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Substations – Volume VI – Voltage Regulators and Capacitors

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Substation Design
Volume VI
Regulators & Capacitors

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This series of courses are based on the "Design Guide for Rural Substations", published by the Rural Utilities Service of the United States Department of Agriculture, RUS Bulletin 1724E-300, June 2001.

Preface

This course is one of a series of thirteen courses on the design of electrical substations. The courses do not necessarily have to be taken in order and, for the most part, are stand-alone courses. The following is a brief description of each course.

Volume I, Design Parameters. Covers the general design considerations, documents and drawings related to designing a substation.

Volume II, Physical Layout. Covers the layout considerations, bus configurations, and electrical clearances.

Volume III, Conductors and Bus Design. Covers bare conductors, rigid and strain bus design.

Volume IV, Power Transformers. Covers the application and relevant specifications related to power transformers and mobile transformers.

Volume V, Circuit Interrupting Devices. Covers the specifications and application of power circuit breakers, metal-clad switchgear and electronic reclosers.

Volume VI, Voltage Regulators and Capacitors. Covers the general operation and specification of voltage regulators and capacitors.

Volume VII, Other Major Equipment. Covers switch, arrestor, and instrument transformer specification and application.

Volume VIII, Site and Foundation Design. Covers general issues related to site design, foundation design and control house design.

Volume IX, Substation Structures. Covers the design of bus support structures and connectors.

Volume X, Grounding. Covers the design of the ground grid for safety and proper operation.

Volume XI, Protective Relaying. Covers relay types, schemes, and instrumentation.

Volume XII, Auxiliary Systems. Covers AC & DC systems, automation, and communications.

Volume XIII, Insulated Cable and Raceways. Covers the specifications and application of electrical cable.

Chapter 1
Substation Voltage Regulators

Both three-phase and single-phase voltage regulators are used in distribution substations to regulate the load-side voltage. Substation regulators are one of the primary means, along with load-tap-changing power transformers, shunt capacitors, and distribution line regulators, for maintaining a proper level of voltage at a customer's service entrance.

A very important function of substation voltage regulation is to correct for supply voltage variation. With the proper use of the control settings and line drop compensation, regulators can correct for load variations as well. A properly applied and controlled voltage regulator not only keeps the voltage at a customer's service entrance within approved limits but also minimizes the range of voltage swing between light and heavy load periods.

The substation regulators may be located on individual feeders or in the transformer secondary circuit for main bus regulation, such as shown in the photo above. Normally, the low-voltage substation bus will be regulated rather than the individual feeders. Individual feeder regulation can usually be justified only when there are extreme variations between individual distribution feeder peak load times. Very long or heavily loaded distribution feeders may require supplemental regulators strategically located out on the line to maintain voltage levels within required limits.

Recommend voltage levels are given in ANSI Std. C84.1, "Voltage Ratings for Electric Power Systems and Equipment (60 Hz)." The American National Standards Institute, ANSI, defines acceptable voltage levels on an electric distribution system. According to ANSI, voltage levels should be within the following ranges shown in Table 1.

Table 1 **Acceptable Voltage Levels** (120 Volt base)		
Range	**Minimum**	**Maximum**
A	114	126
B	110	127

Range "A" is the normal service delivery range. Range "B" defines the limits in which service voltages may vary for limited time duration due to normal system operation. To the utility engineer, this means that the electric system should be designed for operation within the voltage range of 114 - 126 volts and once the voltage level falls into range "B" action should be taken immediately to bring the voltage back into range "A".

Operating an electric system on the low end of the voltage range may cause excessive current demand in motors, which generate additional heat and possibly limit the life of the motor. Incandescent lamps will operate fine at reduced voltage levels, but they will deliver less light output than they would operating at rated voltage. At higher voltages, motors will run cooler and operate more efficiently while incandescent lamps will deliver more light output and will have a shorter life span.

Customers typically will report equipment damage when voltage levels drop below 105 volts or above 130 volts.

Regulators should comply with ANSI Std. C57.15, "Requirements, Terminology, and Test Code for Step-Voltage and Induction-Voltage Regulators," and ANSI Std. C57.95, "Guide for Loading Oil-Immersed Step-Voltage and Induction-Voltage Regulators."

Types

There are two general types of voltage regulators, the *induction regulator* and the *step-type regulator*. Both types are available in single- or three-phase designs. The step-type regulator has by far the wider application in the electric distribution system. The step-voltage regulator has virtually replaced the induction-voltage regulator because it is lower in cost and equally reliable.

A *step-voltage regulator* is a regulator having one or more windings excited from the system circuit or a separate source and one or more windings connected in series with the system circuit for adjusting the voltage, or the phase relation, or both, in steps, without interrupting the load. A step-type voltage regulator consists of an autotransformer and a load-tap changing mechanism built into an integral unit. As with the induction regulator, when a voltage is impressed on the primary winding, the magnetic flux linking the secondary or series winding will induce a voltage in the series winding.

An automatic reversing switch is incorporated to obtain an additive or subtractive voltage from the series winding with respect to the primary voltage. Taps of the series winding are connected to an automatic tap-changing mechanism to regulate the amount of voltage change in equal steps.

The terminal designations of step-type voltage regulators are as follows:

- The terminal connected to the load is designated “L”.
- The terminal connected to the source is designated “S”.
- The common terminal is designated “SL”.

For three-phase regulators, these identifications are Sl, S2, S3, Ll, L2, L3, and SOLO.

Several factors influence the selection of single-phase versus three-phase regulators. For smaller substation sizes, single-phase regulators are usually less expensive. They also do a better job of maintaining balanced phase voltages under conditions of unbalanced loading. Single-phase regulators are also more adaptable to line use because of the relative ease of pole mounting. Regulation by single-phase regulators also gives maximum reliability for the system because a regulator can be removed for maintenance or repair without the need to de-energize transformers or other regulators. Special switches are available to permit removing a regulator from service without interrupting the circuit.

In large distribution substations, the choice of three-phase regulators may be based on costs or on the availability of single-phase regulators of the required size. Three-phase regulators require somewhat less space than three single-phase regulators; however, this is not generally a major factor in selection.

Load-tap-changing power transformers (LTCs) are becoming more common in distribution substations. They consist essentially of a three-phase regulator built into a three-phase power transformer. The relative cost of this combination compared to a separate transformer and either three-phase or single-phase regulators varies depending on the size of the substation. Aside from the base cost of the equipment, the LTC method generally will result in a saving in space, buswork, and supporting structures. Because their controls sense only one phase of a three-phase circuit and since some unbalance may be expected among the phases, the voltage correction of three-phase regulators and LTC transformers will be less precise than that of single-phase regulators.

Ratings

Regulator ratings include kVA ratings, voltage ratings, current ratings, temperature restrictions, altitude restrictions and short circuit ratings.

<u>kVA Rating</u>
The kVA rating of a single-phase regulator is the product of its rated load amperes and its rated range of regulation in kilovolts. For polyphase regulators, this product has to be multiplied by the appropriate phase factors (1.732 for three-phase regulators). The kVA rating of a 10 percent, 7.62 kV, single-phase regulator capable of carrying a rated load current of 100 amperes would be:

$$\textbf{kVA = 7.620 * 0.10 * 100 = 76.2 kVA}$$

In those cases where the range of regulation is different for the "raise" position than for the "lower" position, the larger percentage regulation is used to determine the regulator kVA rating.

The ratings for regulators generally are based on operation at 60 Hz with a range of regulation of 10 percent "raise" and 10 percent "lower" without exceeding the specified temperature rise at the given operating voltage. Regulator losses decrease as the regulator moves from the extreme tap positions (maximum raise or maximum lower) closer to the neutral point. Since the range of regulation required need not always be a full 10 percent, this allows for an extended range of regulator operation.

For the range of regulation of single-phase step regulators rated 19.9 kV and below and for the range of regulation of three-phase, step-voltage regulators rated 13.8 kV and below, see Table 2.

Table 2
Range of Regulation vs. Rated Current

Range of Regulation	Percent of Rated Current	
	Single Phase	Three Phase
10.00%	100%	100%
8.75%	110%	108%
7.50%	120%	115%

6.25%	135%	120%
5.00%	160%	130%

As you can see in Table 2 if regulators are applied to circuits requiring only 5 percent regulation, their current-carrying capabilities can be extended to provide additional capacity—up to 160 percent in the case of single-phase regulators.

Voltage

Preferred *voltage ratings* of step-voltage and induction-voltage regulators based on a voltage range of 10 percent raise and 10 percent lower are given in Tables 3 and 4. Substation regulators should be specified as being capable of providing a range of voltage regulation of ±10 percent and a bandwidth not greater than ±1 volt (on a 120-volt base). For single-phase regulators, see Table 3.

Table 3
Step-Voltage Regulator Sizes (Single-Phase)

Voltage	kVA	Amps
7620/13200Y	38.1	50
	57.2	75
	76.2	100
	114.3	150
	167	219
	250	328
	333	438
	416	546
	509	668
	667	875
	833	1093
14400/24940Y	72	50
	144	100
	216	150
	288	200
	333	231
	432	300
	576	400
	667	463
	833	578

19920/34500Y	100 200 333 400 667 833	50 100 167 201 334 418

For three-phase regulators, see Table 4.

Table 4
Step-Voltage Regulator Sizes (Three-Phase)

Voltage	kVA	Amps
7620/13200Y	1000 1500 2000	437 656 874
14400/24940Y	500 750 1000 1500 2000 2500	125.5 188.3 251 377 502 628
19920/34500Y	500 750 1000 1500 2000 2500	83.7 125.5 167 251 335 418

Most regulators are specified with a ±10 percent range using thirty-two 5/8 percent steps.

Current
Preferred *current ratings* of oil-immersed step-voltage regulators are also listed in Tables 3 and 4.

Temperature
Standard ratings of kVA, voltage, and current for air-cooled voltage regulators are based on ambient air temperature not exceeding 40C and on the average temperature of the cooling air for

any 24-hour period not exceeding 30C. The ratings are based on a temperature rise above the ambient in accordance with Table 5 shown below.

Table 5
Limits of Temperature Rise

Type of Apparatus	Winding Temperature Rise by Resistance (degrees C)	Hot-Spot Winding Temperature Rise (Degrees C)
55C Rise, Liquid-Immersed	55	65
55C Rise Dry-Type	55	65
80C Rise Dry-Type	80	110
150C Rise Dry-Type	150	180

Notes:
1. Metallic parts in contact with or adjacent to the insulation shall not attain a temperature in excess of that allowed for the hottest spot of the windings adjacent to that insulation.
2. Metallic parts other than those mentioned above shall not attain excessive temperature rises.
3. Where a regulator is provided with sealed-tank, conservator, gas-oil seal, or inert-gas-pressure systems, the temperature rise of the insulating oil shall not exceed 55C when measured near the surface of the oil. The temperature rise of insulating oil in a regulator not provided with the oil preservation systems listed above shall not exceed 50C when measured near the exposed surface of the oil.

Altitude

Standard ratings of voltage regulators are based on an altitude not exceeding 3,300 feet. At higher altitudes, the decreased air density has an adverse effect on the temperature rise and the dielectric strength of voltage regulators. Table 6 gives correction factors for dielectric strength at altitudes above 3,300 feet.

Table 6
Altitude Correction Factors For Dielectric Strength

Altitude	Correction Factor
3,300	1.00

4,000	0.98
5,000	0.95
6,000	0.92
7,000	0.89
8,000	0.86
9,000	0.83
10,000	0.80
12,000	0.75
14,000	0.70
15,000	0.67

Short-Circuit Strength

Regulators must be capable of withstanding RMS symmetrical short-circuit currents of 25 times the regulator full-load current for 2 seconds and 40 times the regulator full-load current for 0.8 seconds without injury. Where short-circuit duty on the regulator exceeds its capabilities, current-limiting reactors may be installed in the substation to limit the available fault current.

Regulator Controls

Regulators are equipped with a number of devices and controls that allow the operator to use the regulator effectively. These include means for setting or adjusting the voltage level, bandwidth, time delay, range of regulation, and line drop compensation.

Since a change in the setting of any one of these devices will directly affect the operation of one or more of the other devices, they are all treated as a unit comprising what is known as the *regulator control system*. In earlier regulators, the components of this control system were electromechanical, but regulators manufactured since the mid-1960's are equipped with static-type devices featuring solid-state or microprocessor components. The setting of the individual devices in the newer control systems is based on the same principles. They are, in general, easier to set than the older mechanical type.

The various devices used in the control system are almost all adjusted at the control panel. One exception is the range of regulation, which is made at the position indicator mounted on the regulator. The control panel can be mounted directly on the regulator or remote from the regulator. Microprocessor controls are available with many different options. These options include power and energy metering, harmonics analysis, event logging, and communication packages.

The individual components utilized in the regulator control system are accurate devices and, as such, they enable the regulator to obtain a level of efficiency sufficient to meet Class I accuracy requirements. *Class I accuracy* means that the sum of errors in the control circuit taken individually cannot total more than ±1 percent. A plus error would be one causing the regulator output to be higher than the reference value, while a minus error would be one causing the regulator output to be lower than the reference value.

Because of this accuracy and, more importantly, because of its function in maintaining system voltage levels, the voltmeters and other instruments used in conjunction with regulators should be as accurate as the regulator.

Lightning Protection

CAUTION: Bypass arresters protect only the series winding of the regulator and do not eliminate the need for arresters to protect the regulator itself.

Voltage regulators, like other elements of the distribution system, require protection from lightning and other high-voltage surges. Because voltage regulators are constructed like autotransformers, having one of the windings in series with the primary line, additional protection is required for this series winding. Regulators are normally factory equipped with bypass arresters across this series winding; these arresters may be connected internally or externally, depending on the manufacturer. The bypass arrester limits the voltage developed across the series winding during surges to within safe values.

Chapter 2
Shunt Capacitor Equipment

Shunt capacitor banks at substations improve power factor and voltage conditions by supplying leading kilovars to transmission and distribution systems.

IEEE Std. 1036, "IEEE Guide for Applications of Shunt Power Capacitors," provides guidelines for the application, protection, and ratings of equipment for the safe and reliable utilization of shunt power capacitors. NEMA Std. CP-1, "Standards Publication—Shunt Capacitors," also provides guidelines for the application of shunt capacitors.

System Considerations

Shunt capacitor banks alter an electrical system's response to disturbances, which can impair system performance. Specific issues that designers should consider include transients caused by bank energization and potential resonance conditions. Care should be taken to evaluate system issues, including the effects of switching transients and potential harmonic resonance, with each bank installation.

<u>Switching Transients</u>
Transient voltages and currents occur whenever shunt capacitor banks are energized. Overvoltages can reach twice the system voltage, with inrush currents ranging from 5 to 15 times normal steady-state current. Transient magnitude and duration depend on the natural damping provided by the circuit's resistive elements. Transient voltages and current resulting from capacitor switching have to be controlled to avoid exceeding equipment capabilities and damaging customers' sensitive electronic equipment.

ANSI/IEEE Std. C37.012, "IEEE Application Guide for Capacitance Current Switching for AC High-Voltage Generator Circuit Breakers Rated on a Symmetrical Current Basis," provides guidelines for calculating transient inrush and discharge currents. It is important that the design engineer calculate the peak magnitude and frequency of these transient currents to compare to the capabilities of the shunt capacitor bank's equipment and adjoining substation equipment.

The transient inrush current to a single isolated bank is less than the available short-circuit current at the capacitor location. Since a circuit breaker has to meet the momentary current requirement of the system, transient inrush current is not a limiting factor for this application. However, the momentary rating of other switching devices not intended for fault current interruption should be checked.

Figure 1 illustrates a typical arrangement for two capacitor banks switched back to back. Capacitor banks switched back to back (one being energized when another is already connected to the same bus) produce transient currents of high magnitude and high frequency that flow between the banks on closing of the switching device. The oscillatory current is limited only by the impedance of the capacitor banks and the circuit between them and usually decays to zero in a fraction of a cycle of the power frequency. The component supplied by the power source is usually so small it may be neglected. Additional impedance between capacitor banks may be required in the form of inductors to allow for back-to-back switching.

The magnetic fields associated with high inrush current during energization of shunt capacitor banks (isolated bank or back-to-back switching) in either the overhead conductors or the grounding grid can induce voltages in control cables by both electrostatic and electromagnetic coupling. These induced voltages can be minimized by shielding the cables, using a radial configuration for circuits (circuits completely contained within one cable so inductive loops are not formed), and single-point or peninsula grounding of the capacitor banks.

Figure 1, shown below is a typical capacitor bank with two three-phase capacitor racks.

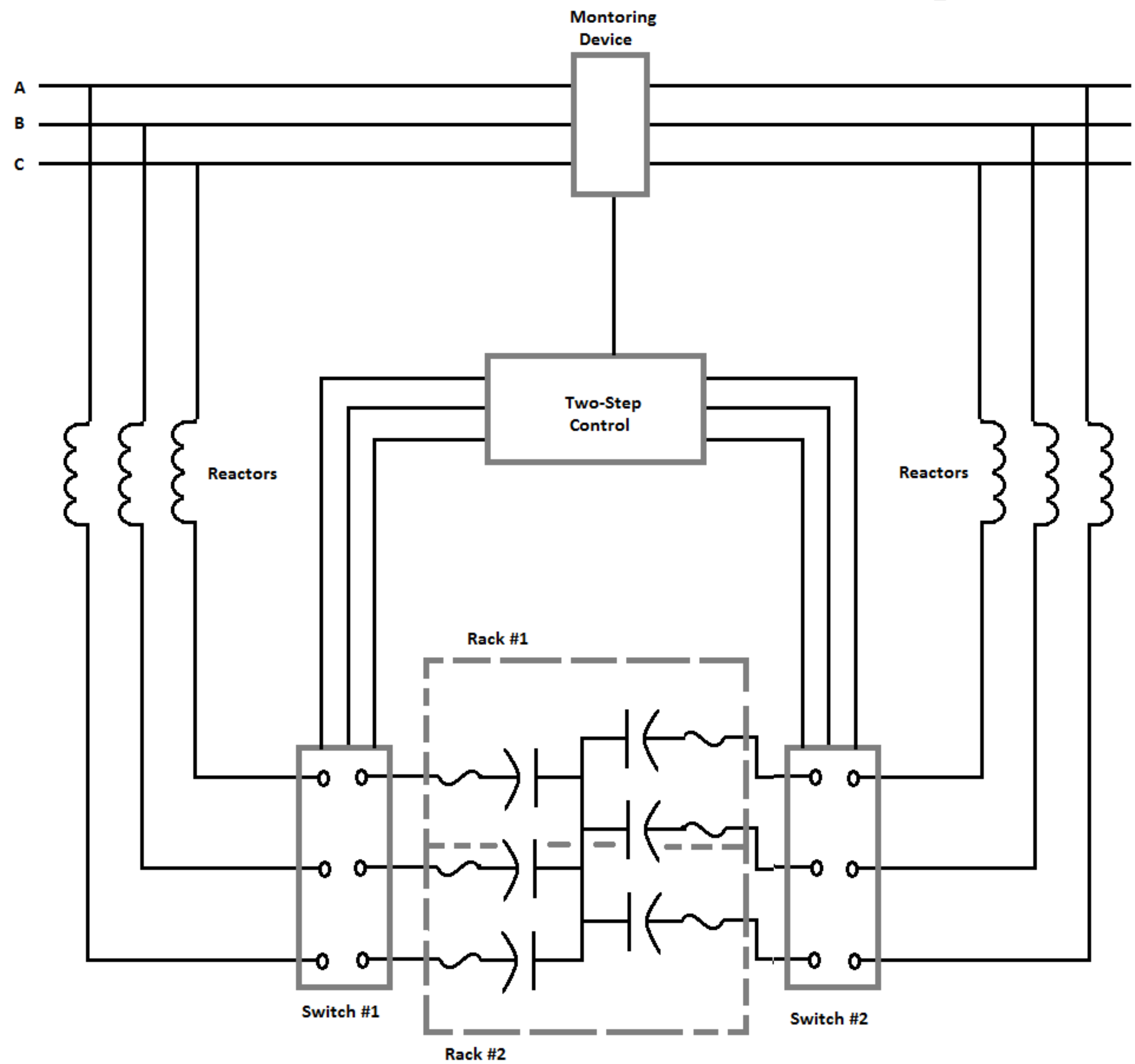

Figure 1

Applying capacitor banks at more than one voltage level in an interconnected system can result in *voltage amplification* that can cause nuisance tripping of adjustable-speed drives, damage to surge suppressors on low-voltage equipment, and, possibly, adverse effects to sensitive electronic equipment.

Voltage amplification occurs when switching transients, initiated by capacitors located on primary systems, become amplified at capacitors located on secondary systems. The reason is that the frequency of the transient initiated by the primary system capacitor approximates the resonant frequency of the circuit formed by the step-down transformer located in series with secondary system capacitors.

The magnitude of switching transients caused by capacitor bank switching may be greatly reduced by adding current-limiting reactance in series with the bank or through application of transient control switching devices.

Transient-control switching devices limit the effects of capacitor switching. Three common methods are used:

- Fitting circuit switchers with pre-insertion inductors,
- Adding pre-insertion resistors to circuit breakers, and
- Incorporating vacuum switches with synchronous closing control.

The first two methods momentarily insert an impedance electrically in series with the capacitor bank when it is energized, dampening transient voltages to acceptable levels. The third method, synchronous closing, attempts to energize each phase of a three-phase capacitor bank at the instant the applied voltage crosses zero. This is achieved through synchronous control of the bank's independent pole vacuum switches. Theoretically, "zero-voltage control" eliminates switching transients. However, experience shows this technique only lowers switching transients because the switching device's electrical and mechanical tolerances provide only near-zero-voltage closing.

Capacitive switching devices have to be capable of providing sufficient dielectric recovery when interrupting capacitive current or the current arc will ignite or *restrike*. A single restrike results in a transient voltage three times system voltage. Modern capacitor switching devices rarely restrike. However, caution must be used to ensure shunt capacitors do not inadvertently de-energize through operation of up line circuit breakers because an underrated circuit breaker could potentially cause restrike. Voltage transients initiated by restrike have been known to cause catastrophic capacitor bank failures. It may be necessary to provide inductive reactance in the form of current-limiting reactors to limit inrush current during capacitor bank switching.

Sometimes adequate impedance to limit the inrush current to the rating of the switch may be obtained by physically locating the banks as far apart from one another in the substation as possible. In other cases, it may be necessary to provide inductive reactance in the form of current-limiting reactors between parallel switched capacitor banks. The required inductance may be calculated from,

$$\mathbf{L_T = \frac{MVAR * 10^6 * (n-1)}{kA^2 * \pi * f * n}}$$

Where:
L_T = Required inductance, μH
MVAR = Megavars per phase at 60 Hz
n = Number of parallel banks
f = Frequency, Hz
kA = Maximum allowable inrush current, kA

This equation will provide the required inductance (in microhenries) to limit the peak inrush current in a substation with a certain number and size of capacitor banks. The following example shows a typical inrush current calculation for back-to-back switching involving.

For example, what is the required inductance to limit inrush current to less than 20,000 amps for a substation with these characteristics?

Two capacitor banks (n=2), each 13,500 kVAR, 14.4 kV, 60Hz, both switched by 15 kV vacuum switchers rated for 20,000 amps momentary peak. The capactiance per phase is 4.5 MVAR (13.5/3=4.5). Using the previous equation we have,

$$L_T = \frac{4.5 * 10^6 * (2-1)}{20^2 * 3.14 * 60 * 2} = 29.8 \text{ uH}$$

For this case, the equipment design would probably specify a 30 μH, 600-ampere reactor in each phase of each bank.

In determining the continuous current rating of the reactor, the increase in current due to applied voltage, capacitance tolerance, and harmonics should be considered. As previously mentioned it is generally adequate to use a total multiplier of 1.25 and 1.35 for ungrounded and grounded banks, respectively. Assuming that the banks are ungrounded, the minimum continuous rating for each reactor would be:

$$\mathbf{I = 1.25 * \frac{kVAR}{kV * \sqrt{3}}}$$

So for our example, the current rating is,

$$I = 1.25 * \frac{13{,}500}{14.4 * \sqrt{3}} = 676 \text{ amps}$$

If the capacitor manufacturer determines and supplies all accessory equipment, including switches and reactors, it is necessary to inform the manufacturer of the total MVAR in the substation, the inductive reactance of the bus between the capacitor banks, and system available fault current. This will allow the manufacturer to calculate the ratings of any required reactors.

When physically locating these reactors, take care to space them as far apart as practical to minimize the effect of mutual reactance. The reactors' continuous current ratings should be at least equal to the continuous current ratings of the switches they protect.

Resonance

Resonance occurs whenever an electrical circuit's inductive and capacitive reactances—connected either in parallel or series—are equal at some frequency. A shunt capacitor bank forms a resonant circuit with system inductive elements. This resonance condition can be excited by remote system disturbances such as remote bank switching or sources of harmonic current. Resonance can cause excessive overvoltages and currents possibly resulting in failure of equipment such as capacitors, surge arresters, instrument transformers, and fuses.

Capacitor banks may resonate with harmonic currents produced elsewhere on the system. Harmonic-current flow into the capacitor bank may excite parallel resonance between the system inductance and bank capacitance. Parallel resonance causes high oscillating currents between inductive and capacitive energy-storage elements. High oscillating currents cause excessive voltage distortion.

Installing current-limiting reactors in series with the shunt capacitor bank can "tune" the bank to the offending harmonic's frequency and eliminate parallel resonance. Essentially, a single-tuned filter is formed by the bank's resistive, inductive, and capacitive elements. The bank traps harmonic current to which it is tuned. Parallel resonance is avoided since harmonic current cannot flow between the system inductance and the bank's capacitance.

Types

Shunt capacitor bank designs include open-rack and metal-enclosed bank designs. *Open-rack* substation capacitor banks are used to provide large blocks of kilovars on distribution and transmission systems at voltages up to 765 kV. *Metal-enclosed substation* capacitor banks are used to apply medium-size blocks of kilovars on distribution systems up to 34.5 kV where a completely enclosed assembly is advantageous for space or safety reasons.

Open-Rack Substation Capacitor Bank

This type of capacitor bank design mounts capacitor units vertically or horizontally in aluminum or galvanized steel frames. Ancillary devices including switching equipment, instrument transformers, and surge protection are mounted on separate structures.

This type of capacitor bank can be furnished with all phases in a single rack or with only one phase in a single rack. The largest standard "upright" rack usually holds 40 capacitor units, and the largest "edge mount" rack usually 32 units. These racks are generally furnished complete with individual capacitor units, unit fuses, insulators, supporting structure, and other equipment necessary for a complete installation.

Open-rack capacitor banks have many exposed, live components and have to be enclosed with a fence. A key interlock system can be used to prevent entry into the enclosure until capacitors are properly grounded. This bank design is susceptible to rodent-related failures since chain-link fences do not keep out all rodents. Additionally, adequate electrical clearances have to be provided for exposed live parts and external expulsion fuses, which results in a large footprint for most open-rack capacitor banks.

For most substation applications in open racks, individual capacitor units are equipped with only one bushing. The second bushing is often unnecessary when the racks themselves form a part of the circuit and are insulated by means of base insulators. In a three-phase delta-connected rack, however, two bushing units are required. Open-rack capacitor banks use capacitor units that are protected through external fuses.

Metal-Enclosed Substation Capacitor Bank

This type of capacitor bank design completely encloses the bank's components within a grounded structure, which eliminates the need for a fenced enclosure and mitigates rodent problems. Enclosed capacitor banks are more aesthetically pleasing compared to open-rack capacitor banks. The capacitor bank assembly is generally furnished with internally fused capacitor units, insulators, current-limiting reactors, vacuum switches, grounding switches, main line fusing, line disconnect switches, surge arresters, instrument transformers, protection, monitoring and control devices, and a cable entrance section. The doors of the enclosure are key interlocked to prevent entry into a live compartment.

Enclosed capacitor banks generally use internally fused capacitor units that are compact in design and more reliable compared to externally fused capacitor units. Enclosed capacitor banks can be completely pre-assembled and shipped to a project site.

Bank Configuration

A capacitor bank of a given size and voltage rating may be made up of a number of series and parallel groups. Use of capacitors with the highest possible voltage rating results in a bank design with the fewest number of series groups, which provides for the most economical design and greatest sensitivity for unbalance detection schemes.

The maximum and minimum number of capacitor units in parallel per series group is limited by capacitor unit design considerations regarding permissible overvoltages and avoidance of case rupture. It is important in any capacitor installation to ensure that the maximum operating voltages do not exceed 110 percent of the rated voltage of any capacitor. Because of this, the number of parallel capacitor units in each series section is selected so that the loss of any one unit in any series section will not result in such overvoltage. Additionally, steady-state voltage rises introduced by the flow of harmonic currents into tuned shunt capacitor banks (banks fitted with current-limiting reactors) have to be considered.

Where only one series section of paralleled capacitors per phase is used and connected either three-phase grounded wye or delta, the unit capacitor fuse is subjected to full system short-circuit available current when its associated unit fails. This generally requires that more expensive, high-interrupting-capacity, current-limiting fuses be applied in situations where available fault currents exceed 4,000 amps. One advantage is that these banks can be designed in very small sizes without encountering unacceptable overvoltages on the remaining capacitors in a phase when one or more capacitors in that phase fails and clears, which simplifies the protection scheme. For open-rack designs, the racks themselves do not have to be insulated from ground, thus saving the cost of base insulators.

When a three-phase wye connection is used with only one series section of paralleled units per phase, it is advantageous from a fusing standpoint to leave the neutral floating. This allows the unfaulted phases to limit the fault current supplied to the faulted phase. The fuse on the faulted unit will "see" a maximum of only three times normal bank phase current. While this may still be considerable current for large equipment, it is far less than usually available from the system, and a much less expensive, low interrupting-capacity fuse can be applied. A calculated risk is taken of simultaneous failure of units in different phases. It should be noted that, in a floating wye connection, the neutral has to have full line insulation between it and ground as well as sufficient ground clearances.

A double-wye configuration is often used where large amounts of kVAR are desired and the equipment is to be equipped with low-interrupting-capacity expulsion fuses. Designing this bank with connected multiple series groups limits the maximum fault current so that individual current-limiting capacitor fuses are not usually required unless the parallel kVAR exceeds 4,650 kVAR. Double-wye banks with only single series groups do not limit the maximum fault current. Therefore, individual capacitor fuses have to be capable of interrupting the system available fault current. Figure 2 illustrates a typical Y-Y connected capacitor bank with one series section per phase and neutrals isolated.

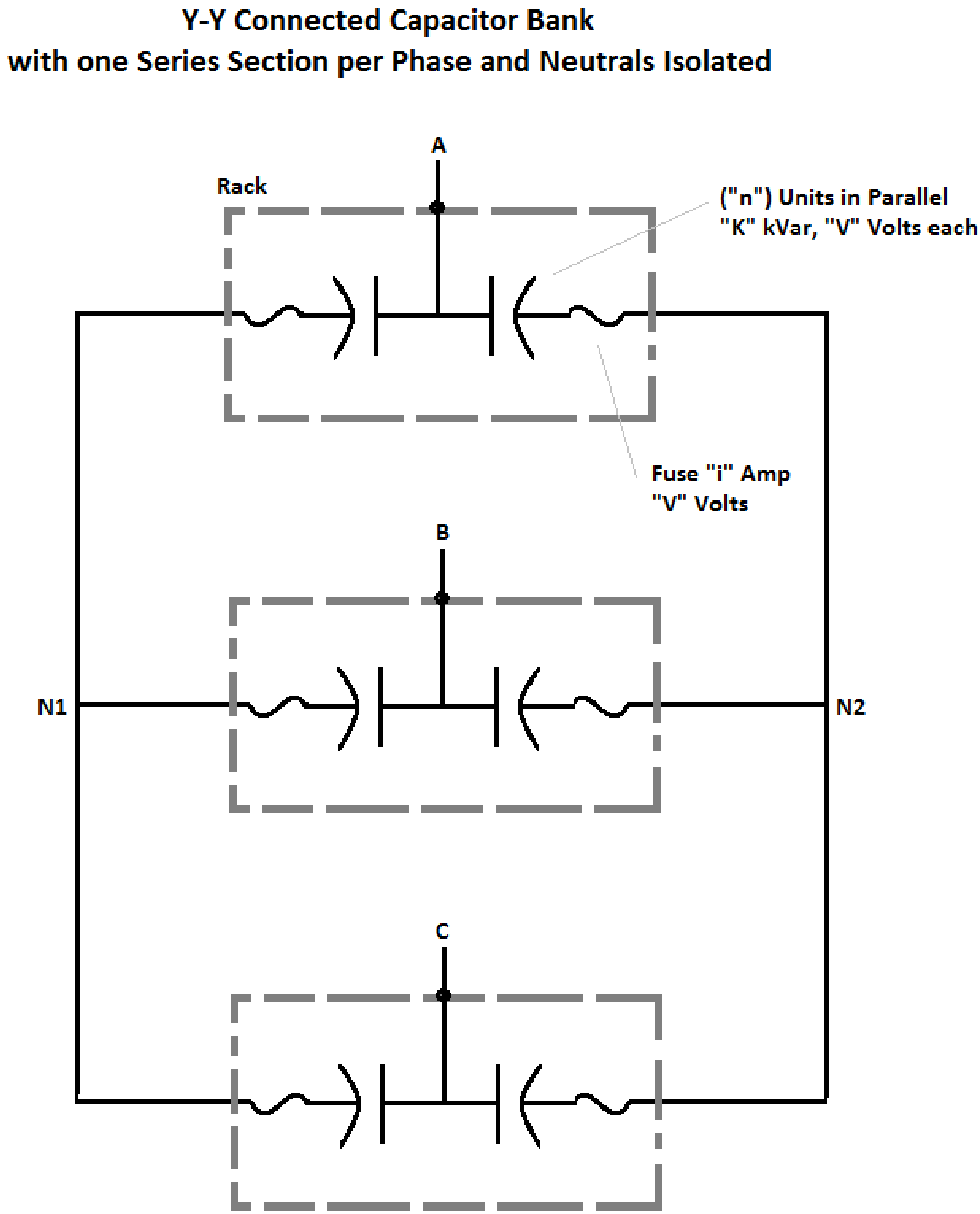

Figure 2

Delta-connected capacitor banks are generally applied only on lower voltage (23 kV or below) systems where the system voltage equals the voltage rating of a unit capacitor. They have to also be properly insulated from ground. Additionally, where one series group per phase is used, individual capacitor unit fuses should be capable of interrupting the system short-circuit phase-to-phase fault current. This usually requires the use of current-limiting fuses.

Capacitor Ratings

Capacitor ratings include voltage, kVAR ratings, BIL, and temperature constraints.

Circuit Voltage

Manufacturers can supply individual capacitor units in voltages ranging from 2.4 to 25 kV. Units of the same or of different voltage ratings can be mixed to obtain the required circuit voltage. Most utilities utilize capacitor equipment at or above 7.2 kV. The desired circuit voltage is obtained by connecting as many capacitor groups in series as necessary to obtain the required voltage. Usually, the best engineering choice is to use the fewest number of series groups as possible. Use of capacitors with the highest possible voltage rating results in fewer series groups. This generally provides the simplest and most economical bank design. However, inventory or other economic considerations may override this rule.

kVAR Rating

Capacitor unit ratings available from domestic manufacturers undergo frequent change in order to provide the most practical and economical sizes for existing conditions. In general, the trend is toward larger unit sizes. Standard capacitor units for shunt capacitor bank applications are 50, 100, 150, 200, 300, and 400 kVAR. No upper limits are defined for internally fused capacitor units. These units are typically sized based on minimizing the number of capacitor units to minimize the bank's physical size while avoiding overvoltage and unbalance conditions with a substantial loss of a capacitor unit's individually fused elements.

The capacitor manufacturer's recommendations should be considered in determining the optimum size of capacitor unit, number of series sections, number of units in parallel, and type of connection to make up the kVAR requirement for a given application.

Basic Insulation Level

Basic impulse insulation levels of individual capacitor units range from 75 to 200 kV. Table 7 summarizes typical basic impulse insulation levels by capacitor unit voltage rating.

Table 7
Capacitor Unit Voltage & BIL Ratings

Capacitor Voltage Rating (kV, RMS)	BIL (kV)
2.4-4.8	75
6.6-12.47	95

13.2-14.4	95 & 125
15.1-19.9	125
19.2 (single bushing)	125 & 150
19.9-24.9	150 & 200

Temperature
The maximum allowable ambient temperature for capacitor equipment installed outdoors with unrestricted ventilation is 40C based on the mathematical average of hourly readings during the hottest day expected at the site. Isolated, multiple row and tiers and metal-enclosed or housed units will have maximum ambient ratings of 46C, 40C, and 40C, respectively. Capacitors are designed for continuous operation at –40C. Where the expected in-service ambient temperatures are lower than –40C, the manufacturer should be consulted.

Switching

The various devices that may be used for capacitor switching include those listed in Table 8.

Table 8
Switching Devices

Medium	Circuit Breakers	Interrupter Switches
Air	✓	
Air-Magnetic	✓	
Oil	✓	✓
SF6	✓	✓
Vacuum	✓	✓

When a capacitor bank is energized or de-energized, current and voltage transients are produced that affect the capacitor bank on the connected system. All capacitor switching devices should be applied within their maximum voltage, frequency, and current ratings, including transient inrush current and frequency. The switching device should have a voltage rating at least equal to 10 percent above rated capacitor voltage since capacitors can be continuously operated at this voltage.

Selection of the switching device’s continuous current rating is based on consideration of factors that increase current flow in the capacitor bank. Multiplying factors are generally applied to include the effects of overvoltage (1.10), capacitor tolerance (1.05 to 1.15), and harmonic component (1.05 for ungrounded capacitor banks: 1.10 for grounded capacitor banks). It is usually considered adequate to use a total multiplier of 1.25 for ungrounded operation and 1.35 for grounded operation.

It is important to understand that most switching devices are derated for capacitor switching. A switching device's rated capacitance switching capability is usually well below the device's continuous current rating. It is also important to select a switching device designed for the application's specific duty to avoid potentially damaging overvoltages.

Rating and application information for switching devices can be found in,

- ANSI/IEEE Std. C37.04, "IEEE Standard Rating Structure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis"
- ANSI Std. C37.06, "American National Standard for Switchgear—AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis—Preferred Ratings and Related Required Capabilities"
- ANSI/IEEE Std. C37.012, "IEEE Application Guide for Capacitance Current Switching for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis,"

Controls

Controls for capacitor switching devices may operate in response to various signals such as voltage, current, VAR, temperature, time, or some combination of these. A variety of options is available in terms of price, features, and quality. These range from high-priced panel-mounted to low-priced socket-mounted controls. In recent years, capacitor controls based on electromechanical relays have been superseded by more modern electronic types including solid-state and microprocessor-based controllers. Figure 3 shows a typical capacitor control schematic.

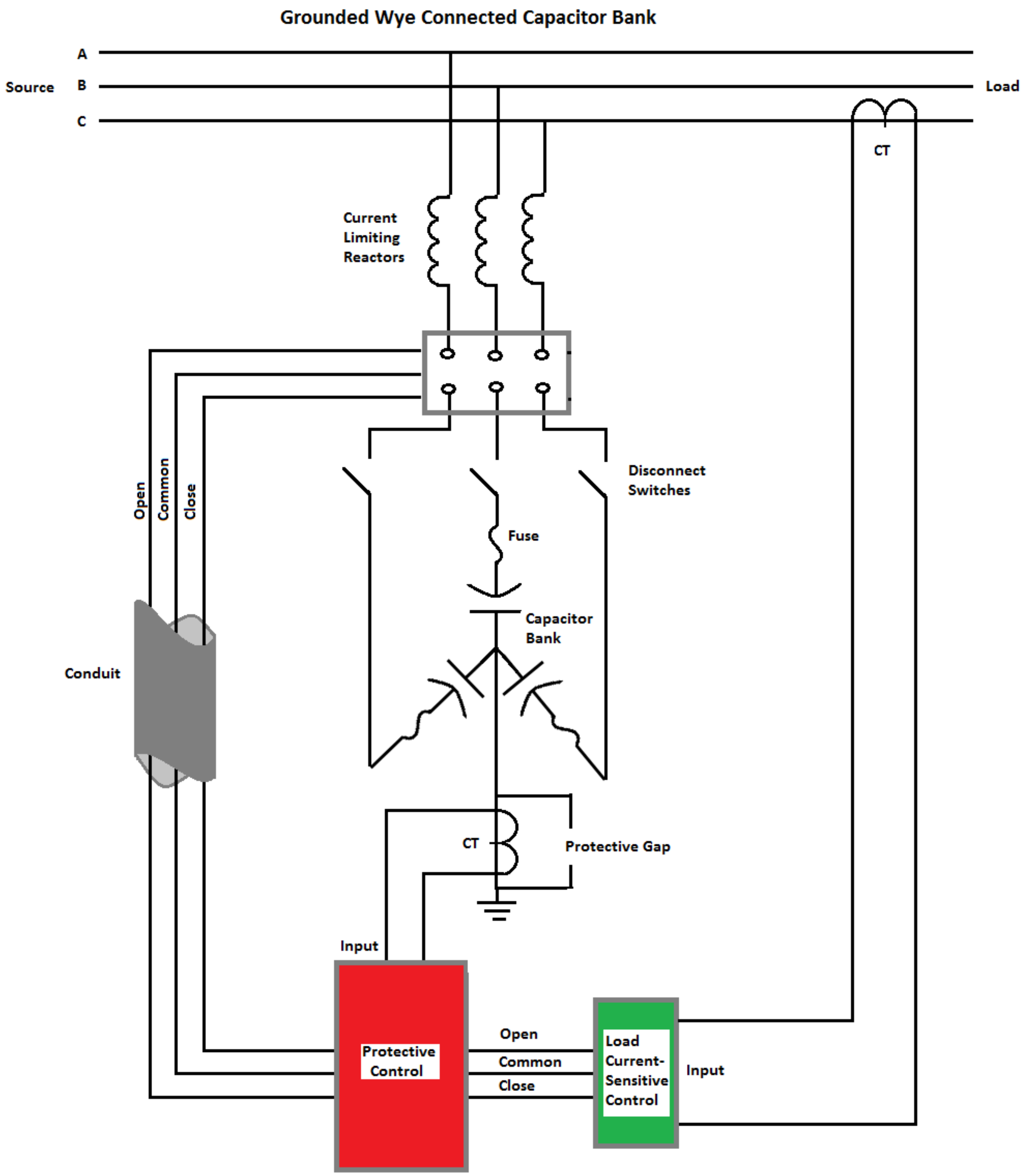

Figure 3

Control and application of capacitors are such closely related subjects that a discussion of one has to necessarily involve the other. In fact, in the typical situation, both the type of control and its adjustment are dictated by the objectives of the capacitor installation.

Capacitor switching controls provide outputs that are basically single-pole, double-throw switches activated by control signals selected to reflect kVAR requirements. Theoretically, at least, any intelligence that changes only when a change in the kVAR supply is needed can be utilized to switch capacitors automatically. In practice, however, selecting a signal that accurately reflects the requirements of the system often turns out to be the most difficult part of the problem. The single-input types, such as voltage and time controls, are generally less expensive in initial cost and installation, less complex, and easier to adjust but less flexible in application than the dual-input types such as kilovar and current-biased voltage controls.

The selection of a control for a particular switched capacitor bank requires careful evaluation of several related factors. Some of the more important considerations are listed below. No attempt has been made to list them in any particular order, since their relative importance and probably even the factors themselves will vary considerably from one system to another.

- Purpose - The purpose of the bank affects selection of the appropriate controller. The purpose may be to reduce losses, improve voltage under normal or emergency operating conditions, reduce thermal loading of lines and equipment, etc.

- Location - The location of the bank affects what control parameter best represents changes in kVAR requirements. The bank's location influences whether voltage will drop appreciably as load increases, whether direction of feed is likely to change frequently because of normal or emergency circuit rearrangements, etc.

- Coordination - Coordination with related supplementary voltage regulation equipment including switched capacitors and voltage regulators affects the type of control strategy to be implemented.

- Cost - The cost to implement each control strategy varies depending on sophistication and whether potential, current, or both inputs are required and the required control and auxiliary equipment (operating transformer, control secondary, current transformer, etc.).

The optimum choice of control will always be the least expensive type that will switch the capacitor bank on the required schedule. To facilitate comparison, the operating characteristics and relative cost of common controls used are summarized below

Capacitor Bank Control Types

There are several types of capacitor bank control systems and a few of the common methods are discussed below.

<u>Manual</u>
No control device necessary since the bank's switching device is operated by substation personnel and requires attendants at the substation.

The simplest means to accomplish capacitor bank switching is the manual control. Substation personnel, observing the need for capacitor banks to be switched, either go out to the yard and physically operate capacitor bank switching devices or operate them remotely from a panel.

Time

Non-electrical control input allows application at any point on the circuit. These can only be applied on feeders where power factor and demand have a regular daily variation that is repeated weekly. Use limited to locations where established switching schedule will not cause high voltage on holidays or during other abnormally light load periods. They are insensitive to abnormal voltage conditions.

Utilities wishing to relieve their personnel of the responsibility for manual capacitor bank control can substitute automatic controls. One of the most economical automatic controls is the time device. Time control switches the capacitor bank on or off at a fixed time each day. It usually takes the form of a clock that operates on station service AC. An electrical or mechanical carryover device is required for each time clock to keep it running during temporary power outages. It may include provisions for omitting control on weekends. Time control is most useful when the reactive load is periodic and predictable. This should be determined by examining the daily load curves. The time control does not require the monitoring of any electrical quantities.

Modern time clock controllers are microprocessor based, which provides 24-hour, 7-day programmable control. These devices typically use lithium batteries for backup during power outages.

Temperature

Non-electrical input allows application at any point on the circuit. It connects capacitors when the outside ambient temperature exceeds a temperature set point and should only be applied where direct correlation with load increases and temperature can be established such as air conditioning loads.

In certain areas of the country, the reactive load is more closely aligned with temperature variation than with anything else. Such loads do not exhibit the periodicity that would suggest the use of time clocks. They are often associated with the operation of air conditioners. A temperature control can be used to apply shunt capacitors with increases or decreases in ambient temperature. The temperature controller's thermostat responds to changes in ambient temperature to provide input to the switching device. A determination of the relationship between kVAR load and air temperature is required to be able to set the temperature controller. As with time controls, these devices are relatively economical and do not require the monitoring of electrical quantities.

Voltage

Applies and removes shunt capacitors when system voltages operate outside of allowable voltage tolerances. Voltage controls can only be applied where voltage drops appreciably under load. This type is more difficult to coordinate with voltage regulators and other switched capacitor banks. It requires separate potential transformer.

The most straightforward and simplest of the controls that respond to changes in electrical conditions is the voltage control. The voltage found at a point on an electrical system is the summation of all conditions on the system. Capacitors increase the voltage at the point where they are applied. Thus, a low voltage would suggest the need for capacitors, and a high voltage would call for their removal. This would not be true at a location close to the output of a compensated regulator where high voltage is developed with peak loads.

A simple capacitor control based only on voltage would not give the desired results if applied in a segment of the system where compensation in regulators cancelled the significance of high and low voltage as an indicator of loads. The bandwidth of the control should be larger than the voltage change caused by switching of the capacitor bank to prevent "hunting." Hunting refers to unintentional cycling of capacitor banks "on" and "off" due to incorrect settings on capacitor controllers.

Voltage controls usually respond to signals from a nominal 120-volt source ranging between 108 and 132 volts. If the switching device is a vacuum switch, the primary of the VT monitoring voltage should be protected by means of a distribution class surge arrester. This protects against high voltages produced by the chopping effect of the switches.

Current

Can be applied at any point on the circuit where the load current can be monitored. While these controls respond to current changes, they are nondirectional. Current and voltage source must available for general testing on feeder and requires a current transformer. Adjustment is slightly more complex than other controls.

A simple answer too many of the desired objectives of capacitor control is the measurement and subsequent switching of the capacitors according to the flow of current. This type of controller is suitable where voltage is well regulated and the power factor of the load remains constant with variation in kilowatt loading, or if the power factor of the circuit varies predictably with variation in kilowatt loading.

This solution is particularly attractive on circuits consisting primarily of a known group of electric motors. Typical examples would be a circuit for pumps on a major water supply or for irrigation, driven by electric motors and located a considerable distance from the source, or on any application where there is a dependent relationship of reactive (kVAR) load with current.

Heavy loads on circuits of this type could occur at any time of day or night and any day of the week. Capacitors used on this application would be dedicated to serving these motor loads. Switching of the capacitors is, therefore, logically a function of these loads.

Current controls are sensitive to signals between 0.5 and 5 amperes from a 5-ampere CT secondary. As a safety feature to protect against high secondary open-circuit voltages, the control should be arranged to short circuit the CT secondary leads automatically when the control circuit is opened.

In some instances several banks of capacitors are placed in the same substation to facilitate incremental application of kVAR to the bus. There might be, for example, a fixed capacitor bank and two switched banks controlled by a two-step voltage controller. In addition to setting multi-step controls to avoid "hunting," the capacitor switches should be selected with the aim of protecting them from the consequences of back-to-back capacitor switching.

Kilovar

Most effective in minimizing losses because it senses fundamental quantity being corrected (kVAR). This is the most expensive control method. Reversing direction of feed will reverse signal which may create problems. These systems are insensitive to abnormal voltage conditions and they require current transformer and potential transformer.

The most sophisticated control method, the VAR control, responds directly to VAR demand. This type of controller is suitable where voltage is regulated and power factor varies unpredictably with variation in kilowatt loading.

Care has to be taken to set the control so that the response of the system to the presence or absence of the capacitor bank is less than the bandwidth represented by the maximums and minimums of the settings on the control. For example, if a 2100 kVAR bank of capacitors is applied, the "turn off" setting of the control should be greater than the "turn on" setting +2100 kVAR. This is necessary to prevent "hunting."

VAR controls are usually arranged to respond to signals from a VT with a secondary rating of 120 volts connected across two phases and a CT with a secondary rating of 5 amperes in the third phase. This arrangement provides a 90-degree phase angle between the voltage and the current signals at unity power factor.

Some VAR controls have capacitors in either the voltage or current inputs to retard the phase angle and thus make it possible to read VAR signals by monitoring fewer than three phases.

Other Control Issues

In addition to the above controls, there are a number of combination types, of which the most common are time and temperature, and voltage with current bias.

Modern capacitor controllers allow implementation of one or more of the above control functions to meet each project's unique requirements. The following functions are commonly used:

- Time and temperature
- Voltage with current bias
- Voltage with time bias

Capacitor switching devices are also arranged to operate in response to signals from protective controls.

Most controls with lockout relays require nominal 120 volts AC for operation, but they can be arranged for other voltages. The switches that are controlled, however, may be AC or DC at any number of voltages.

Many controls have selector switches for “automatic or manual” operation and for “local or remote” location. When the “local–remote” switch is set for “local” and the “automatic–manual” switch is set for “manual,” the capacitor switching device may be controlled from the local control cabinet. If the “automatic–manual” switch is set for “automatic,” the capacitor switching device will respond to automatic control signals from the bank’s controller unless a protective override opens the device and locks it out.

Protection

Electric devices are generally fused for one or both of two basic reasons:

1. To protect the device from overloads, and
2. To protect the system from failure within the device.

In some cases, such as group fusing with cutouts, the fuse may be used as a manual disconnect or switching means. This is not, however, a basic function of a capacitor fuse. Because capacitors, for economic reasons, are designed for operation at high dielectric stress, a certain calculated failure rate is to be expected. Thus, capacitor unit fuses are used primarily to protect the electrical system from dielectric failures that are expected to occur.

Conventional capacitor units are typically protected by an external fuse connected in series with each capacitor unit. Internally fused units are available that eliminate the need for external fuses. Internally fused capacitor units utilize fuse links connected in series with each of the unit’s capacitor elements. An internally fused capacitor unit comprises a large number of capacitor elements connected in parallel with only a few groups of parallel elements connected in series. Figure 4 illustrates capacitor units utilizing external and internally fused capacitor elements.

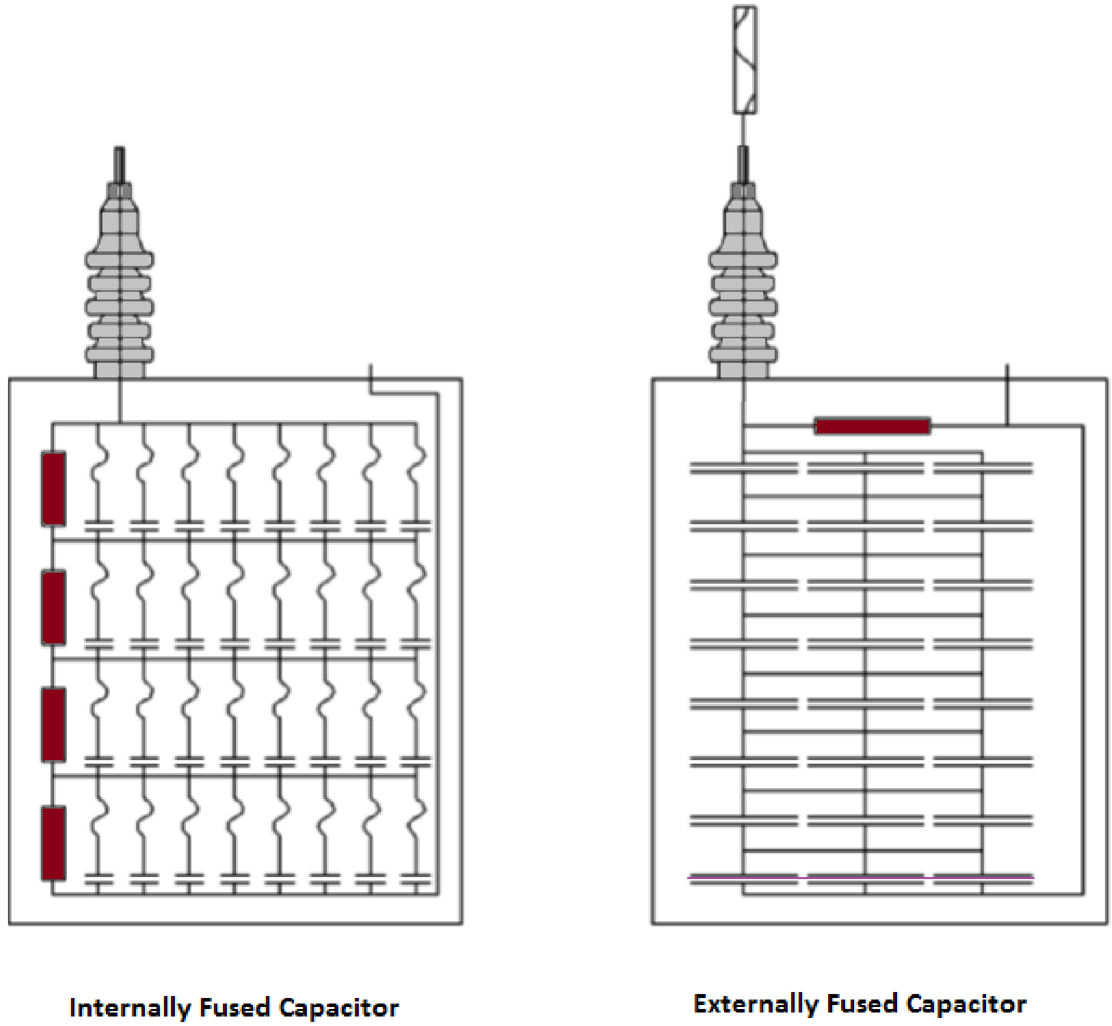

Figure 4

In general, capacitor banks utilizing internally fused capacitor units are configured with fewer capacitor units in parallel and more series groups compared to banks configured with external fuses.

Recent advances in capacitor bank design include the application of fuse less capacitor banks. This design utilizes capacitor units manufactured from polypropylene film. This technology provides a highly reliable design, virtually eliminating the need for fuses in many applications. These capacitor banks are simpler and more economical to build and operate compared to fused banks. The fuse less design has been mainly applied at voltages ranging from 69 kV to 230 kV.

Capacitor fuses have to accomplish the following principal functional requirements:

1. Isolate a faulted capacitor unit, bank, or portion of a bank from the circuit to which it is connected with negligible disturbance to the remainder of the bank or system.

2. Prevent case rupture by clearing the faulted capacitor from the circuit before the gas generated by the internal fault bursts the capacitor case, possibly damaging adjacent units or equipment, injuring personnel, or discharging dielectric liquid into the ecosystem.

3. Indicate the location of the failed capacitor (externally fused units only).

4. Carry normal capacitor overloads, transient inrush currents, discharge currents and rated current without spurious operation and without affecting the ability of the fuse to perform the first three functions.

There are two general schemes used for external fusing of capacitor banks:

1. Group fusing, and
2. Individual fusing.

Within the limits of the four required fuse functions, fuses may be applied to individual groups of paralleled capacitor units. Group fuses have to also be capable of interrupting the expected 60 Hz fault current. This type of fusing is not often used on substation capacitor banks.

Group fusing of capacitor banks may be advantageous for relatively small ungrounded-wye capacitor banks where operation of a group fuse isolates an entire phase without detrimental effect on the system. Elimination of the unit fuses permits more compact rack designs and simpler buswork.

However, care should be taken in the application of group fuses to be sure that fault current through the fuse will cause it to operate and clear before the combined system fault current and current discharge from adjacent capacitors into the faulted unit can cause case rupture. By providing adequate coordination between the fuses' "maximum total clearing" curve and the capacitor's case rupture curve, case rupture can be avoided.

In a capacitor bank or equipment having a number of units connected in parallel, each capacitor unit will usually have its own fuse. The series combination of each capacitor unit and fuse will be in parallel with other capacitors. Often, for multiphase arrangements and various series parallel groupings, backup bus fault protection is also provided by either circuit breakers or large power fuses.

With individual fusing, the loss of any individual capacitor does not necessarily result in the loss of the bank, the phase, or even the series section. Adjacent units discharge into the faulted unit and its fuse, allowing the fuse to quickly clear the fault.

Finally, if for any reason a reduction needs to be made in the kVAR of the bank, this can be accomplished easily by simply removing the appropriate fuses or links. The spare rack spaces then serve as a storage shelf for the extra capacitors. The requirements for individual capacitor fuses are affected by the capacitor bank connections as well as the system to which the bank is connected.

Non-current-limiting fuses, which are cheaper than the current-limiting type, can be used wherever bank connections can be arranged to limit the available fault current. Possible capacitor bank connections are the following:

Where only one series section of paralleled units per phase is used, and the equipment is connected three-phase grounded wye or delta, the unit fuse is subjected to the full available system short circuit whenever a capacitor unit fails. High-interrupting capacity, current-limiting fuses are required in these situations when the fault current is on the order of 4,000 amperes or higher.

When a three-phase wye connection is used with only one series section of paralleled units per phase and the neutral is left floating, the unfaulted phases will limit the current supplied to the faulted phase from the system. The fuse on the faulted unit will see a maximum of only three times normal bank phase current, and generally a less expensive low-interrupting-capacity fuse can be used. The small risk of simultaneous failure occurring in units of different phases that would result in a phase-to-phase fault is usually accepted.

The above applies to capacitor banks where single-bushing capacitor units have been mounted on insulated racks. However, capacitor units should be capable of interrupting system phase-to-ground fault current where two-bushing capacitor units are mounted on grounded racks. If lower rated fuses are used, fault clearing might not be accomplished by the fuse, which will require the bank's overcurrent relaying to operate a switching device capable of interrupting the fault current.

Series-connected groups of paralleled capacitor units can provide an effective means of limiting fault current to a level where less expensive non-current-limiting fuses can be used. This applies to installations where the parallel kVAR of individual groups does not exceed 4,650 kVAR. The bank voltage rating is the principal factor that determines what series-parallel arrangement to use, along with the type of equipment. Multiple series section arrangements are not practical in equipment below 15 kV and in housed equipment. Consult the capacitor manufacturer regarding fusing for a given bank arrangement and specified maximum fault current.

Protective Controls

The purpose of a capacitor bank's protective control is to remove the bank from the bus before any units are exposed to more than 110 percent of their voltage rating. When capacitor units in a capacitor bank fail, the amount of increase in voltage across the remaining units depends on the connection of the bank, the number of series groups of capacitors per phase, the number of units in each series group, and the number of units removed from one series group. Protective controls are available for grounded neutral capacitor banks, ungrounded neutral capacitor banks, and capacitor banks connected wye-wye.

Where the capacitor bank is switched by a circuit breaker, the protective control does not need a lockout relay since breakers are usually equipped internally with lockout functions. However, where other switching means are provided, the protective control should have a lockout with a manual reset function.

The most straightforward protective control for grounded neutral capacitor banks is the neutral relaying control. This scheme operates on the neutral current generated because of the unbalance caused by capacitor failures in any phase. The major advantage of the *neutral protection scheme* is that it is relatively inexpensive. If there aren't too many series sections, this control can be set to alarm and trip at two different levels of neutral current to provide early detection that a problem exists in the bank and adequate protection should additional capacitor units fail. It is important to be aware of this protective control's disadvantages. Third-order harmonics have to be blocked out of the control, since they will flow in the neutral regardless of whether or not the bank is unbalanced. This blocking is often accomplished by means of a small capacitor in the control that tunes the sensitive element to 60 Hz.

This control is not sensitive to overvoltages caused by the loss of equal number of capacitor units in one or more groups in each phase. However, this is usually not a significant limitation. It may be too sensitive and turn off the bank on unit failures occurring in different series sections of the same phase, even though no series group experiences greater than 110 percent overvoltage. Finally, since the associated CT has to be large enough to handle continuously the third-order harmonics (usually assumed to be 10 percent per phase of fundamental phase current, if no better information is available), the signal at the CT secondary may be too small for relays of ordinary sensitivity. This can be overcome by using three CTs, one in each phase, and connecting the secondaries in parallel and relaying for the zero sequence current. This protective scheme responds only to capacitor overvoltages caused by unbalance and does not protect against capacitor overvoltage due to changes in three-phase supply voltage.

The floating-neutral protective control is similar to that for the grounded neutral bank, except that a voltage transformer (VT) is used in the neutral (usually rated 15 kV) to indicate neutral voltage shift on loss of units. The control is voltage sensitive and subject to the same limitations and advantages as the protective control for grounded neutral capacitor banks.

The wye-wye capacitor bank may be protected by means of a CT between the two ungrounded neutrals. Care should be taken to avoid exceeding individual capacitor unit fuses' interrupting ratings when applying wye-wye banks having one series group per phase. Dependent on the number of capacitors in each phase, there may be sufficient discharge current from parallel capacitor units into the faulted unit to exceed its fuses' interrupting rating. The impedance of the neutral CT is negligible; however, it cannot limit discharge currents into the faulted unit. This scheme tends to be fairly sensitive, and the CT does not require gap protection, even if a vacuum switch is used. The buswork, however, can be difficult to design.

Protection of Current and Voltage Transformers Installed in Capacitor Banks

Switching of capacitors produces transient currents that can produce over-voltages on secondary circuits. Overvoltage protection is required to prevent damage to the current transformer winding and connected burdens. Secondary protection generally involves the correct application of a high-current-rated varistor or spark gap connected directly across the current transformer terminals. Varistors applied to secondary windings should be selected with sufficient energyabsorbing capability to withstand secondary oscillations. Additionally, current transformers that have wound primary windings require overvoltage protection by adding an arc gap or arrester across the primary.

AC voltage sources of various types are used in capacitor bank applications for control and protection schemes. Overvoltage protection of these devices is normally required since transients or surges produced during switching can overstress primary-to-secondary insulation and secondary-to-ground insulation. Surge arresters are typically used for primary protection. Varistors or spark gaps are typically used for secondary protection. AC voltage sources should be specified for full line voltage with primary overvoltage protection added to provide additional protection.

Bus Insulation Systems

Unlike enclosed capacitor banks, open-rack capacitor banks have exposed live parts. In some cases, this exposure has resulted in bank outages due to isolation of faults originated by birds or animals bridging live parts or live parts to ground. One straight forward method to prevent this is to use edge-mounted equipment, since the electrical clearances in the racks used in this equipment are sufficiently liberal and make it highly unlikely that any bird or animal will be large enough to bridge any of the live parts.

However, if upright racks are used and bird proofing is deemed necessary, bus bar insulation systems are commercially available that can be used to protect against accidental bridging of conductors commonly caused by birds and animals. Heat shrinkable tubes, tapes, and sheets and molded fittings allow for simple installation and flexibility to cover most conductor shapes and sizes. Although enclosed capacitor banks have very little exposure to faults by rodents, bus bar insulation systems are sometimes applied in areas where animals such as snakes and lizards are prevalent. Capacitor bank manufacturers can apply bus insulation at the factory, or it can be applied in the field.

Lightning

Lightning surges and the switching of capacitors can result in significant over-voltages. Generally, capacitor banks installed in a substation will be protected from lightning and switching surges by the same devices that protect the substation. However, in regions where lightning activity is high, or in applications involving frequent switching of a capacitor bank, it may be appropriate to install surge arresters at the capacitor bank to limit transient over-voltages. Coordinate insulation levels of installed equipment—substation and shunt capacitor bank—for effective lightning and switching surge protection.

Corona

For systems with voltages above 100 kV, consult the capacitor manufacturer about the advisability of providing corona shields.

Grounding and Short-Circuiting of Capacitor Banks

Substation capacitor units are built with internal discharge resistors so that the residual voltage is reduced to 50 volts or less within 5 minutes after the capacitor unit has been disconnected from its source of supply.

Manually operated switches should be provided to short-circuit and ground each series section of the capacitor bank after it has been disconnected from the circuit but before it is handled by personnel to avoid potentially exposing personnel to hazardous voltages at capacitor terminals.

The duty on these switches is not severe, and most bank manufacturers can supply single hook-stick operated switches for open-rack bank designs and gang-operated switches for enclosed capacitor bank designs to perform both the shorting and grounding functions. While not always required, it may be desirable to specify interlock schemes to prevent the operation of shorting and grounding switches on live circuits and to keep personnel from access to capacitor bank live components when the banks have not been shorted and grounded.

Mounting

There are two common positions for mounting capacitor units in outdoor substation racks: upright and edge mount.

The *upright mounting* position is generally preferred for capacitor units up to 10 kV and edge mount for units above 10 kV. Upright racks are relatively compact and provide a metal framework on the outside, which tends to protect the capacitor units. *Edge-mount* units provide ample clearances and protection from bus and bushing flashovers caused by birds, rodents, and other causes. They do, however, require more physical ground space.

Where units are protected by means of expulsion fuses, it is necessary to provide a minimum of three feet of air clearance plus strike distance between the ends of the fuses and any grounded metal objects to prevent inadvertent flashovers on fuse operation caused by ionized gases contacting the metal objects. For non-expulsion fuses, the additional three feet of clearance is unnecessary.

Normally, capacitor equipment and its substructures are designed to withstand minor earthquake conditions, 80 mph wind, and 0.5 inch of ice (non-simultaneously). Capacitor racks and housings have provisions for mounting of up to three tiers, with no more than two rows of units per tier. There should be unrestricted air circulation around the units. If ambient conditions are extremely dusty, smoky, or salty, consult the capacitor manufacturer as to the advisability of extra creep bushings and insulators and more generous strike clearances between live parts.

Capacitor equipment is often mounted on 8-foot substructures to provide adequate ground clearance, personnel safety, ventilation, and a place to mount accessories. This clearance should be carefully checked and increased if necessary to meet applicable safety codes.

Manufacturers of enclosed capacitor banks custom design each bank for its unique application. Efforts are made by the manufacturer to provide a compact design. The overall size of the enclosure depends on the number of installed components and orientation and mounting of these components. The designer may mount individual capacitor units horizontally or vertically to reduce the overall size of the bank.

Non-expulsion, capacitor-rated, current-limiting fuses are used rather than expulsion type to fuse externally fused capacitor units. Expulsion fuses are not to be used since they do not support a compact bank design. These fuses require clearances for fuse expulsion in addition to electrical clearances. Internally fused capacitor units are often used since no external fuses are required and they allow for a more compact design.

Factory Tests

In the United States, shunt power capacitors are usually tested in accordance with NEMA Std. CP1, which includes production and design tests.

Inspection and Maintenance

IEEE Std. 1036 provides guidelines for inspection, maintenance, and field testing of shunt capacitor banks.

Summary

This volume of the series on Substation Design has focused on voltage regulators and capacitors. Voltage regulators provide the very important function of maintaining the desired delivery voltage from a substation. With the proper use of the control settings and line drop compensation, regulators can correct for load variations as well. A properly applied and controlled voltage regulator not only keeps the voltage at a customer's service entrance within approved limits but also minimizes the range of voltage swing between light and heavy load periods.

Shunt capacitor banks can be used at substations to improve power factor and voltage conditions by supplying leading kilovars to transmission and distribution systems.

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