2.5 V are common.
- *Time delay* — This is the waiting time between the time when the voltage goes out of band and when the controller initiates a tap
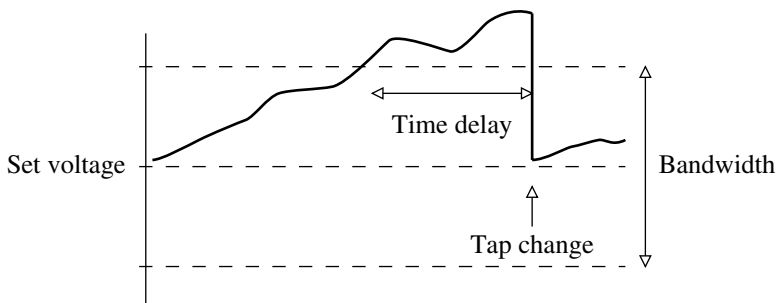

FIGURE 5.5
Regulator tap controls based on the set voltage, bandwidth, and time delay.

change. Longer time delays reduce the number of tap changes. Typical time delays are 30 to 60 sec.

If the voltage is still out of bounds after a tap change, the controller makes additional tap changes until the voltage is brought within bounds. The exact details vary by controller, and some provide programmable modes. In some modes, controllers make one tap change at a time. In other modes, the controller may initiate the number of tap changes it estimates are needed to bring the voltage back within bounds. The time delay relay resets if the voltage is within bounds for a certain amount of time.

A larger bandwidth reduces the number of tap changes, but at a cost. With larger bandwidth, the circuit is not as tightly regulated. We should include the bandwidth in voltage profile calculations to ensure that customers are not given over or under voltages. Voltage that was used for bandwidth can be used for voltage drop along the circuit. With a higher bandwidth we may need more regulators on a given line. So, use at least two times the step size, but do not use excessively high bandwidths such as 3 or 3.5 V.

In addition to these basics, regulator controllers also have line-drop compensation to boost voltages more during heavy load. Controllers also may have high and low voltage limits to prevent regulation outside of a desired range of voltages. In addition to the regulator and control application information provided here, see Beckwith (1998), Cooper Power Systems (1978), General Electric (1979), and Westinghouse (1965).

Many regulators are bi-directional units; they can regulate in either direction, depending on the direction of power flow. A bi-directional regulator measures voltage on the source side using an extra PT or derives an estimate from the current. If the regulator senses reverse power flow, it switches to regulating the side that is normally the source side. We need reverse mode for a regulator on circuits that could be fed by an alternate source in the reverse direction. Without a reverse mode, the regulator can cause voltage problems during backfeeds. If a unidirectional regulator is fed "backwards," the regulator PT is now on the side of the source. Now, if the voltage drops, the regulator initiates a tap raise. However, the voltage the PT sees does not change because it is on the source side (very stiff). What happened was the voltage on the load side went down (but the regulator controller does not know that because it is not measuring that side). The controller still sees low voltage, so it initiates another tap raise which again lowers the voltage on the other side of the regulator. The controller keeps trying to raise the voltage until it reaches the end of its regulation range. So, we have an already low voltage that got dropped by an extra 10% by the unidirectional regulator. If the controller initially sees a voltage above its set voltage, it ratchets all the way to the high end causing a 10% overvoltage. Also, if the incoming voltage varies above and below the bandwidth, the regulator can run back and forth between extremes. A bi-directional regulator prevents these runaways. Depending on its mode, under reverse power, a bi-directional regulator can regulate in the reverse direction, halt tap changes, or move to the

neutral point (these last two do not require PTs on both sides but just power direction sensing).

Regulators also have an operations counter. The counter helps identify when a regulator is due for refurbishment. Regulators are designed to perform many tap changes, often over one million tap changes over the life of a regulator. A regulator might change taps 70 times per day, which is 25,000 times per year (Sen and Larson, 1994). A regulator counter also provides a good warning indicator; excessive operations suggest that something is wrong, such as wrong line drop compensation settings, a bandwidth or time delay that is too small, or widely fluctuating primary voltages.

Regulators have "drag hands" — markers on the tap position indicator that show the maximum and minimum tap positions since the drag hands were last reset. The drag hands are good indicators of voltage problems. If maintenance reviews continually show the drag upper hand pegging out at +10%, the upstream voltage is probably too low. More work is needed to correct the circuit's voltage profile. Advanced controllers record much more information, including tap change records and demand metering to profile voltages, currents, and power factors.

5.4.1 Line-Drop Compensation

LTC transformer and regulator controls can be augmented with line-drop compensation. During heavy load, the controller boosts voltage the most, and during light load, voltage is boosted the least. The line-drop compensator uses an internal model of the impedance of the distribution line to match the line impedance. The user can set the *R* and *X* values in the compensator to adjust the compensation. The controller adjusts taps based on the voltage at the voltage regulating relay, which is the PT voltage plus the voltage across the line-drop compensator circuit (see Figure 5.6). With no compensation, the voltage regulating relay adjusts the taps based on the PT voltage.

Since load on a typical distribution line is distributed, *R* and *X* compensator settings are chosen so that the maximum desired boost is obtained
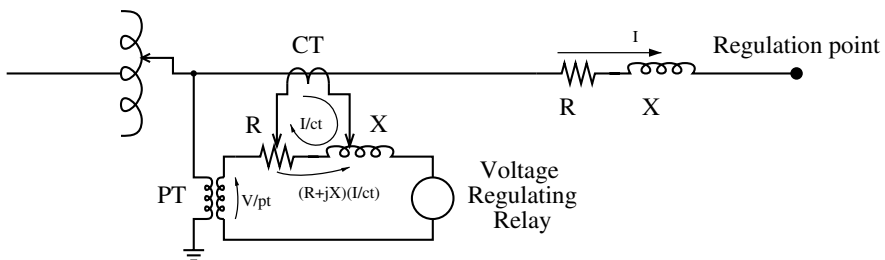

FIGURE 5.6
Line drop compensator circuit.

under heavy load while a given voltage is obtained under light load. There are two main approaches for selecting settings:

- *Load center* — The settings are chosen to regulate the voltage at a given point downstream of the regulator.
- *Voltage spread* — The R and X settings are chosen to keep the voltage within a chosen band when operating from light load to full load. The R and X settings may or may not be proportional to the line's R and X.

The main complication of all of the methods is that the load and power factors change (especially with downstream capacitor banks). Many regulators are set up without line drop compensation. It is obviously easier and less prone to mistakes, but we are losing out on some significant capability. If we set the regulator set voltage at 120 V, and we do not get enough boost along the line, we will need more regulators. With a higher set voltage such as 126 V, we do not need as many regulators, but we have high voltages at light load and possibly overvoltages if the circuit has capacitors. With line drop compensation, we have boost when we need it during heavy load, but not during light load (see Figure 5.7). Line-drop compensation also normally leads to a smaller range of fluctuations in voltage through the day for customers along the circuit.

5.4.1.1   Load-Center Compensation

The classic way to set compensator settings is to use the *load-center* method. Consider a line with impedances R_L and X_L with a load at the end. Now, if we pick the R_{set} and X_{set} of the compensator to match those of the line, as the load changes the regulator responds and adjusts the regulator taps to keep the voltage constant, not at the regulator but at the load. To achieve this, we can set the R_{set} and X_{set} of the regulator as

$$R_{set} = \frac{I_{CT}}{N_{PT}} R_L$$

$$X_{set} = \frac{I_{CT}}{N_{PT}} X_L$$

where
 R_{set} = regulator setting for resistive compensation, V
  X_{set} = regulator setting for reactive compensation, V
  I_{CT} = primary rating of the current transformer, A
  N_{PT} = potential transformer ratio (primary voltage/secondary voltage)
  R_L = primary line resistance from the regulator to the regulation point, Ω
  X_L = primary line reactance from the regulator to the regulation point, Ω
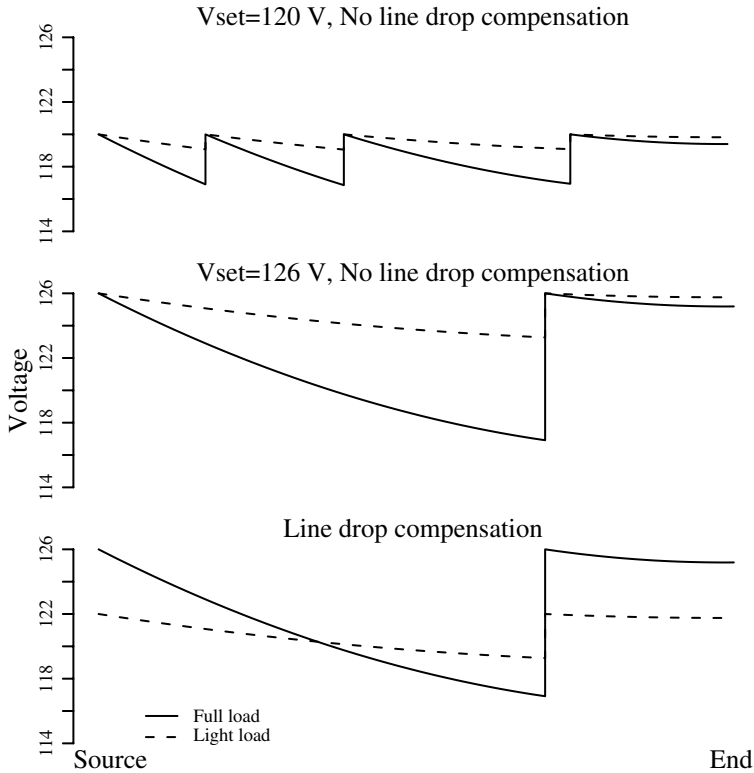
FIGURE 5.7
Voltage profiles on a circuit with various forms of regulation.

A regulator's *R* and *X* compensator settings are in units of volts. By using volts as units, we can directly see the impact of the regulator on a 120-V scale. Consider an example where the set voltage is 120 V. With a current at unity power factor and R_{set} = 6 V (X_{set} does not matter at unity power factor), the controller regulates the voltage to 120 + 6 = 126 V when the current is at the peak CT rating. If the current is at half of the CT rating, the controller regulates to the set voltage plus 3 or 123 V. Available compensator settings are normally from –24 to +24 V.

Note that the primary CT rating is an important part of the conversion to compensator settings. The CT rating may be the same as the regulator rating or it may be higher. The CT rating is given on the nameplate. Table 5.6 shows the regulator ratings and primary CT current rating for one manufacturer. Regulators may be applied where the nameplate voltage does not match the system voltage if they are close enough to still allow the desired regulation range at the given location. Also, some regulators have taps that allow them to be used at several voltages. Make sure to use the appropriate PT ratio for the tap setting selected.

TABLE 5.6

Regulator and Primary CT Ratings in Amperes

Regulator Current Ratings	CT Primary Current
25	25
50	50
75	75
100	100
150	150
167, 200	200
219, 231, 250	250
289, 300	300
328, 334, 347, 400	400
418, 438, 463, 500	500
548, 578, 656, 668	600
833, 875, 1000, 1093	1000
1332, 1665	1600

When specifying impedances for the line-drop compensator, use the correct line impedances. For a three-phase circuit, use the positive-sequence impedance. For a single-phase line, use the loop impedance Z_S which is about twice the positive-sequence impedance.

On a delta regulator, either an open delta or a closed delta, divide the PT ratio by $\sqrt{3}$. On a delta regulator the PT connects from phase to phase, but the internal circuit model of the line-drop compensator is phase to ground, so we need the $\sqrt{3}$ factor to correct the voltage.

Line-drop compensation works perfectly for one load at the end of a line, but how do we set it for loads distributed along a line? If loads are uniformly distributed along a circuit that has uniform impedance, we can hold the voltage constant at the midpoint of the section by using:

- 3/8 *rule* — For a uniformly distributed load, a regulator can hold the voltage constant at the midpoint of the circuit if we use line-drop compensation settings based on 3/8 of the total line impedance. A circuit with a uniformly distributed load has a voltage drop to the end of the circuit of one half of the drop had all of the loads been lumped into one load at the end of the circuit. Three-fourths of this drop is on the first half of the circuit, so (1/2)(3/4) = 3/8 is the equivalent voltage drop on a uniformly distributed load.

Make sure not to allow excessive voltages. We can only safely compensate a certain amount, and we will have overvoltages just downstream of the regulator if we compensate too much. Check the voltage to the voltage regulating relay to ensure that it is not over limits. The maximum voltage is

$$V_{max} = V_{set} + (pf \cdot R_{set} + qf \cdot X_{set})\, I_{max}$$

where

    V_{set} = regulator set voltage
    R_{set} = resistive setting for compensation, V
    X_{set} = reactive setting for compensation, V
    pf = load power factor
    qf = load reactive power factor = $\sin(\cos^{-1}(pf))$
    I_{max} = maximum load current in per unit relative to the regulator CT rating

If V is more than what you desired, reduce R_{set} and X_{set} appropriately to meet your desired limit.

5.4.1.2   *Voltage-Spread Compensation*

In another method, the *voltage-spread* method, we find compensator settings by specifying the band over which the load-side voltage should operate. For example, we might want the regulator to regulate to 122 V at light load and 126 V at full load. If we know or can estimate the light-load and full-load current, we can find R and X compensator settings to keep the regulated voltage within the proper range. If we want the regulator to operate over a given compensation range C, we can choose settings to satisfy the following:

$$C = V - V_{set} = pf \cdot R_{set} + qf \cdot X_{set}$$

where

    R_{set} = resistive setting for compensation, V
    X_{set} = reactive setting for compensation, V
    pf = load power factor
    qf = load reactive power factor = $\sin(\cos^{-1}(pf))$
    C = total desired compensation voltage, V
    V_{set} = regulator set voltage, V
    V = voltage that the controller will try to adjust the regulator to, V

With line current operating to the regulator CT rating limit (which is often the regulator size) and the current at the given power factor, these settings will boost the regulator by C volts on a 120-V scale. Any number of settings for R_{set} and X_{set} are possible to satisfy this equation. If we take $X_{set} = \frac{X}{R} R_{set}$ where the *X/R* ratio is selectable, the settings are

$$R_{set} = \frac{C}{pf + \frac{X}{R} qf}$$

$$X_{set} = \frac{\frac{X}{R} C}{pf + \frac{X}{R} qf} = \frac{X}{R} R_{set}$$

where

$\frac{X}{R}$ = X/R ratio of the compensator settings

Note that C must be given as seen on the regulator PT secondaries, on a 120-V base. As an example, if the feeder voltage should be not more than 126 V at the limit of the regulator, and the desired voltage at no load is 122 V, set the regulator set voltage at 122 V and find R_{set} and X_{set} to give $C = 4$ V. For a power factor of 0.85 and $\frac{X}{R} = 3$, the equations above give $R_{set} = 1.64$ V and $X_{set} = 4.94$ V.

To control the voltage range for a light load other than zero and for a peak load other than the regulator CT rating, we can use the following to find the voltage swing from light load to full load as

$$V_{max} - V_{min} = (pf \cdot R_{set} + qf \cdot X_{set})I_{max} - (pf \cdot R_{set} + qf \cdot X_{set})I_{min}$$

where

V_{max} = desired voltage at the maximum load current on a 120-V base, V
V_{min} = desired voltage at the minimum load current on a 120-V base, V
I_{max} = maximum load current in per-unit relative to the regulator CT rating
I_{min} = minimum load current in per-unit relative to the regulator CT rating

Now, the R and X settings are

$$R_{set} = \frac{V_{max} - V_{min}}{(pf + \frac{X}{R} qf)(I_{max} - I_{min})}$$

$$X_{set} = \frac{X}{R} R_{set}$$

And, the regulator set voltage is

$$V_{set} = V_{min} - (pf \cdot R_{set} + qf \cdot X_{set})I_{min} = V_{min} - \frac{V_{max} - V_{min}}{I_{max} - I_{min}}I_{min}$$

With a compensator X/R ratio equal to the line X/R ratio, these equations move the effective load center based on the choice of voltage and current minimums and maximums.

Just like we can choose to have the compensator X/R ratio equal the line X/R ratio, we can choose other values as well. There are good reasons why we might want to use other ratios; this is done mainly to reduce the sensitivity to power factor changes. The *zero reactance* method of selecting compensator makes $X_{set} = 0$ (and the compensator $X/R = 0$) but otherwise uses the same equations as the voltage spread method (General Electric, 1979).

By making X_{set} zero, the compensator is not sensitive to variations in power factor caused by switched capacitors or load variation; only real power changes cause regulator movement. This method also simplifies application of regulators. The equations become

$$R_{set} = \frac{V_{max} - V_{min}}{pf(I_{max} - I_{min})}$$

$$X_{set} = 0$$

And, the regulator set voltage is

$$V_{set} = V_{min} - (pf \cdot R_{set})I_{min}$$

The equations simplify more if we assume that $I_{min} = 0$ (our error with this is that voltages run on the high side during light load). A further simplification is to assume that the power factor is one. If the power factor is less than that at full load, the regulator will not boost the voltage quite as much. Often, we do not know the power factor at the regulator location anyway.

This method is useful with switched capacitor banks close to the regulator. It does not perform well for low power factors if we have assumed a power factor near unity. With this control, the regulator will not provide enough boost with poor power-factor load.

Another option is to take $X/R = 0.6$, which weights the real power flow more than the reactive power flow, but not as extremely as the zero reactance compensation method. So, although the controller is somewhat desensitized to changes in power factor, the regulator provides some action based on reactive power. Figure 5.8 shows several X/R compensator settings chosen to provide an operating band from 121 V at light load to 127 V at full load. The settings were chosen based on a power factor of 0.9, and the curves show the voltage as the power factor varies. The middle graph with $X/R = 0.6$ performs well over a wide range of power factors. The graph on the left, where $X/R = 3$ which is the line X/R ratio, has the most variation with changes in power factor. If power factor is lower than we expected, the compensator will cause high voltages.

With $X/R = 0.6$ and $pf = 0.9$, the voltage spread equations are

$$R_{set} = 0.86 \frac{V_{max} - V_{min}}{(I_{max} - I_{min})}$$

$$X_{set} = 0.6R_{set}$$
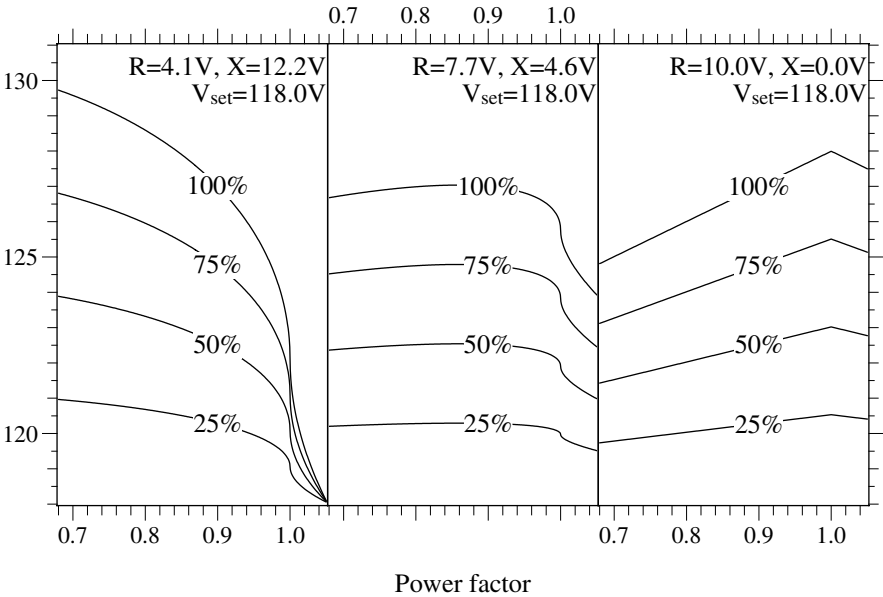
And, the regulator set voltage is

FIGURE 5.8
Regulated voltage based on different compensator settings and power factors with the percentage loadings given on the graph. All settings are chosen to operate from 121 V at light load (33%) to 127 V at full load (100% of the primary CT ratio) at a power factor of 0.9.

$$V_{set} = V_{min} - \frac{V_{max} - V_{min}}{I_{max} - I_{min}} I_{min}$$

The *universal compensator* method fixes compensation at R_{set} = 5 V and X_{set} = 3 V to give a 6-V compensation range with current ranging up to the regulator CT rating (General Electric, 1979). For other voltage ranges and maximum currents, we can use:

$$R_{set} = \frac{5}{I_{max}} \frac{(V_{max} - V_{min})}{6}$$

$$X_{set} = \frac{3}{I_{max}} \frac{(V_{max} - V_{min})}{6}$$

And we assume that $I_{min} = 0$, so the regulator set voltage is

$$V_{set} = V_{min}$$

To make this even more "cookbook," we can standardize on values of V_{max} and V_{min}, for example, values of 126 V and 120 V. If the full-load is the CT

rating (which we might want in order to be conservative), the default settings become $R_{set} = 5$ V and $X_{set} = 3$ V. The universal compensation method is easy yet relatively robust.

With any of the voltage-spread methods of setting the R and X line-drop compensation, the peak current is an important parameter. If we underestimate the load current, the regulator can overcompensate and cause high voltages (if we do not have a voltage override limiter or if it is disabled). Check regulator loadings regularly to ensure that the compensation is appropriate.

5.4.1.3 Effects of Regulator Connections

On an open-delta regulator, one regulator is connected leading, and the other lagging. We need to adjust the compensator settings to account for the 30° phase shift. On the leading regulator, the current leads the voltage by 30°; so we need to subtract 30° from the compensator settings, which is the same as multiplying by 1∠30° or (cos 30° − j sin 30°). Modify the settings for the leading regulator (Cooper Power Systems, 1978; Westinghouse Electric Corporation, 1965) with

$$R'_{set} = 0.866\ R_{set} + 0.5X_{set}$$

$$X'_{set} = 0.866\ X_{set} - 0.5R_{set}$$

And for the lagging regulator we need to add 30°, which gives

$$R'_{set} = 0.866\ R_{set} - 0.5X_{set}$$

$$X'_{set} = 0.866\ X_{set} + 0.5R_{set}$$

For an X/R ratio above 1.67, R'_{set} is negative on the lagging regulator; and for a ratio below 0.58, X'_{set} is negative on the leading regulator. Most controllers allow negative compensation.

In the field, how do we tell between the leading and the lagging regulator? Newer regulator controllers can tell us which is which from phase angle measurements. For older controllers, we can modify the compensator settings to find out (Lokay and Custard, 1954). Set the resistance value on both regulators to zero, and set the reactance setting on both to the same nonzero value. The unit that moves up the most number of tap positions is the lagging unit (with balanced voltages, this is the unit that goes to the highest raise position). If the initial reactance setting is not enough, raise the reactance settings until the leading and lagging units respond differently.

With a closed-delta regulator, all three regulators are connected either leading or lagging. All three regulators have the same set of compensator settings; adjust them all with either the leading or the lagging equations described for the open-delta regulator.

On a three-phase regulator, even on a delta system, the compensator settings do not need adjustment. The controller accounts for any phase shift that might occur inside the regulator.

5.4.2   Voltage Override

Use the *voltage override* feature on the regulator controller. No matter how we select the line-drop compensation settings, an important feature is an upper voltage limit on the regulation action. The regulator keeps the regulated voltage below this limit regardless of the line-drop compensation settings. Always use this feature to protect against overvoltages caused by incorrect line-drop compensation settings or unusually high loadings. This upper voltage limiter is also called "first house protection," as it is the first few customers downstream that could have overvoltages due to regulator action. With a voltage limit, we can set line-drop compensator settings more aggressively and not worry about causing overvoltages to customers. On a regulator without an upper limit (normally older units), increase estimated peak loadings when calculating line-drop compensation settings in order to reduce the risk of creating overvoltages. Voltage override functions usually have a deadband type setting on the voltage limit to prevent repeated tap changes. For example, we might set a 126-V upper limit with a deadband of an extra 2 V. Above 128 V the controller immediately taps the regulator down to 126 V, and between 126 and 128 V the controller prohibits tap raises (different controllers implement this function somewhat differently; some include time delays). Even without line-drop compensation, the voltage override function helps protect against sudden changes in upstream voltages (the out-of-limit response is normally faster than normal time-delay settings programmed into regulators).

5.4.3   Regulator Placement

With no feeder regulators, the entire voltage drop on a circuit must be within the allowed primary voltage range. One feeder regulator can cover primary voltage drops up to twice the allowed voltage variation. Similarly, two supplementary regulators can cover primary voltage drops up to three times the allowed variation. For a uniformly distributed load, optimum locations for two regulators are at distances from the station of approximately 20% of the feeder length for one and 50% for the other. For one feeder regulator, the optimum location for a uniformly distributed load is at 3/8 of the line length from the station.

When placing regulators and choosing compensator settings, allow for some load growth on the circuit. If a regulator is applied where the load is right near its rating, it may not be able to withstand the load growth. However, it is more than just concern about the regulator's capability. If we want to keep the primary voltage above 118 V, and we add a regulator to a circuit

right at the point where the primary voltage falls to 118 V, that will correct the voltage profile along the circuit with present loadings. If loadings increase in the future, the voltage upstream of the regulator will drop below 118 V. As previously discussed, when setting line-drop compensator settings, the maximum load on the regulator should allow room for load growth to reduce the chance that the regulator boosts the voltage too much.

Several regulators can be strung together on a circuit. Though this can meet the steady-state voltage requirements of customers, it will create a very weak source for them. Flicker problems from motors and other fluctuating loads are more likely.

Also consider the effect of dropped load on regulators. A common case is a recloser downstream of a line regulator. If the regulator is tapped up because of heavy load and the recloser suddenly drops a significant portion of the load, the voltage downstream of the regulator will pop up until the regulator controller shifts the taps back down.

5.4.4 Other Regulator Issues

Normally, voltage regulators help with voltage unbalance as each regulator independently controls its phase. If we aggressively compensate, the line-drop compensation can cause voltage unbalance. Consider a regulator set to operate between 120 V at no load and 126 V at full load. If one phase is at 50% load and the other two are at 0% load, the line-drop compensator will tap to 123 V on the loaded phase and to 120 V on the unloaded phases. Depending on customer placements, this may be fine if the voltages correct themselves along the line. But if the unbalance is due to a large tapped lateral just downstream of the regulator, the regulator needlessly unbalances the voltages.

Capacitor banks pose special coordination issues with regulators. A fixed capacitor bank creates a constant voltage rise on the circuit and a constant reactive contribution to the current. Either fixed or switched, capacitors upstream of a regulator do not interfere with the regulator's control action. Downstream capacitors pose the problem. A capacitor just downstream of a regulator affects the current that the regulator sees, but it does not measurably change the shape of the voltage profile beyond the regulator. In this case, we would like the line-drop compensation to ignore the capacitor. The voltage-spread compensation with a low compensator X/R or the zero-reactance compensator settings work well because they ignore or almost ignore the reactive current, so it works with fixed or switched banks downstream of the regulator. The load-center approach is more difficult to get to work with capacitors.

We do not want to ignore the capacitor at the end of a circuit section we are regulating because the capacitor significantly alters the profile along the circuit. In this case, we do not want zero-reactance compensation; we want some X to compensate for the capacitive current.

Switched capacitors can interact with the tap-changing controls on regulators upstream of the capacitors. This sort of interaction is rare but can

happen if the capacitor is controlled by voltage (not radio, not time of day, not vars). A regulator may respond to an upstream or downstream capacitor switching, but that does not add up to many extra tap changes since the capacitor switches infrequently. Normally, the capacitor cannot cycle back and forth against the regulator. The only case might be if the regulator has negative settings for the reactive line-drop compensation.

With several regulators in series, adjustments to the time delay settings are the proper way to coordinate operations between units. Set the downstream regulator with the longest time delay so it does not change taps excessively. For multiple regulators, increase the time delay with increasing distance from the source. Tap changes by a downstream regulator do not change the voltage upstream, but tap changes by an upstream regulator affect all downstream regulators. If a downstream regulator acts before the upstream regulator, the downstream regulator may have to tap again to meet its set voltage. Making the downstream regulator wait longer prevents it from tapping unnecessarily. Separate the time delays by at least 10 to 15 sec to allow the upstream unit to complete tap change operations.

5.5   Station Regulation

Utilities most commonly use load tap changing transformers (LTCs) to control distribution feeder voltages at the substation. In many cases (short, urban, thermally limited feeders) an LTC is all the voltage support a circuit needs.

An LTC or a stand-alone voltage regulator must compensate for the voltage change on the subtransmission circuit as well as the voltage drop through the transformer. Of these, the voltage drop through the transformer is normally the largest. Normally, the standard ±10% regulator can accomplish this. A regulator can hit the end of its range if the load has especially poor power factor. The voltage drop across a transformer follows:

$$V_{drop} = I_R \cdot R + I_X \cdot X$$

Since a transformer's X/R ratio is so high, the reactive portion of the load creates the most voltage drop across the transformer. Consider a 10% impedance transformer at full load with a load power factor of 0.8, which means the reactive power factor is 0.6. In this case, the voltage drop across the transformer is 6%. If the subtransmission voltage is 120 V (on a 120-V scale), the maximum that the regulator can boost the voltage to is 124 V. If this example had a transformer loaded to more than its base open-air rating (OA or ONAN), the regulator would be more limited in range. In most cases, we do not run into this problem as power factors are normally much better than these.

In most cases, bus regulation suffices. For cases where circuits have significant voltage drop, individual feeder regulation can be better. Individual feeder regulation also performs better on circuits with different load cycles. If commercial feeders are on the same bus as residential feeders, it is less likely that a bus regulator can keep voltages in line on all circuits. Normally, we handle this by using bus regulation and supplementary line regulators. In some cases, individual feeder regulation in the station is more appropriate.

The voltage on feeders serving secondary networks is controlled at the primary substation with LTC transformers. These circuits are short enough that feeder regulators are unnecessary. Network feeders are often supplied by parallel station transformers; paralleling LTC units raises several issues that are discussed in the next section.

5.5.1 Parallel Operation

With care, we can parallel regulators. The most common situation is in a substation where a utility wants to parallel two LTC transformers. If two paralleled transformers do not have the same turns ratio, current will circulate to balance the voltages. The circulating current is purely reactive, but it adds extra loading on the transformer.

Some of the methods to operate LTC transformers in parallel (Jauch, 2001; Westinghouse Electric Corporation, 1965) include

- *Negative-reactance control* — The reactance setting in the line-drop compensator is set to a negative value, so higher reactive current forces the control to lower taps. The transformer with the higher tap has more reactive current, and the transformer with the lower tap is absorbing this reactive current (it looks capacitive to this transformer). So, a negative-reactance setting forces the transformer with the highest tap (and most reactive current) to lower its taps and bring it into alignment with the other unit. This method limits the use of line-drop compensation and can lead to lower bus voltages.

- *Master-follower* — One controller, the master, regulates the voltage and signals the other tap changers (the followers) to match the tap setting. The master control normally gets feedback from the followers to confirm their operation.

- *Var balancing* — The controller adjusts taps as required to equalize the vars flowing in parallel transformers. Auxiliary circuitry is required. This method has the advantage that it works with transformers fed from separate transmission sources.

- *Circulating current method* — This is the most common control. Auxiliary circuitry is added to separate the load current through each transformer from the circulating current. Each transformer LTC control is fed the load current. The controller adjusts taps to minimize

the difference in current between parallel units. Removing a unit does not require changing controller settings.

The complications associated with paralleling regulators are another reason utilities normally avoid closed bus ties in distribution substations.

5.5.2 Bus Regulation Settings

Although too often left unused, bus regulators (whether stand-alone regulators or load tap changing transformers) can use line-drop compensation. The concept of a load center rarely has good meaning for a bus supporting several circuits, but the voltage spread methods allow the regulator to boost voltage under heavy load.

The voltage-spread equations assume that the power factor at full load is the same as the power factor at light load. If the power factor is different at light and peak loads, we can use this information to provide more precise settings. We could solve the following to find new R and X settings with different power factors

$$V_{max} - V_{min} = (pf_{max} \cdot R_{set} + qf_{max} \cdot X_{set})I_{max} - (pf_{min} \cdot R_{set} + qf_{min} \cdot X_{set})I_{min}$$

However, it is easier to use the equations in Section 5.4.1.2 and use the average of the power factor at peak load and the power factor at light load. With line-drop compensation for bus regulation, the voltage-override feature helps to ensure that the LTC or regulator does not cause excessive voltages.

Individual substation feeder regulators are set the same as line feeder regulators. We can tune controller settings more precisely based on the individual characteristics of a given feeder. If the first part of the feeder is an express feeder with no load on it, we could boost the voltage higher than normal, especially if the circuit is voltage limited. Our main constraint is making sure that the first customer does not have high voltage.

5.6 Line Loss and Voltage Drop Relationships

Line losses are from the line current flowing through the resistance of the conductors. After distribution transformer losses, primary line losses are the largest cause of losses on the distribution system. Like any resistive losses, line losses are a function of the current squared multiplied by the resistance (I^2R). Ways to reduce line losses include

- Use a higher system voltage
- Balance circuits

- Convert single-phase circuits to three-phase circuits
- Reduce loads
- Increase power factor (capacitors)
- Reconductor with a larger size

Because losses are a function of the current squared, most losses occur on the primary near the substation. Losses occur regardless of the power factor of the circuit. Reducing the reactive portion of current reduces the total current, which can significantly impact losses.

Approximations using uniform load distributions are useful. A uniformly distributed load along a circuit of length *l* has the same losses as a single lumped load placed at a length of *l*/3 from the source end. For voltage drop, the equivalent circuits are different: a uniformly distributed load along a circuit of length *l* has the same voltage drop as a single lumped load placed at a length of *l*/2 from the source end. This 1/2 rule for voltage drop and the 1/3 rule for losses are helpful approximations when doing hand calculations or when making simplifications to enter in a load-flow program.

For a uniformly increasing load, the equivalent lumped load is at 0.53*l* of the length from the source. Figure 5.9 shows equivalent circuits for a uniform load and a uniformly increasing load.

Line losses decrease as operating voltage increases because the current decreases. Schultz (1978) derived several expressions for primary feeder I^2R losses on circuits with uniform load densities. His analysis showed that most 15 to 35 kV circuits are not voltage-drop limited — most are thermally limited. As the system voltage varies, the losses change the most for voltage-limited circuits (Schultz, 1978):

$$L_2 = \left(\frac{V_1}{V_2}\right)^2 L_1 \qquad \text{for a voltage-limited circuit}$$

$$L_2 = \left(\frac{V_1}{V_2}\right)^{2/3} L_1 \qquad \text{for a thermally-limited circuit}$$

where
V_1, V_2 = voltage on circuits 1 and 2
L_1, L_2 = feeder I^2R losses on circuits 1 and 2

On a system-wide basis, losses are expected to change with voltage with an exponent somewhere between 2/3 and 2.

Losses, voltage drop, and capacity are all interrelated. Three-phase circuits have the highest power transfer capacity, the lowest voltage drop, and the lowest losses. Table 5.7 compares capacity, voltage drop, and losses of a balanced three-phase system with several other phasing configurations.
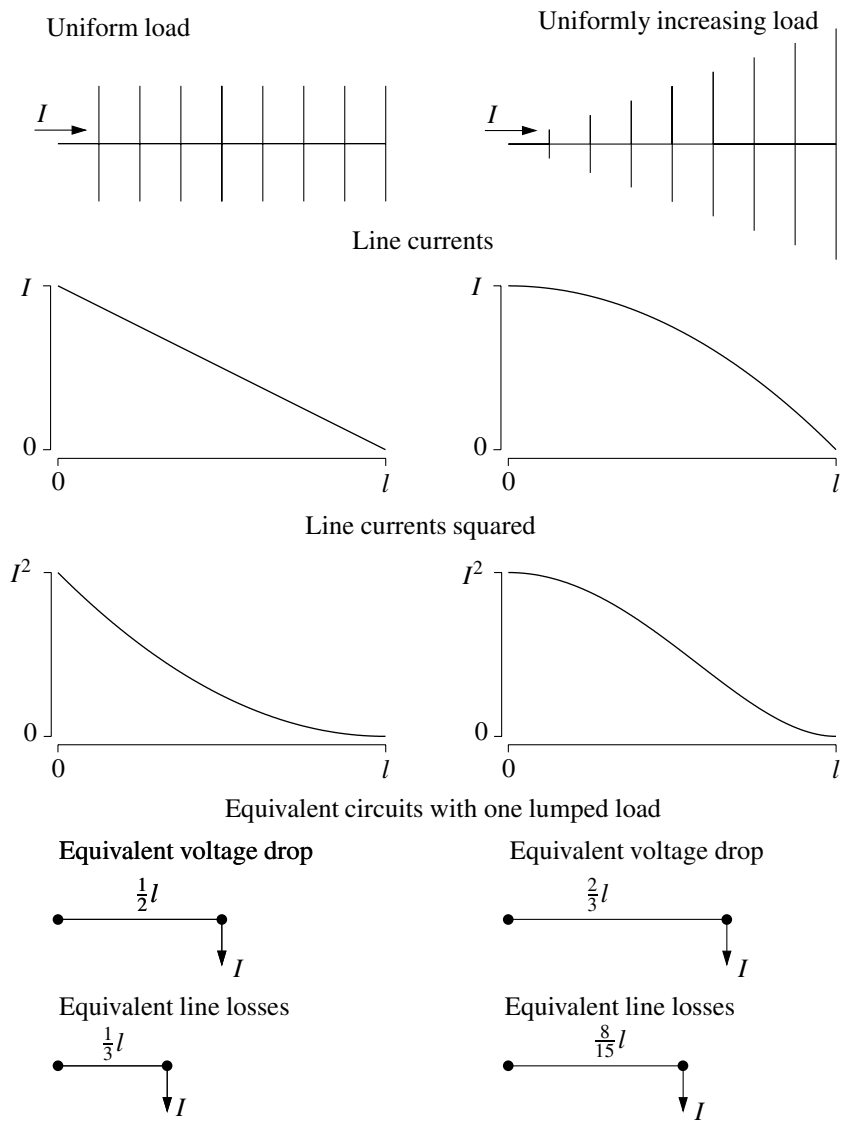
Uniform load

Uniformly increasing load

Line currents

I

0

0 l

I

0

0 l

Line currents squared

I^2

0

0 l

I^2

0

0 l

Equivalent circuits with one lumped load

Equivalent voltage drop

$\frac{1}{2}l$

I

Equivalent voltage drop

$\frac{2}{3}l$

I

Equivalent line losses

$\frac{1}{3}l$

I

Equivalent line losses

$\frac{8}{15}l$

I

FIGURE 5.9
Equivalent circuits of uniform loads.

TABLE 5.7

Characteristics of Various Systems

System	Capacity in per Unit	Voltage Drop in per Unit for Equal kVA	Line Losses in per Unit for Equal kVA
Balanced three phase	1.0	1.0	1.0
Two phases	0.5	2.0	2.0
Two phases and a multigrounded neutral	0.67	2.0–3.3	1.2–3.0
Two phases and a unigrounded neutral	0.67	2.5–4.5	2.25
One phase and a multigrounded neutral	0.33	3.7–4.5	3.5–4.0
One phase and a unigrounded neutral	0.33	6.0	6.0

Note: The two-phase circuits assume all load is connected line to ground. Neutrals are the same size as the phases. Reduced neutrals increase voltage drop and (usually) line losses. The voltage drop and line loss ratios for circuits with multigrounded neutrals vary with conductor size.

Utilities consider both peak losses and energy losses. Peak losses are important because they compose a portion of the peak demand; energy losses are the total kilowatt-hours wasted as heat in the conductors. The peak losses are more easily estimated from measurements and models. The average losses can be found from the peak losses using the loss factor F_{ls}:

$$F_{ls} = \frac{\text{Average losses}}{\text{Peak losses}}$$

Normally, we do not have enough information to directly measure the loss factor. We do have the load factor (the average demand over the peak demand). The loss factor is some function of the load factor squared. The most common approximation (Gangel and Propst, 1965) is

$$F_{ls} = 0.15F_{ld} + 0.85F_{ld}^2$$

This is often used for evaluating line losses and transformer load losses (which are also a function of I^2R). Load factors closer to one result in loss factors closer to one. Another common expression is $F_{ls} = 0.3F_{ld} + 0.7F_{ld}^2$. shows both relationships.
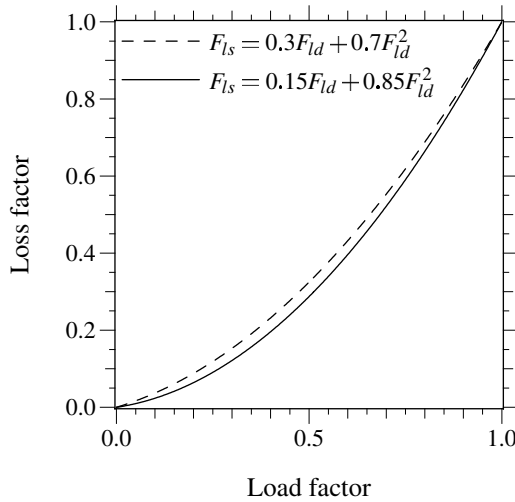
FIGURE 5.10
Relationship between load factor and loss factor.

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