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Substations – Volume VII – Other Major Equipment

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Substation Design
Volume VII
Other Major Equipment

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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
Air Switches

This chapter deals with high-voltage air switches used in substations. Items discussed include applicable national standards, types of air switches, various constructions of outdoor air switches, service conditions, ratings, and tests.

An *air switch* is defined as a switching device designed to close and open one or more electrical circuits by means of guided separable contacts that separate in air. Air, at atmospheric pressure, is also the insulating medium between contacts in the open position.

All varieties of air switches used in a substation need to generally conform to all applicable national standards and guides. The principal standards and guides for air switches are the following:

- ANSI Std. C29.1, "Test Methods for Electrical Power Insulators"
- ANSI Std. C29.8, "Wet-Process Porcelain Insulators (Apparatus, Cap and Pin Type)"
- ANSI Std. C29.9, "Wet-Process Porcelain Insulators (Apparatus, Post Type)"
- ANSI Std. C29.10, "Wet-Process Porcelain Insulators (Indoor Apparatus Type)"
- ANSI Std. C37.32, "Standard for Switchgear—High-Voltage Air Switches, Bus Supports, and Switch Accessories—Schedules of Preferred Ratings, Manufacturing Specifications and Application Guide"
- ANSI/IEEE Std. C37.100, "IEEE Standard Definitions for Power Switchgear"
- IEEE Std. C37.34, "Test Code for High-Voltage Air Switches"
- IEEE Std. C37.35, "Guide for the Application, Installation, Operation and Maintenance of High-Voltage Air Disconnecting and Load-Interrupter Switches"
- NEMA Std. SG-6, "Power Switching Equipment"

Types of Air Switches

The main types of air switches are determined by and named according to their application. And there are standard definitions describe their general functions.

<u>Disconnecting or Isolating Switch</u>

A *disconnecting* or isolating switch is a mechanical switching device used for changing the connections in a circuit, or for isolating a circuit or equipment from the source of power. This switch is required to carry normal load current continuously and, also, abnormal or short-circuit currents for short intervals as specified. It is also required to open or close circuits either when negligible current is broken or made, or when no significant change in the voltage across the terminals of each of the switch poles occurs. Typical Applications include,

1. Circuit breaker isolation
2. Power transformer isolation
3. Voltage transformer disconnecting
4. Equipment bypassing
5. Bus sectionalizing

Where the current to be broken or made is not negligible, a horn-gap switch should be used.

Grounding Switch

A *grounding switch* is a mechanical switching device by means of which a circuit or piece of apparatus may be electrically connected to ground. Grounding switches are often mounted on the jaw or hinge end of disconnecting or horn-gap switches. Typical Applications include,

1. To ground buses or circuits (for safe maintenance) after they are first isolated
2. To intentionally ground a circuit (using an automatic high-speed device) in order to activate a remote protective relaying scheme

Horn-Gap Switch:

A *horn-gap switch* is a switch provided with arcing horns. To de-energize or energize a circuit that possesses some limited amount of magnetic or capacitive energy, such as transformer exciting current or line charging current. The arcing horns protect the main contacts during opening or closing and enhance the ability of the switch to perform its task. Where the amount of current to be broken or made is not clearly within the switch's capability, consult the manufacturer or use an interrupter switch.

Interrupter Switch:

An *interrupter switch* is an air switch, equipped with an interrupter, for making or breaking specified currents, or both. The nature of the current made or broken, or both, may be indicated by suitable prefix, that is, load interrupter switch, fault interrupter switch, capacitor current interrupter switch, etc. Typical applications are indicated by the above-named prefixes.

Selector Switch

A *selector switch* is a device arranged to permit connecting a conductor to any one of a number of other conductors. In substation applications, it is unlikely that more than two conductors would be subject to selection. Typical Applications include,

1. To connect a potential device to either of two buses
2. To perform a joint disconnecting and grounding function

Various Constructions of Outdoor Air Switches

Outdoor air switches are constructed in many different styles or construction classifications. Preferred standard ratings are listed in Tables 1, 2, and 3.

Table 1
Typical Voltage Ratings
Station Class Outdoor Air Switches

Rated Maximum Voltage (kV, RMS)	Rated Withstand Voltage			Corona and Radio Influences Test Voltages	
	Lightning Impulse (kV Peak)	Power Frequency (kV, RMS)		Test Voltage (kV, RMS)	Limit of RIV (mV @ 1 MHz)
		Dry 1 Minute	Wet 10 Seconds		
8.25	95	35	30	-	-
15.5	110	50	45	-	-
25.8	150	70	60	-	-
38.0	200	95	80	-	-
48.3	250	120	100	-	-
72.5	250 350	120 175	100 145	-	-
121	350 450 550	175 235 280	145 190 230	77 77 77	500 500 500
145	350 450 550 650	175 235 280 335	145 190 230 275	92 92 92 92	500 500 500 500
169	450 550 650 750	235 280 335 385	190 230 270 310	107 107 107 107	500 500 500 500
242	550 650 750 900 1050	280 335 385 465 545	230 275 315 385 455	154 154 154 154 154	500 500 500 500 500
362	1050 1300	545 610	455 525	230 230	500 500
550	1550 1800	710 810	620 710	349 349	500 500

800	2050	940	830	508	750

Table 2
Preferred Switching Impulse Withstand Voltage Station Class Outdoor Switches

Rated Maximum Voltage (kV, RMS)	Rated Lightning Impulse (kV, Peak)	Switching Impulse Withstand Voltage (kV, Peak)	
		To Ground	Across Open Gap
362	1050	750	655 + (295)
362	1300	885	825 + (295)
550	1550	1050	880 + (450)
550	1800	1150	1000 + (450)
800	2050	1300	1000 + (650)

Table 3
Preferred Continuous & Withstand Currents Station Class Outdoor Switches

Continuous Current Rating (Amps)	Withstand Currents	
	Short-Time Withstand (Symmetrical, kA)	Peak Withstand (kA)
600	25	65
1200	38	99
1600	44	114
2000	44 63	114 164

3000	63 75	164 195
4000	75	195

Construction Classifications

A pictorial representation of each classification is shown in Figure 1. The various constructions are described below.

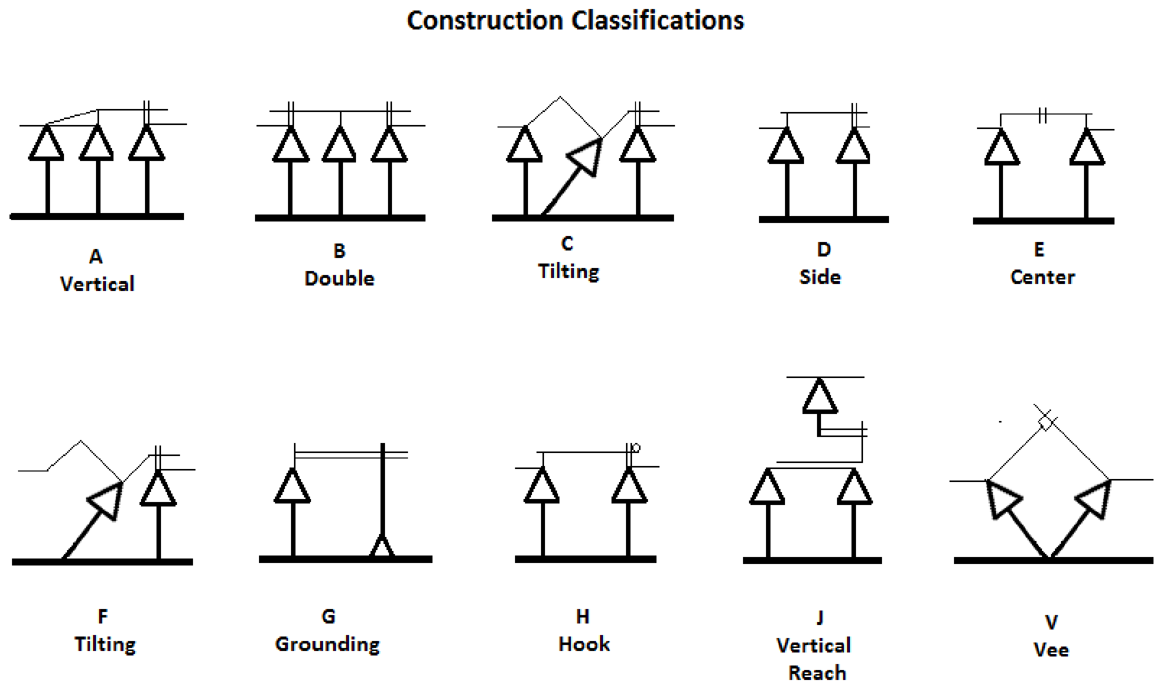


Figure 1

Vertical Break Switch (Construction Classification A)
A *vertical break switch* is one in which the travel of the blade is in a plane perpendicular to the plane of the mounting base. The blade in the closed position is parallel to the mounting base. The hinge end includes two insulators, one of which is caused to rotate by the operating mechanism and thereby open and close the blade.

Double Break Switch (Construction Classification B)
A *double break switch* is one that opens a conductor of a circuit at two points. The center insulator stack rotates to accomplish the opening and closing operation.

Tilting-Insulator Switch (Construction Classifications C & F)
A *tilting-insulator switch* is a device in which the opening and closing travel of the blade is accomplished by a tilting movement of one or more of the insulators supporting the conducting parts of the switch. This type of switch is seldom used today. However, this switch is still in

service on many existing installations. It is included here since it will be necessary to modify or replace such switches on occasion.

Side-Break Switch (Construction Classification D)
A *side-break switch* is one in which the travel of the blade is in a plane parallel to the base of the switch. The hinge-end insulator rotates to accomplish the opening and closing operation.

Center-Break Switch (Construction Classification E)
A *center-break switch* is one in which travel of the blade is in a plane parallel to the base of the switch and that opens in the center at only one point. Both insulators rotate to accomplish the opening and closing operation.

Grounding Switch (Construction Classification G)
A *grounding switch* – as previously noted - is a mechanical switching device by means of which a circuit or piece of apparatus may be electrically connected to ground. The pictorial representation in Figure 1shows a type where an insulated blade, connected to a bus or a piece of equipment, is made to contact ground. Some types use a normally grounded blade, which is made to contact the bus or equipment to be grounded.

Hook Stick Switch (Construction Classification H)
A *hook stick switch* is one that is opened manually by means of a switch stick. Both insulators remain stationary when the blade, hinged at one end, is unlatched and opened or closed by the switch stick. These are single-pole (single-phase) switches.

Vertical Reach Switch (Construction Classification J)
A *vertical reach switch* is a device in which the stationary contact is supported by a structure separate from the hinge mounting base. The blade in the closed position is perpendicular to the hinge mounting base.

Service Conditions

The ratings of all high-voltage air switches covered by the standards are based on specific temperature and altitude conditions. Ambient temperature of cooling air over the switch is within the range of -30C to +40C for non-enclosed indoor or outdoor switches. Ambient temperature of cooling air over the switch does not exceed 55C for enclosed indoor or outdoor switches. Maximum ambient temperature outside the enclosure does not exceed 40C. Altitude does not exceed 3,300 feet. Correction factors should be applied above 3,300 feet as shown in Table 4.

Table 4
Altitude Correction Factors
High Voltage Air Switches

Altitude	ACF	
	Rated	Rated

	Withstand Voltage	Current
3,300	1.00	1.00
4000	0.98	0.995
5000	0.95	0.99
6000	0.92	0.985
7000	0.89	0.98
8000	0.86	0.97
9000	0.83	0.965
10000	0.80	0.95
12000	0.75	0.95
14000	0.70	0.935
16000	0.65	0.925

Ratings

The main rating definitions applicable to disconnecting switches are listed here and generally to the other switch types.

Rated voltage is the highest nominal system voltage on which it is intended to be applied.

Rated maximum voltage is the highest RMS voltage at which the device is designed to operate.

Rated continuous current is the maximum direct current, or RMS current, in amperes at rated frequency which it will carry continuously without exceeding the limit of observable temperature rise.

Allowable continuous current at a specific ambient temperature is the maximum direct or alternating current in amperes, RMS at rated frequency which it will carry without exceeding the allowable temperature for any of its parts.

The allowable continuous current may be determined using,

$$\mathbf{I_A = I_R * \sqrt{\frac{\theta_{max} - \theta_A}{\theta_r}}}$$

Where,

I_A = Allowable continuous current at ambient temperature (T_A)
I_R = Rated continuous current
θ_{max} = Allowable temperature of switch parts
θ_r = Limit of observable temperature rise (C) at rated current of switch part.

The values of "θr" can be found in IEEE Std. C37.34 and is used to maintain a loadability of 1.22 at 25C where the *loadability* of a non-enclosed air switch is the ratio of allowable continuous current at 25C ambient temperature to rated current. The loadability of an enclosed air switch is the ratio of allowable continuous current at 40C inside ambient temperature to rated current. Users in colder climates and those with maximum load currents, known to occur during ambients lower than 40C, should carefully consider the possible cost benefits from taking advantage of allowable continuous currents when selecting the continuous current rating of any air break switch. In such applications, a lower continuous current rating may be sufficient, compared to a rating based strictly on the maximum direct, or RMS alternating current, of the circuit in question.

Rated momentary current is the RMS total current which the switch shall be required to carry for at least one cycle. The current shall be the RMS value, including the direct-current component, during the maximum cycle as determined from the envelope of the current wave, and the test period shall be at least ten cycles.

Rated three-second current is the RMS total current, including any direct current component, that the switch shall be required to carry for three seconds.

Rated withstand voltage shall be the voltage which the device has to withstand without flashover or other electric failure when voltage is applied under specified conditions.

The preferred ratings of voltage, continuous current, short-time current ratings, dielectric withstand voltages, and radio influence test voltages of various constructions of outdoor air switches (at 60 Hz) shall be in accordance with Tables 1, 2 and 3.

Other Requirements

Insulators
Insulators used need to have sufficient strength to withstand the magnetic forces produced by the rated momentary current ratings specified in Table 3. An approximation of the electromagnetic force exerted between two current-carrying conductors is given by the following equation,

$$\mathbf{F = M * \left(\frac{5.4 * I^2}{S * 10^7}\right)}$$

Where:
F = Pounds per foot of conductor.
M = Multiplying factor (determined from Table 5).
I = Short-circuit maximum peak current in amperes in accordance with Table 5.

S = Spacing between centerlines of conductors in inches.

The force calculated from the above operation will, in most cases, be conservative, tending to compensate for the neglect of resonant forces. It should, therefore, be reasonably accurate for the majority of practical situations.

Table 5 Multiplying Factor (M) for Calculation of Electromagnetic Forces		
Circuit	**Condition (Amps)**	**Multiplying Factor (M)**
DC	Maximum Peak	1.0
AC, 3-phase	Max Peak	0.866
AC, 3-phase	RMS Asymmetrical	2.3
AC, 3-phase	RMS Max Symmetrical	6.9
1-phase of 3-phase or 1-phase	Max Peak	1.0
1-phase of 3-phase or 1-phase	RMS Asymmetrical	2.66
1-phase of 3-phase or 1-phase	RMS symmetrical	8.0

<u>Terminal Loadings</u>

Terminal pad loadings should be in accordance with Table 6. See Figure 2 for a graphical representation of the conditions in Table 6. The arrangement of bolt hole centerlines in terminal pads should be in accordance with Figure 3. Holes should accommodate bolts ½ inch in diameter. Two or more interleaved 4-hole pad configurations can be used as shown in Figure 3. All dimensions are in inches.

Table 6 Terminal Loadings for Switches (See Figure 00 for graphic represntation)				
Max Voltage (kV)	**Current Rating (Amps)**	**F_1 & F_2 (lbs)**	**F_3 (lbs)**	**F_4 (lbs)**

4.8 – 72.5	200-1200 >2000	90 90	30 30	30 30
121-169	600-1600 >2000	120 120	40 40	110 250
242-362	1200-1600 >2000	180 230	60 75	375 685
500>	All	500	150	750

Terminal Loading Conditions

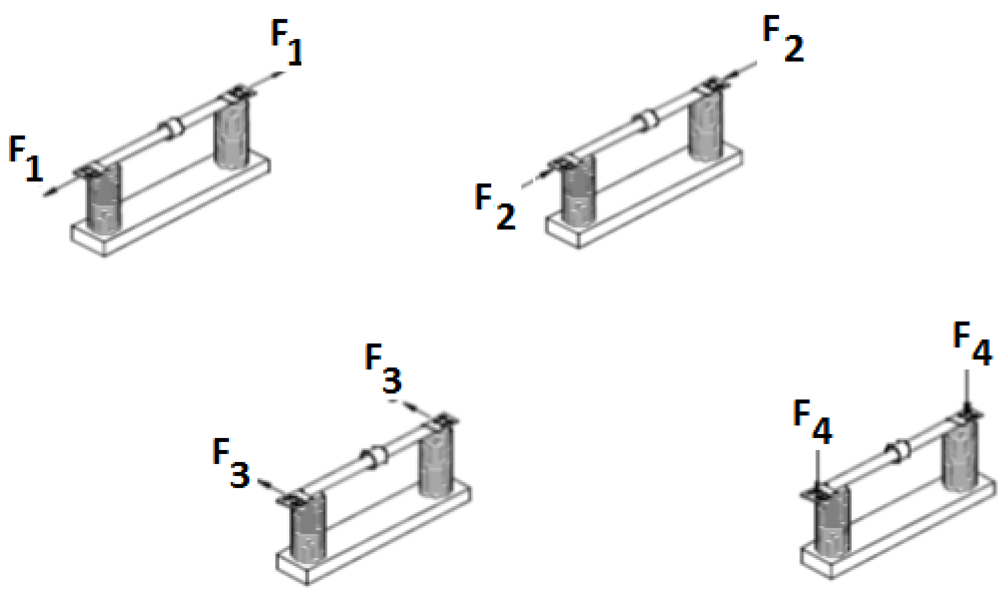


Figure 2

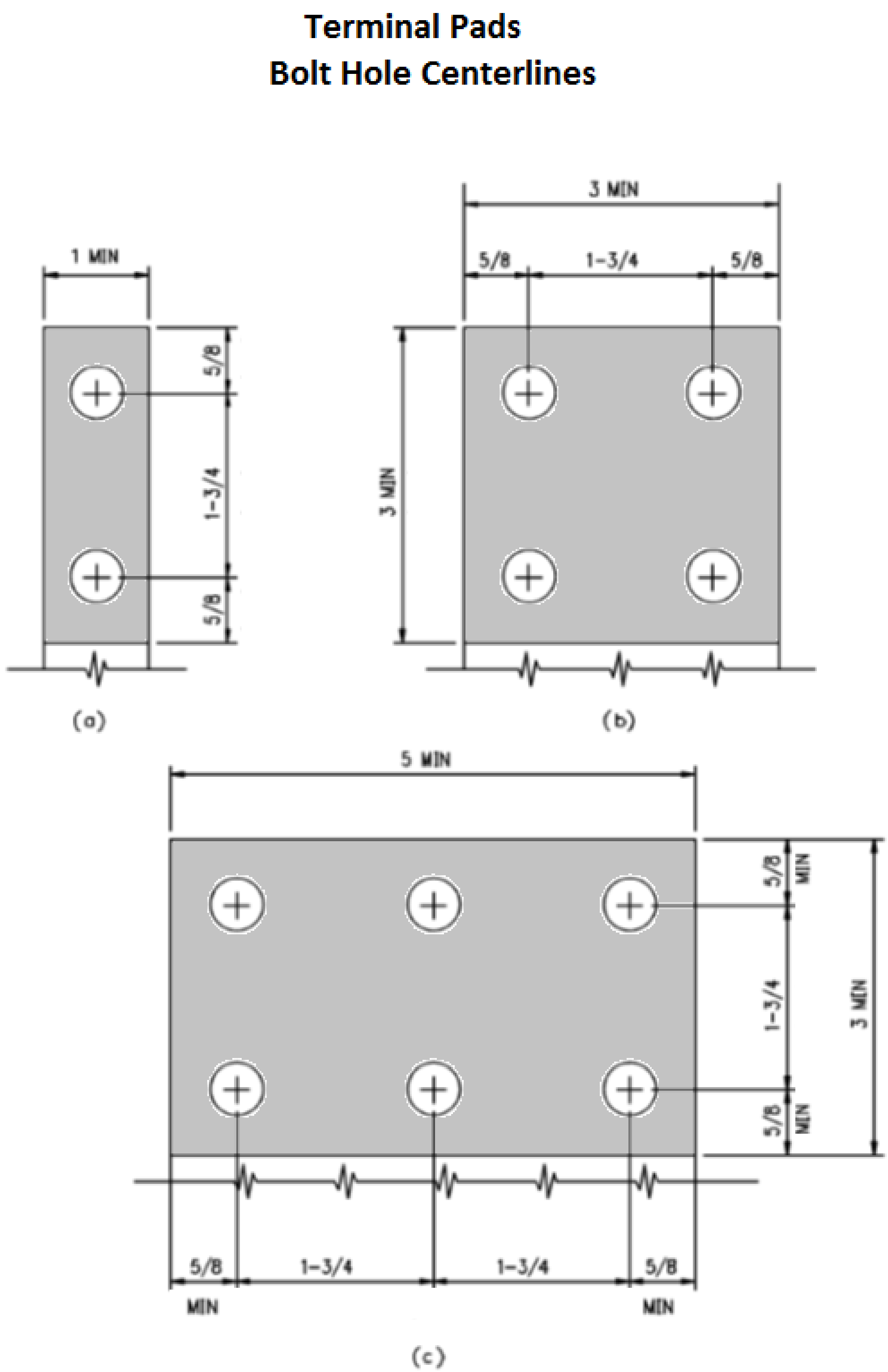

Terminal Pads
Bolt Hole Centerlines
1 MIN
5/8
1-3/4
5/8
(a)
3 MIN
5/8
1-3/4
5/8
3 MIN
(b)
5 MIN
5/8
MIN
1-3/4
5/8
MIN
3 MIN
5/8
1-3/4
1-3/4
5/8
MIN
MIN
(c)

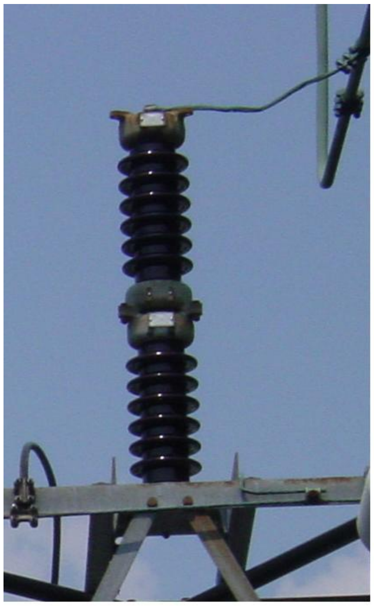
Figure 3

Mounting Considerations

Air switches should be mounted on supports strong enough to ensure that current carrying contacts mate properly when opened and closed, since considerable reaction forces are exerted on the supports during operation. Whenever possible, air switches should be oriented so that the blade is dead when the switch is open. The intended mounting arrangement of air break switches should be made known to the manufacturer so that the insulators will be properly assembled.

Chapter 2
Surge Arresters

This chapter deals with the application of surge arresters for the protection of equipment in substations. While information is provided for silicon-carbide valve arresters, metal oxide arresters are preferred and recommended due to their improved protective characteristics.



Surge arresters are the basic protective devices against system transient overvoltages that may cause flashovers and serious damage to equipment. They establish a baseline of transient overvoltage above which the arrester will operate to protect the equipment. When a transient overvoltage appears at an arrester location, the arrester conducts internally and discharges the surge energy to ground. Once the overvoltage is reduced sufficiently, the arrester seals off, or stops conducting, the flow of power follow current through itself and the circuit is returned to normal. As voltage-sensitive devices, arresters have to be carefully selected to correlate properly with the system operating voltages.

Classification of Arresters

Surge arresters are classified as station, intermediate, and distribution arresters. Classifications are determined by prescribed test requirements. Primary differences in the use of the classes involve the voltage levels the arresters will withstand and protect and the current levels the arresters will discharge. All three classes may be used in substation applications.

Relative protective capabilities and initial costs of surge arresters, in descending order, are station-class, intermediate-class, and finally distribution-class arresters. The appropriate arrester has to be determined from an analysis of the protective characteristics required, the importance of the equipment protected, the level of reliability desired, and the overall cost of protection.

Station-class arresters are more ruggedly constructed than those in either the intermediate or distribution class. They have greater surge current discharge ability and lower IR voltage drop, thus affording better protection. In the event of arrester failure, their ability to vent safely during high system short-circuit currents is better than the other classes of arresters. Station-class arresters are recommended for all substations of large capacity (10,000 kVA and above) and on smaller substations that are of prime importance. They should be applied on transmission circuits longer than approximately 100 miles or where shunt capacitor banks are installed.

Station-class arresters are also desirable on substations using reduced insulation (BIL) or those located in high lightning exposure areas. They should be used where the system short-circuit current exceeds the venting capability of intermediate-class arresters. They are the only class of arrester available for use on systems above 150 kV.

Intermediate-class arresters may be used in substations rated below 10,000 kVA at a cost saving when compared to station-class arresters. Their electrical protective characteristics (sparkover and IR) are higher than station-class arresters, but are usually adequate for small substations. In the event of arrester failure, intermediate-class arresters can safely vent with short-circuit current of 16,000 amperes or less. Intermediate-class arresters are available in ratings 3 kV through 120 kV.

Distribution-class arresters may be used on the low-voltage side of distribution substations. Install them on the load side of feeder overcurrent protective devices (reclosers or breakers). They are frequently applied connected to the low-voltage bushings of small distribution substation transformers. Their protective characteristics are not as good as either intermediate- or station-class arresters. If distribution-class arresters are used in substations, use only the direct-connected type with ground lead disconnector (isolator).

The major protective characteristics of the gapped silicon-carbide arresters are summarized in Tables 7, 8 and 9.

Table 7

Protective Characterisitcs of Gapped Silicon Station Arrresters

Voltage Class (kV, RMS)	Impulse Sparkover Voltage			Switching Surge Sparkover kV Crest	Discharge Voltage for 8x20us Discharge Current Wave kV Crest					
	Front-of-Wave		1.2x50 μs kV Crest		1500A	3000A	5000A	10000A	20000A	40000A
	Rate of Rise Test Voltage (kV/μs)	Kv Crest								
3	25	10-18	10-14	-	4.7-6	5.6-6.5	6-7	6.7-7.5	7.7-8.3	-9.2
6	50	19-28	16-23	-	9.3-11	10-12	11.9-13	13.4-14.3	15.3-16.3	-18.5
9	75	28.5-38	24-32	-	13.9-17	16-18	17.8-19	20-21.5	22.9-24.3	-28
12	100	36-48	32-41	-	18.5-22	21.3-24	23.5-25.5	26.7-28.5	30.1-32.1	-37
15	125	45-57	40-51	-	23.1-27.5	26.6-30	29.5-32	33.4-36	38.2-40	-46
21	175	63-76	54-68	-	32.3-38.5	37.2-42	41-45	46.8-50	53.4-55.5	-65
24	200	71-86	62-77	-	36.9-44	42.5-48	47-51	53.4-57	61-63.5	-74
30	250	89-103	77-93	-	46.1-55	53.1-60	59-64	66.9-72	76.3-79	-92.5
36	300	107-118	92-108	-	55.3-66	63.7-72	70.5-76	80-85	91.5-94.5	-111
39	325	115-125	100-114	-	60-71.5	69-78	76.5-82.5	56.5-92	99.1-102	-120

48	400	143-148	122-132	-	73.8-88	84.9-96	94-102	106-114	122-126	-148
60	500	170-190	141-165	136-153	95-109	110-120	118-130	132-143	150-158	-185
72	600	204-226	169-190	163-178	114-131	130-144	141-155	159-170	180-189	-222
90	750	254-275	210-235	203-215	142-163	162-180	176-194	199-213	225-237	-277
96	800	270-295	218-245	218-225	151-174	173-192	188-218	212-227	240-253	-296
108	900	304-325	245-270	245-250	170-196	194-216	212-245	238-256	270-284	-333
120	1000	338-360	272-300	272-275	188-218	216-240	235-272	265-285	300-319	-370
168	1400	460-525	380-404	380-381	263-305	303-336	329-362	371-399	420-442	-517
240	2000	620-735	535-577	533-545	374-436	432-480	470-518	530-570	605-630	-739
258	2000	760-790	575-620	573-585	402-438	465-474	505-515	569-575	650-666	-795

Table 8

Protective Characterisitcs of Gapped Silicon Intermediate Arrresters

Voltage Class (kV, RMS)	Impulse Sparkover Voltage			Switching Surge Sparkover kV Crest	Discharge Voltage for 8x20us Discharge Current Wave kV Crest				
	Front-of-Wave								
	Rate of Rise Test Voltage (kV/µs)	Kv Crest	1.2x50 µs kV Crest		1500A	3000A	5000A	10000A	20000A
3	25	111-12	11-12	-	5.2-7.5	6-8	6.6-9	7.5-10	8.7-12
6	50	21-21	19-19	-	10.4-13.5	11.9-14	13.2-15.5	15-17.5	17.4-20
9	75	31-33	27.5-32	-	15.6-21	17.9-23	19.88-25	22.5-28	26.1-31
12	100	38-42	35.5-37	-	20.8-27	23.8-29	26.4-32	30-34	34.8-37.5
15	125	47-51	43.5-46.5	-	25.9-34	29.7-36.5	32.9-39.5	37.5-43	43.5-47.5
21	175	67-73	58-64	-	36.3-47.5	41.6-51	46.1-56	52.5-60	60.9-66
24	200	75-78	66-75	-	41.5-54	47.6-58	52.7-64	60-68	69.6-75
30	250	91-97	81-91	-	51.8-68	59.4-73	65.8-79	75-86	87-95
36	300	108-116	95-103	-	62.2-82	71.3-87	79-95	90-102	104-113

39	325	116-126	102-110	-	67.4-91	77.3-97	85.5-106	97.5-114	113-126
48	400	143-154	121-132	-	83-109	95-116	105-127	120-136	139-150
60	500	166-190	147-155	185-206	104-136	119-145	131-159	150-171	174-189
72	600	201-230	171-191	219-245	124-163	143-174	158-191	180-204	209-225
90	750	250-283	223-233	274-304	155-204	178-218	197-239	225-256	261-282
96	800	268-300	236-250	292-323	166-217	190-232	211-254	240-273	278-300
108	900	283-335	258-265	328-362	187-244	214-261	237-286	270-307	313-338
120	1000	299-370	276-295	351-400	207-272	238-290	263-319	300-338	348-380

Table 9

Protective Characterisitcs of Gapped Silicon Distribution Arrresters

Voltage Class (kV, RMS)	Impulse Sparkover Voltage					Discharge Voltage for 8x20us Discharge Current Wave kV Crest				
	Front-of-Wave kV Crest			1.2x50 µs						
	Rate of Rise Test Voltage (kV/µs)	Without External Gap	With External Gap	Without External Gap	With External Gap	1500A	3000A	5000A	10000A	20000A
3	25	14-25	24-38	12-22	24-37	8-10	8.4-11.5	10-12.4	11.5-13.8	13.5-15.7
6	50	27-35	45-57	23-33	35-55	16-20	17-23	20-24	22.5-26	25-30
9	75	39-48	60-76	34-45	48-65	24-30	25-34	29-36.5	32.5-41	36-52
10	83.3	40-48	62-76	35-49	48-67	25-30	37.5-34	29.5-37	32.5-44	36-52
12	100	49-60	73-96	44-57	59-85	32-40	34-46	29.5-48	43-53	49-61.5
15	125	47-75	80-115	49-65	69-100	40-50	42-55	39-60	54-65.5	60-76
18	150	55-90	96-113	58-76	79118	48-60	51-66	46-72	65-78	71-91
21	175	63-90	110-139	66-78	-123	56-70	59.75	68-80.5	73-90	82-103
24	225	79-102	-	75-98	-	70-80	76-86	82-94	90-105	99-121
30	250	86-114	-	81-100	-	76-89	84-97	91-105	100-116	111-134

Table 10 indicates the *maximum continuous operating voltage* (MCOV) and duty-cycle ratings for metal oxide surge arresters.

Table 10
Metal Oxide Arrester Ratings
(kV, RMS)

Duty Cycle Voltage	MCOV		Duty Cycle Voltage	MCOV
3	2.55		132	106
6	5.10		144	115
9	7.65		168	131
10	8.40		172	140
12	10.20		180	144
15	12.70		192	152
18	15.30		228	180
21	17.00		240	190
24	19.50		258	209
27	22.00		264	212
30	24.40		276	220
36	29.00		288	230
39	31.50		294	235
45	36.50		312	245
48	39.00		396	318
54	42.00		420	335
60	46.00		444	353
72	57.00		468	372
90	70.00		492	392
96	76.00		540	428
108	84.00		564	448
120	96.00		576	462

The major protective characteristics of metal oxide arresters are summarized in Table 11.

Table 11

Protective Characterisitcs of Metal Oxide Station and Intermediate Arresters

Station Class Arresters									
Steady State Operation System Voltage & Arrester Ratings				Protective Levels Range of Maximum Per Unit Crest of MCOV			Durability Charateristics		
System Voltage L-L (kV.RMS)	System Voltage L-G (kV/RMS)	MCOV Rating (kV/RMS)	Duty Cycle Ratings (kV/RMS)	0.5us FOW Discharge Voltage (DV)	8x20us wave DV	Switching Surge DV	High Current Withstand Crest (kA)	Transmission Line Discharge (Miles)	Pressure Relief (kA, sym)
4.37	2.52	2.55	3	2.32-2.48	2.10-2.20	1.70-1.85	65	150	40-65
8.73	5.04	5.1	6-9	2.32-2.48	1.97-2.23	1.70-1.85	65	150	40-65
13.1	4.56	7.65	9-12	2.32-2.48	1.79-2.23	1.70-1.85	65	150	40-65
13.9	8.00	7.65	9-15	2.32-2.48	1.97-2.23	1.70-1.85	65	150	40-65
14.5	8.37	8.4	10-15	2.32-2.48	1.97-2.23	1.70-1.85	65	150	40-65
26.2	15.12	15.3	18-27	2.32-2.48	1.97-2.23	1.70-1.85	65	150	40-65
36.2	20.92	22	27-36	2.43-2.48	1.97-2.23	1.70-1.85	65	150	40-65
48.3	27.89	29	36-48	2.43-2.48	1.97-2.23	1.70-1.85	65	150	40-65
72.5	41.86	42	54-72	2.19-2.40	1.97-2.18	1.64-1.84	65	150	40-65
121	69.86	70	90-120	2.19-2.40	1.97-2.18	1.64-1.84	65	150	40-65
145	83.72	84	104-144	2.19-2.40	1.97-2.17	1.64-1.84	65	150	40-65
169	97.57	98	120-172	2.19-2.40	1.97-2.17	1.64-1.84	65	175	40-65
242	139.72	140	172-240	2.19-2.40	1.97-2.17	1.64-1.84	65	175	40-65
362	209.00	209	258-312	2.19-2.40	1.97-2.17	1.71-1.85	65	200	40-65
550	317.54	318	396-564	2.01-2.25	2.01-2.25	1.71-1.85	65	200	40-65
800	461.88	462	576-612	2.01-2.25	2.01-2.25	1.71-1.85	65	200	40-65
Immediate Class Arresters									
4.37-169	2.52-97.67	2.8-98	3-144	2.38-2.85	2.28-2.55	1.80-2.10	65	100	-

Ratings

The *voltage rating–duty cycle* is the designated maximum permissible operating voltage between its terminals at which an arrester is designed to perform its duty cycle. It is the voltage rating specified on the nameplate. This rating is applicable specifically to the silicon-carbide valve arrester and is also typically listed with the MCOV rating for the metal oxide arrester.

The *power-frequency sparkover voltage* is the root-mean-square value of the lowest power frequency sinusoidal voltage that will cause sparkover when applied across the terminals of an arrester. This rating is applicable to the silicon-carbide valve arrester.

The *Impulse Sparkover Voltage* is the highest value of voltage attained by an impulse of a designated wave shape and polarity applied across the terminals of an arrester prior to the flow of discharge current. This rating is applicable to the silicon-carbide valve arrester. Standard wave shape is a 1.2 x 50 μs wave, i.e., a wave that rises to crest in 1.2 μs and decays to one-half crest value in 50 μs.

The *maximum continuous operating voltage* (MCOV) is the maximum RMS power frequency operating voltage that may be applied continuously to the terminals of the arrester. When applying metal oxide surge arresters, the minimum value of this voltage is usually the maximum system line-to-ground voltage.

The *discharge current* is the current that flows through an arrester as a result of a surge.

The *discharge voltage* is the voltage that appears across the terminals of an arrester during the passage of discharge current. Maximum values are usually available from the manufacturer for currents of 1.5, 3, 5, 10, 20, and 40 kA with a wave shape of 8 x 20 μs. The discharge voltage resulting from a standard 8 x 20 μs current wave shape approximates the standard 1.2 x 50 μs voltage wave shape reasonably well between the current magnitudes of 5 kA and 20 kA. The 8 x 20 μs standard current wave shape is one that rises to crest in 8 μs and decays to one-half crest value in 20 μs. The 1.2 x 50 μs voltage wave shape is one that rises to crest in 1.2 μs and decays to one-half crest value in 50 μs.

The discharge-voltage current characteristic is the variation of the crest values of discharge voltage with respect to discharge current.

The term *System Voltage* carries two designations: nominal voltage and maximum system voltage. *Nominal voltage* is the approximate phase-to-phase voltage distinguishing one system from another. The nominal voltage is the voltage by which the system may be designated and is near the voltage level at which the system normally operates. The nominal voltage is usually approximately 5 to 10 percent below the maximum system voltage. *Maximum system voltage* is the highest RMS phase-to-phase operating voltage that occurs, the highest phase-to-phase voltage for which equipment is designed for satisfactory continuous operation without derating of any kind. It is the starting basis on which surge arresters are applied.

Maximum system voltages are generally those prescribed in ANSI Std. C84.1, "Voltage Ratings for Electric Power Systems and Equipment (60 Hz)." On systems rated 345 kV and below, it is expected that the maximum system voltage may be 5 to 10 percent higher than nominal voltage.

Grounded vs. Ungrounded Systems

Systems have been historically referred to as *effectively grounded* when the coefficient of grounding (COG) does not exceed 80 percent, or non-effectively grounded or ungrounded when the coefficient of grounding exceeds 80 percent. The *coefficient of grounding* (COG) is the ratio of the line-to-ground voltage to the line-to-line voltage (E_{LG} /E_{LL}.)

The COG is expressed as a percentage of the highest RMS line-to-ground, E_{LG}, on a sound phase, at a selected location, during a fault to ground affecting one or more phases to the line-to-line voltage, E_{LL}, that would be obtained, at the selected location, with the fault removed.

A COG value not exceeding 80 percent is obtained approximately when, for all system conditions, the ratio of zero sequence reactance to positive sequence reactance (X_0/X_1) is positive and less than three, and the ratio of zero-sequence resistance to positive-sequence reactance (R_0/X_1) is positive and less than one.

On certain distribution systems of the four-wire type where transformer neutrals and neutral conductors are directly grounded at frequent points along the circuit, the positive sequence resistance (R) may be significant due to small conductors and should be considered.

Neglecting the resistance component may result in higher rated arresters than normally required. In these cases, use ratios R_0/Z and X_0/Z_1. The COG for such systems may be as low as 67 percent. On many high-voltage transmission systems, the COG may be as low as 70 percent. Recognize the possibility of increases in the COG due to system switching or changes.

Application Guide for Silicon-Carbide Valve Arresters

The voltage rating assigned to a surge arrester should exceed the maximum 60 Hz voltage across its terminals during normal or fault conditions. In general, the surge arrester voltage rating should be at least 25 percent higher than the phase-to-ground voltage when the system is operating at maximum phase-to-phase voltage. On an isolated neutral system, which may be a delta system or an ungrounded-wye system, this rating should be approximately 105 percent of, and never less than, the maximum rating of the system. Such an arrester is called a *full-rated* or 100 percent arrester. On effectively grounded systems, the arrester maximum rating can generally be 80 percent or less of the maximum system voltage. In special cases, arresters as low as 75 percent or even 70 percent of maximum system voltage rating may be applied, depending on the coefficient of grounding of the system.

Maximum Phase-to-Ground Voltage

The first step in selecting a lightning arrester is to determine the maximum phase-to-ground power-frequency overvoltage at the arrester location. This maximum overvoltage may occur as a result of a fault condition, sudden loss of load, or resonance. Overvoltages experienced as a result of loss of load or resonance are determined by system operating experience or by computer studies. Overvoltages that result from these two conditions are not expected to be significant for most applications at 230 kV and below. At 345 kV, the *switching surge protection level* may be more significant than the *lightning impulse protection level*. At the higher voltage level, capacitance of the line will be more significant. On any long line, the voltage of the line will increase over distance. With the line energized during switching operations from one end of the line only, the remote end will experience a voltage increase. In addition, if the energizing source is a relatively weak source, the line could experience transient oscillations resulting in additional voltage increase. The additional line capacitance will tend to make the line more susceptible to transients than the lower voltage lines. Switching of a 345 kV line terminated with a transformer could result in transients if resonance conditions are present.

These conditions could result in the overstressing of surge arresters due to multiple restrikes through the arrester. *Transient network analysis* (TNA) or *electromagnetic transient program analysis* (EMTP) may be necessary to determine the size of the arrester to be applied. The study could also determine other means to control transient overvoltage conditions such as the application of reactors, pre-insertion resistors, or specific operating practices to be followed during switching.

Determination of the overvoltage due to a fault condition is necessary for any power system where less than full line-to-line rated arresters are to be considered. The maximum line-to-line voltage at the point of arrester application multiplied by the COG based on a fault at the arrester location will often result in the maximum voltage to be applied. This may vary, however, depending on the system configuration. The application of neutral impedance elements may shift the location of the maximum voltage on a line with the shift of the transformer neutral during a phase-to-ground fault.

The COG may be estimated or calculated from system values. When calculating the COG for use with machines, the subtransient reactance of the machine is recommended for use. With EHV systems, consider the effects of shunt reactors, capacitance, series capacitance, or reactors when applicable.

Protective Margins

The lower the arrester rating on a given system, the greater the protective margin for the insulation of the protected equipment. When system studies or calculations show that protective margins would be more than adequate, the BIL of major equipment may be reduced for substantial savings. Generally, the accepted practice is to provide a minimum margin of 20 percent between transformer BIL and surge arrester maximum IR, and 15 percent in the case of switching surges. The switching surge withstand strength of transformer insulation is usually specified at 83 percent of impulse BIL. Greater margins may be required where a condition of insulation degradation may be present.

Examine the protective margins over the full volt–time characteristics of the insulation that is to be protected and the volt–time characteristics of the arrester. Also maintain sufficient margin regardless of the relative physical location of the arrester and protected equipment in the substation. Locate the arrester as close to the major equipment as possible, and the arrester ground resistance should be low. Connect surge arrester grounds reliably to the substation ground grid and with the frames of all equipment being protected.

Thermal Capacity

The arrester thermal capacity or ability to pass repeated or long-duration surge currents (such as switching surges) without an internal temperature rise, which could fail the arrester, has to be checked. This is especially true in all cases where there are long lines or shunt capacitor banks with high stored energy. Available switching surge energy increases as the square of the system voltage and directly with the length of lines. Thus, on 138 kV lines of equal length to 69 kV lines, the surge arresters have to have at least four times the discharge capacity.

Direct Stroke Shielding

Surge arresters are applied primarily based on their effectiveness in limiting overvoltages in the form of traveling waves entering the substation over connecting lines. High-energy lightning strokes hitting a substation bus at or near the arrester could easily destroy the arrester while it is attempting to pass the surge current to ground. Even if the arrester is not destroyed, the protective margins provided may become nonexistent as a result of the effect of the steep fronts and high IR voltage produced by the arrester.

Therefore, a basic principle of surge arrester application is the provision of overhead ground wires and/or grounded conducting masts to shield substation electrical equipment against direct lightning strokes. Effective shielding also permits greater separation of a surge arrester from the equipment being protected since the overvoltage impulses are less steep and are usually of lower magnitude.

Multiple Lines

The severity of a lightning impulse arriving at a substation is reduced by the effect of multiple lines. Traveling waves coming into a substation will divert part of the energy in the wave over all line connections. It is difficult, however, to take full advantage of this because we cannot be sure the lines will be connected when needed. In addition, in substations with long buses, etc., the distances sometimes prevent effective use of this principle.

Standards

There are two principal national standards or guides pertaining to silicon-carbide valve surge arresters: IEEE Stds. C62.1 and C62.2.

IEEE C62.1, “IEEE Standard for Gapped Silicon-Carbide Surge Arresters for Alternating-Current Power Circuits.” This standard contains much basic information on arresters such as definitions, service conditions, classification and voltage ratings, performance characteristics and tests, test procedures, design tests, conformance tests, and construction.

A guide for application of valve-type lightning arresters for alternating-current systems can be found in ANSI/IEEE Std. C62.2. This standard is an excellent guide on application of arresters. It contains information on general procedures; systematic procedures for protection of transformers and substation equipment; and protection of other equipment such as booster transformers, reactors, current transformers, etc. Of particular interest is the Typical Voltage–

Time Curve for Coordination of Arrester Protective Levels with Insulation Withstand Strength. This curve illustrates the protection provided by an arrester to transformer insulation.

IEEE Std. C62.2, Protective Characteristics of Surge Arresters, contains data on protective characteristics of available arresters compiled from domestic manufacturers. This is very useful for general studies, but it should be kept in mind that the voltage values given are the maximums of the published protective characteristics. Consult specific manufacturer's information for more accurate insulation coordination.

Application of Valve-Type Surge Arresters

An example of surge arrester selection will be worked out along with each guide step to illustrate the procedure. The example is an arrester selection for a 230 kV substation coordinated with the transformer BIL. The 230 kV substation is supplied by one 230 kV line. Both the substation and the line are effectively shielded.

Step 1. Determine the maximum phase-to-ground temporary overvoltage at the arrester location.

In most cases, this will depend on the coefficient of system grounding. In this example we assume that, at the surge arrester location, system parameters are:

$R_1 = R_2 = 0.1*X_1$
$R_0/X_1 = 0.8$
$X_0/X_1 = 2.5$
COG = 75%

Therefore,

The maximum system voltage is 230 kV * 1.05 = 242 kV

The maximum phase-to-ground overvoltage during a ground fault is 242 kV * 0.75 = 181 kV.

No other conditions including switching configurations are considered to result in temporary overvoltages that will exceed this voltage level.

Step 2. Estimate the waveshape and magnitude of arrester discharge current.

The magnitude is determined largely by the effectiveness of the shielding against direct lightning strokes. The standard arrester discharge current curve (8 x 20 μs wave) represents the most severe current waveshape to be expected at a substation that is effectively shielded. Surge arrester discharge voltage characteristics (IR drop) are based on this standard curve. A conservative value of maximum current with effective shielding is 10 kA. The current could reach as high as 20 kA or higher if the substation is not effectively shielded.

Step 3. Tentatively select arrester class and voltage rating.

A station-class surge arrester has to be selected since this is the only type available at this voltage level. The substation size and importance may indicate a station-class arrester regardless of system voltage. Arrester voltage rating has to be at least 181 kV, as determined in Step 1. Another rule of thumb recommends that the arrester voltage rating be not less than 125 percent of the voltage to ground when the system is operating at maximum system voltage:

$$1.25 * 1.05 * 230 \text{ kV} / \sqrt{3} = 174 \text{ kV}$$

The next standard arrester rating above 174 kV and 181 kV is 192 kV (note, Table 10 shows standard arrester voltage ratings). Therefore, 192 kV is selected as the tentative arrester rating.

Step 4. Determine the impulse and switching surge protective levels of the tentatively selected arrester.

For example, the typical surge arrester characteristics are obtained from the arrester manufacturer's published data. These characteristics include,

- Maximum sparkover (S.O.) on front of wave;
- Maximum S.O. on full wave of 1.2 x 50 µs;
- Maximum S.O. on switching surge (S.S.),
- Maximum discharge voltage for 5, 10, and 20 kA of discharge current; and
- Minimum S.O. on 60 Hz voltage.

Calculate the maximum theoretical surge voltages that could appear at the insulation to be protected. These will depend on many factors, such as effectiveness of shielding, number of lines normally connected, and relative location of an arrester to protected equipment. For most applications, it is sufficient to rely on the recommended minimum margins between protection levels provided by the surge arrester and the BIL of the protected equipment.

Calculate the minimum permissible withstand strength of the insulation to be protected. The necessary information may be obtained from manufacturers of the equipment. Approximate information may be obtained from applicable standards on the type of equipment.

The impulse withstand strength of equipment is defined by its full-wave impulse test voltage using a standard 1.2 x 50 µs wave. The strength is greater for shorter duration voltage peaks. See Figure 4 for curves showing withstand strength of a power transformer over the range of zero to 5,000 µs.

Step 5. Evaluate Insulation Coordination

Front of Wave	20 percent
Maximum discharge	20 percent
Maximum switching surge	15 percent

See Figure 4 for the coordination of surge arrester protective levels with 230 kV transformer BIL. Possible BILs of 900, 825, 750, and 650 kV are shown. All BILs are adequately protected from impulses or switching surges. However, other factors have to be considered such as 60 Hz withstand, both internal and external; future deterioration of the insulation; surge arrester location with respect to the transformer; etc. A BIL of 750 kV would appear to be a proper choice based on the conditions assumed. The surge arrester voltage rating of 192 kV is a proper selection unless there are unusual system conditions that could subject the arrester to voltages above its rating.

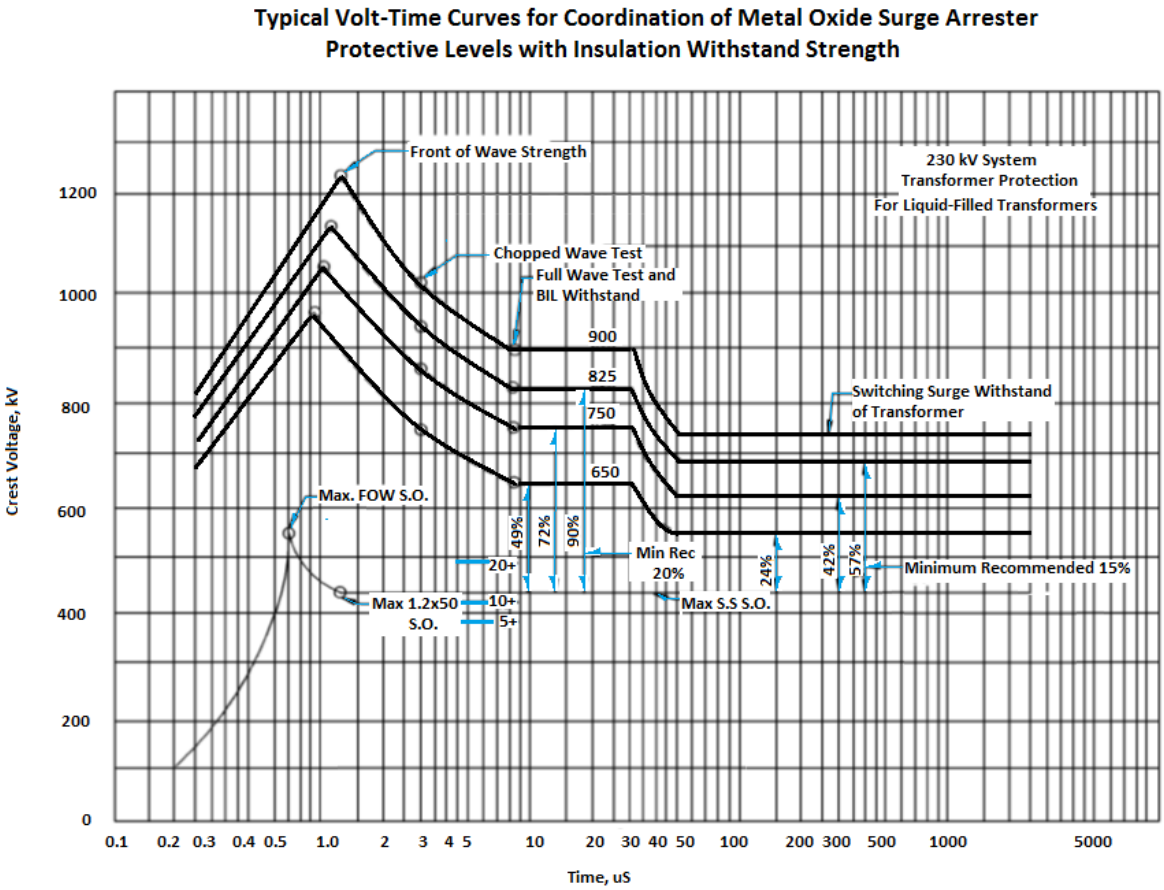


Figure 4

When coordination cannot be achieved, the solution may be to select a different arrester, improve arrester location relative to protected equipment, increase the insulation level of protected equipment, improve shielding, or install additional arresters.

Step 6. When the transformer high-voltage side arrester has been chosen, compare the rating on a per unit basis to the arrester rating for the low-voltage winding.

The arrester applied to the low voltage of a transformer should have a rating slightly higher than the rating of the high-voltage winding. An impulse that hits the high-voltage winding will also be transformed to the low-voltage winding via the transformer turns ratio with the corresponding voltage and current. If the energy is discharged through the low-voltage winding arresters, the current discharged through the low-voltage winding arresters will be the transformer turns ratio times the high-voltage arrester discharge current. Make sure that energy will discharge through the high-voltage winding arresters before it will discharge through the low-voltage winding arresters.

Metal Oxide Surge Arresters

Metal oxide arresters were developed after the application of silicon-carbide valve arresters to electric power systems. The primary component of the arrester that differentiates metal oxide arresters from the previous arresters is the zinc oxide valve that has significantly greater non-linear volt – current characteristics as compared to previous devices. The zinc oxide valve operates more closely to that of a zener diode that is applied in the electronic industry. The valve is capable of being applied without any gaps in the design, eliminating the sparkover characteristic of previous arresters as it eases into conduction. The zinc oxide valve typically provides lower discharge voltages than available with previous designs.

Types of Metal Oxide Surge Arresters
In addition to the silicon-carbide station, intermediate, and distribution classes of arresters, development of the metal oxide arrester has produced three basic categories of arresters. These categories are known as the gapless, shunt-gapped, and series-gapped metal oxide arresters.

Gapless Metal Oxide Surge Arrester consists of a stack or multiple stacks of metal oxide disks. Above the MCOV rating, the arrester exhibits a very non-linear behavior. This arrester is applied directly to the line terminal and ground with only its inherent impedance limiting the amount of leakage current through the arrester.

Shunt-Gapped Metal Oxide Surge Arresters consist of a stack of metal oxide disks that are bridged by shunt gaps. When the disks start to conduct current upon the arrival of a surge, the discharge voltage will increase to the point where the gaps will spark over and short the associated disks. The sparkover of the gaps, typically at several hundred amps, has the effect of reducing the discharge voltage of the arrester. A decrease in the amount of discharge current will eventually extinguish the gap current, causing the voltage to increase to its initial curve.

The *series-gapped metal oxide arresters* use fewer disks in series with a series gap impedance network. As the arrester starts to conduct, the voltage is divided between the disks and the gap network. When the voltage across the gapped impedance network increases to the point the gap sparks over, the voltage is reduced across the total arrester to be that which is across the metal oxide disks.

The application of metal oxide surge arresters is similar to the application of silicon-carbide arresters in terms of the system information that is required. The system parameters of the maximum system operating voltage and temporary overvoltages are of primary importance in the application of this type of arrester. The discharge current levels are also important to the application of this arrester.

Operating Conditions

Usual operating conditions for surge arresters include continuous air temperature ratings between –40C and +40C with maximum air temperatures of +60C at elevations less than 6,000 ft. Unusual operating considerations could include operation in enclosed areas or in areas contaminated by gas fumes or external air contamination. Confirm special operating conditions with the manufacturer before the applications are made.

Maximum Phase-to-Ground Voltage

Metal oxide arresters are applied primarily based on the MCOV. Metal oxide arresters have been assigned dual voltage ratings based on the conventional duty-cycle rating and the newer MCOV rating (see Table 10). Of primary importance is the requirement that the MCOV of the applied arrester be above the maximum continuous operating voltage of the electric system. For a solidly grounded system with the maximum operating allowance of 5 percent, the minimum MCOV is calculated using this equation,

$$\mathbf{MCOV_{Min}} = \boldsymbol{E_{LL}} * \frac{\mathbf{k}}{\sqrt{\mathbf{3}}}$$

Where:
E_{LL}= Voltage, Line-to-Line, kV.
k = Percentage of operating voltage allowance over the nominal operating voltage

For a 34.5 kV nominal voltage solidly grounded system with a 5 percent maximum operating voltage allowance, the MCOV is calculated as follows:

$$34.5 \text{ kV} * 1.05 / 3 = 21 \text{ kV}$$

According to Table 10, the nearest MCOV rating above this value is 22 kV. This would be the minimum rating of the arrester to receive consideration.

The application of arresters on ungrounded or impedance-grounded systems is normally applied on the basis of their associated duty-cycle rating. Using the arresters on the basis of 100 percent voltage application, the minimum duty-cycle rating for the arresters on an ungrounded system will be the maximum anticipated operating line-to-line voltage. For a 34.5 kV nominal voltage impedance-grounded or ungrounded system with a 5 percent maximum operating voltage allowance, the duty-cycle rating is calculated as follows:

$$\textbf{Rating} = \mathbf{E_{LL}} * \mathbf{k}$$

Where:
E_{LL}= Voltage, Line-to-Line, kV
k = Percentage of operating voltage allowance over the nominal operating voltage

For a 34.5 kV system,

$$34.5 \text{ kV} * 1.05 = 36.2 \text{ kV}$$

According to Table 10, the next highest duty-cycle voltage rating for the arrester is 39 kV. The corresponding MCOV for this arrester is 31.5 kV. With this MCOV rating, the arrester will move into conduction should one of the phases be grounded or be faulted. It then becomes a judgment of the engineer to assess the amount of time the arrester will be required to conduct under these conditions. Applying a metal oxide arrester under these conditions will make use of the inherent improved temporary overvoltage capabilities of the devices. Follow the manufacturer's recommendations regarding the extent of overvoltage capabilities for a particular arrester when applying arresters on this basis.

In addition to the MCOV, any temporary operating voltages above the MCOV have to be considered for magnitude and duration. These conditions may arise due to conditions that include line-to-ground fault conditions, loss of neutral on a normally grounded system, sudden load rejection, oscillations due to system resonance, switching surges, switching conditions, etc.

Evaluate each of the conditions resulting in temporary overvoltage in terms of the effect it has on the system. The magnitude and duration of the overvoltage will assist in determining the proper application of the arresters. Metal oxide arresters have a significantly improved ability to operate during temporary overvoltages. Manufacturers typically publish curves, similar to the one shown in Figure 5-39, to indicate the magnitudes and durations of overvoltages under which the arresters will successfully operate. Apply the arresters within the limitations the manufacturer recommends for acceptable overvoltage within the manufacturer's specified time limits.

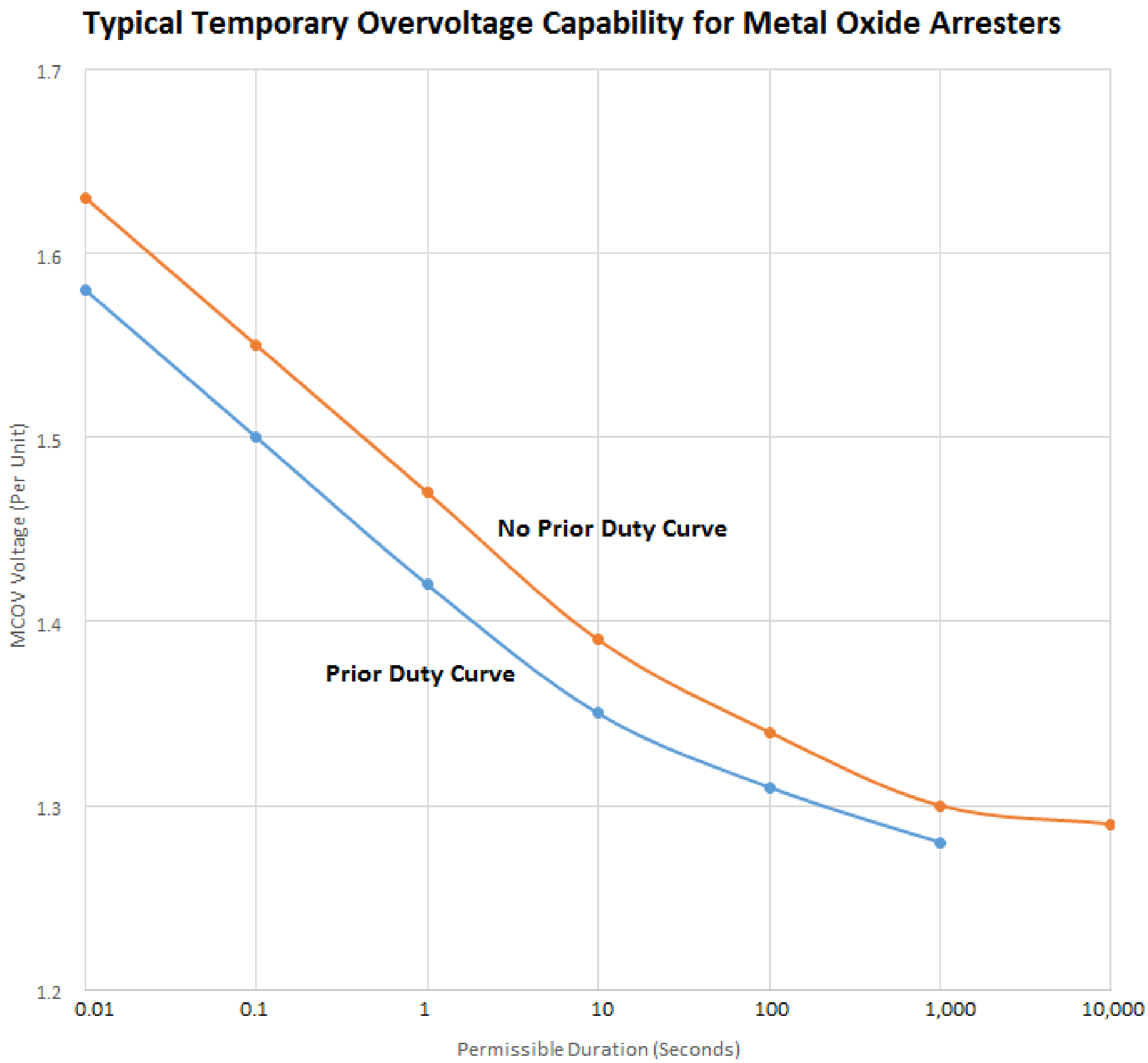


Figure 5

Temporary overvoltages are most often associated with the overvoltages experienced by the un-faulted phases during a phase-to-ground fault. These overvoltages are determined in the same way as for silicon-carbide arresters. Other overvoltage conditions on higher voltage lines may require transient network analysis or similar studies to determine the actual parameters that are required.

Arrester Discharge Currents

The magnitude of discharge current is largely determined by the effectiveness of the shielding against direct lightning strokes. Discharge currents of 5 kA to 20 kA are commonly used to calculate the maximum discharge voltage.

Switching surges are seldom a consideration below 345 kV. Accurate determination of surge withstand capabilities will require a transient network analysis or electromagnetic transient study to be performed. These studies can simulate the transmission system elements, including the arresters, determine the surge levels that are expected, and size the surge arresters based on the energy absorption characteristics of the arresters. Approximations of the surge currents can be made using the following equation,

$$\mathbf{I_A = \frac{E_S - E_A}{Z}}$$

Where:
I_A = Surge current (amps)
E_s = Surge voltage (volts)
E_A = Discharge voltage (volts)
Z = Line surge impedance (ohms)

Arrester Discharge Energy
Arrester discharge energy is estimated using this equation,

$$\mathbf{J = 2 * L * E_A * I_A / c}$$

Where:
J = Discharge Energy, kilojoules.
L = Distance of the transmission line
c = Speed of light at 186 miles per µs.

Values of the surge current or the energy may be compared to the manufacturer's data regarding the surge discharge capability of the arresters.

Insulation Coordination
BILs, BSLs, and CWW levels for equipment are obtained from the equipment standards. Procedures for establishing the coordination are previously given for silicon-carbide arresters.

Typical characteristics collected include the front of wave value at 0.5 µs, the maximum switching surge protective level, and maximum discharge voltages at 5 kA, 10 kA, and 20 kA. Since the metal oxide arresters have no sparkover, the front-of-wave value is used in place of the sparkover value.

Acceptable protective margins are considered to be similar to the silicon-carbide protective levels. Generally accepted practice is to provide a 20 percent margin between the *transformer front of wave* (TFOW) strength and the arrester front of wave rating based on the *arrester front of wave rating* (AFOW), a 20 percent margin between the BIL withstand rating (BIL) and the arrester *lightning protective level* (LPL), and a 15 percent margin between the transformer switching surge withstand (BSL) and the *arrester surge protective level (*SPL). The switching surge withstand strength of the transformer insulation is usually specified at 83 percent of impulse BIL. These ratings are summarized as follows:

TFOW / AFOW	= 1.20
BIL / LPL	= 1.20
BSL / SPL	= 1.15

Direct Stroke Shielding

This topic is covered under the application for silicon-carbide arresters.

Multiple Lines

This topic is covered under the application for silicon-carbide arresters.

Standards

There are two principal national standards pertaining to metal oxide valve surge arresters: IEEE C62.11 and IEEE 62.22.

IEEE C62.11, "IEEE Standard for Metal-Oxide Surge Arresters for Alternating Current Power Circuits." This standard contains basic information on arresters such as definitions, service conditions, classification and voltage ratings, performance characteristics and tests, test procedures, design tests, conformance tests, and construction.

IEEE Std. C62.22, "Guide for the Application of Metal-Oxide Surge Arresters for Alternating-Current Systems." This standard is an excellent guide to the basic application of metal oxide arresters in electric substations. It contains information on general procedures, systematic procedures for protection of transformers and substation equipment, and protection of other equipment such as dry-type insulation, shunt capacitor banks, underground cables, gas-insulated substations, and rotating machines. Of particular interest is the Typical Voltage–Time Curve for Coordination of Arrester Protective Levels with Insulation Withstand Strength for liquid-Filled Transformers (See Figure 6).

Typical Volt-Time Curve for Coordination of Arrester Protective Levels with Insulation Withstand Strengty for Liquid Filled Transformers

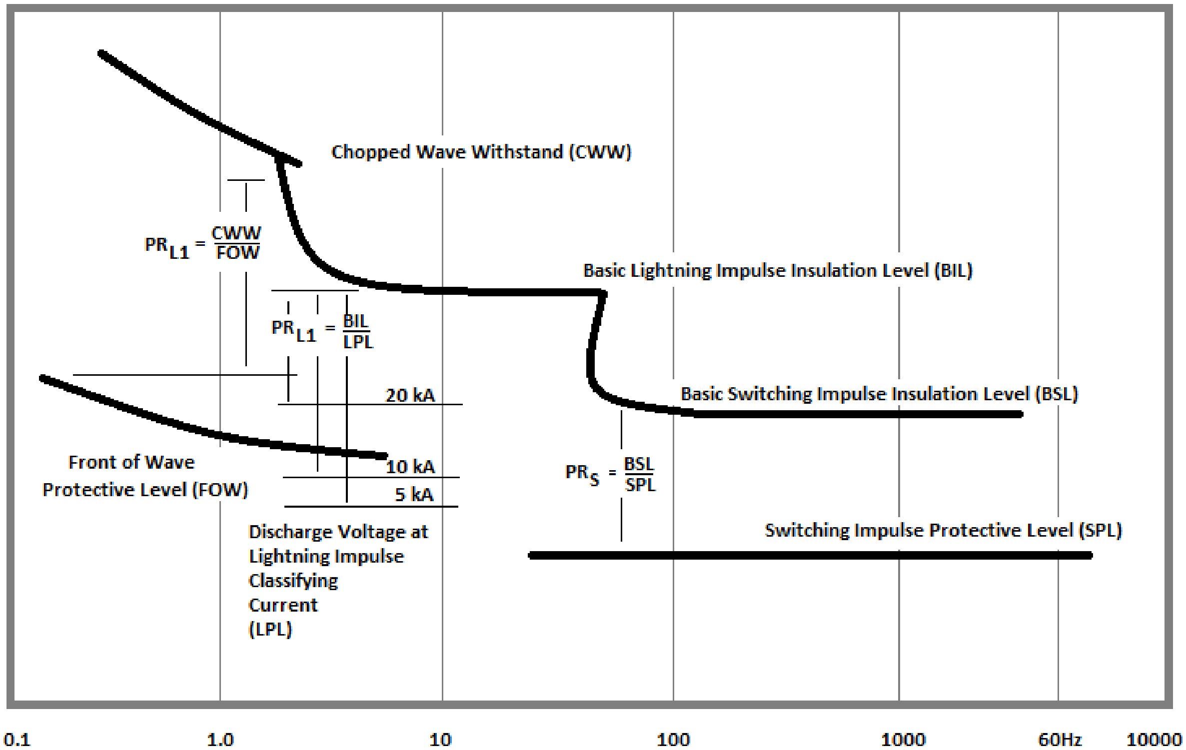


Figure 6

Guide for the Application of Metal Oxide Surge Arresters

An example of surge arrester selection will be worked out along with each guide step to illustrate the procedure. The example is arrester selection for a 230 kV substation coordinated with the transformer BIL. The 230 kV substation is supplied by one 230 kV line. Both the substation and the line are effectively shielded. This is the same example used with the silicon-carbide arresters.

The conditions are as indicated as follows:

$E_{LL\ (MAX)} = 242$ kV
$E_{LG(MAX)} = 140$ kV

Coefficient of grounding (COG),

$R_1 = R_2 = 0.1 *X_1$,
$R_0/X_1 = 0.8$
$X_0/X_1 = 2.5$
COG = 75%

$E_{LG(MAX\ TOV)} = 181$ kV for less than 1 sec during fault conditions (242 * 0.75 = 181)

Possible transformer BILs to investigate (kV): 900, 825, 750, 650
Impulse currents to consider (kA): 5, 10, 20
Switching surge: Not applicable for transformer

Minimum MCOV rating for the application is 140 kV equal to the $E_{LG(MAX).}$ Table 10 indicates this rating is a standard rating and, as such, is chosen as the initial MCOV rating for the arrester.

The *temporary overvoltage* (TOV) is a maximum line-to-ground voltage of 181 kV for less than one second. The TOV is evaluated to determine if adjustments are to be made to the arrester selection. The per unit applied voltage based on the MCOV rating is 181/140 = 1.29. Figure 5 indicates that 1.29 per unit voltage may be applied to the arrester for more than 100 seconds. The magnitude and duration of the TOV do not warrant increasing the MCOV rating of the arrester.

Figure 7 indicates the insulation coordination for the 230 kV transformer protected with a typical metal oxide arrester. The protection curves for the selected transformer BILs are plotted along with the applicable points for the 140 kV MCOV arrester. The discharge current voltage levels and the switching surge voltage levels are indicated. The protective margins for the BILs and the surge levels are indicated. The protective ratios realized by the protective levels of the arrester substantially exceed the recommended ratios of 20 percent for the front-of-wave and lightning impulse levels, and 15 percent for the switching surge level.

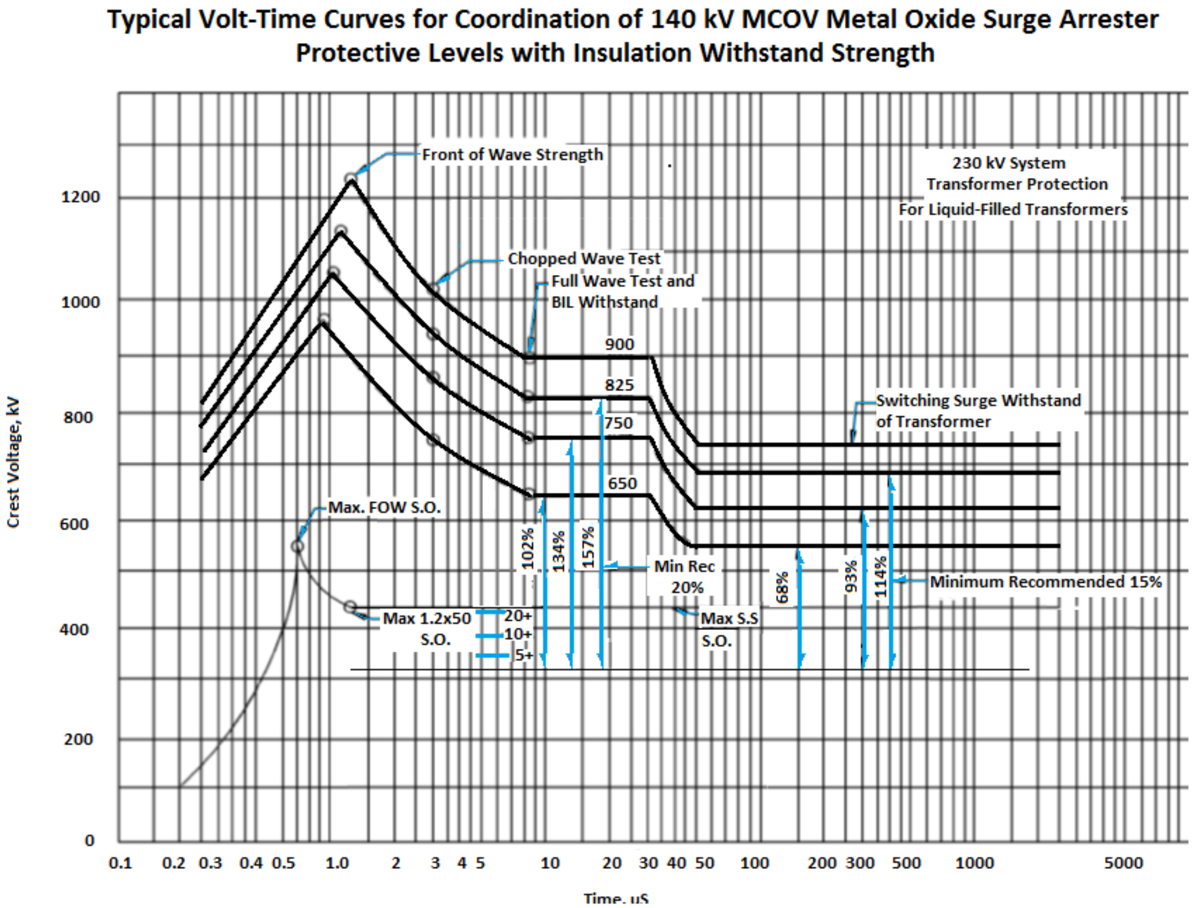


Figure 7

Figure 8 shows curves for a 152 kV MCOV surge arrester with a corresponding duty-cycle rating of 192 kV, the same as the example used for the silicon-carbide arrester. The protective ratios realized by the protective levels of the arrester substantially exceed the recommended ratios of 20 percent for the front-of-wave and lightning impulse levels, and 15 percent for the switching surge level.

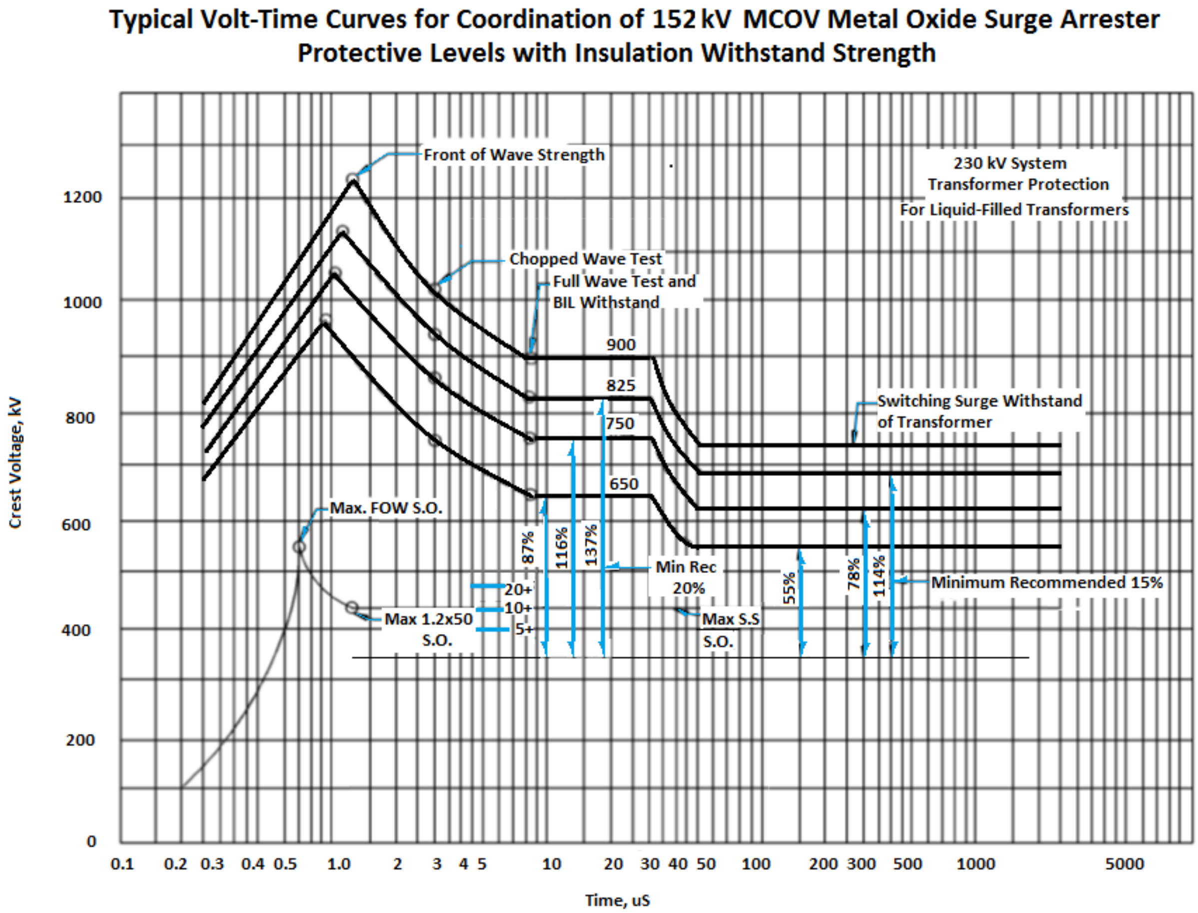


Figure 8

Substantial improvement in protective margins is realized with the use of metal oxide arresters. Protection provided by two ratings of arresters is shown: 192 kV, which corresponds to the arrester rating in Figure 5, and a 172 kV arrester, which corresponds to an MCOV rating of 140 kV, the minimum recommended rating for the 230 kV voltage class.

Location

In general, surge arresters should be located at or near the main transformers on both the high- and low-voltage sides. It may be desirable to also locate arresters at the line entrances or, in some cases, on a bus that may be connected to several lines. They should be located to give maximum possible protection to all major substation equipment. In many cases, the arresters protecting the main transformer may be mounted directly on the transformer.

Lightning strokes can produce surges with steep wave fronts, voltage gradients, reflections, or oscillations and high rates of rise of current, which can result in large differences in the line-to-ground voltage between even closely spaced points. It is extremely important to locate the arresters as close as practical to the apparatus requiring protection. The arrester lead length should be kept as short as practical. If possible, the arrester should be connected directly to the jumper connecting the equipment to the system. Following is a general guide for determining maximum separation distances between arrester lead tap and transformer, considering the effect of arrester lead length.

Arrester Separation Distance and Lead Length

The voltage impressed on the substation transformer after arrester operation may be much higher than the arrester discharge voltage if either arrester separation distance (S) or lead length (L) is excessive. Consequently, these factors have to always be considered in applying arresters. Application curves have been developed to facilitate this.

Arrester separation distance (S) is defined as the distance from the line arrester lead junction to the transformer bushing. Voltage reflections result when the discharge voltage traveling as a wave arrives at the transformer. If the arrester is very close to the transformer, these reflections are cancelled almost instantaneously by opposite polarity reflections from the arrester. As the separation distance increases, the cancellation becomes less and less effective, and the voltage at the transformer may increase to almost twice the arrester discharge voltage.

Arrester lead length (L) is defined as the total length of the conductor from the junction of the surge arrester lead with the line or transformer circuit to physical ground, but not including the length of the arrester itself. When the arrester discharges, surge current flows to ground over the lead length. The resulting voltage drop proportional to the lead length and adds to the arrester discharge voltage.

Special Situations

On smaller substations with high-side fuses, the arrester should be located on the line side of the fuse so as to prevent the lightning discharge from passing through the fuse.

Arresters need not be installed on the line side of high-voltage air-break switches. However, they should be connected close enough to protect the switch adequately when the switch is closed. Line entrance gaps may be used on the line side for protection when the switch is open.

Arresters of the valve type may be installed on the low-voltage distribution bus. They should be installed on the load side of the feeder overcurrent device (recloser, fuse, or circuit breaker) and any related disconnecting switch.

Continuous metallic sheath cables from substation to overhead lines should be protected by arresters at the junction, and should be grounded effectively at the base of the cable terminal structure and directly to the cable sheath. If the overhead line is unshielded, additional protective devices may be required a few spans before the junction.

The cable sheath should be bonded to the substation ground at the substation end. It may also be necessary to install arresters at the substation equipment end if the cable is such that two times the protection level of the junction arrester exceeds 80 percent of the substation BIL. This is due to reflection at the equipment end.

On high-voltage wye-connected transformers with ungrounded neutral, voltage reflections at the neutral can approach two times the voltage applied simultaneously at the line terminals. It is therefore necessary to employ a surge arrester from neutral to ground to limit these surge voltages, especially if the transformer has graded insulation. The rating of the arrester should be approximately 1.2 times the normal line-to-neutral system voltage.

Protection at Line Entrances

Lightning wave fronts may approach 1000 kV/μs, resulting in a gradient of 1.0 kV/ft difference in line to-ground potential. Most, however, do not exceed 500 kV/μs, and this value is considered a basis for good practice. At open circuit points, these waves are reflected back at nearly double the original rate of rise, increasing the possibility of a flashover or equipment damage close to that point. It is apparent that protection should be considered for the line entrances on large substations, especially where line breakers and disconnect switches may be open, constituting dead-end reflections. Surge arresters will provide the most effective means of protection, but line entrance gaps may be sufficient. Line entrance protective gaps may be considered as an economical alternative to surge arresters at substation entrances of all overhead lines 23 kV and above to provide additional protection for substation insulation under the following conditions:

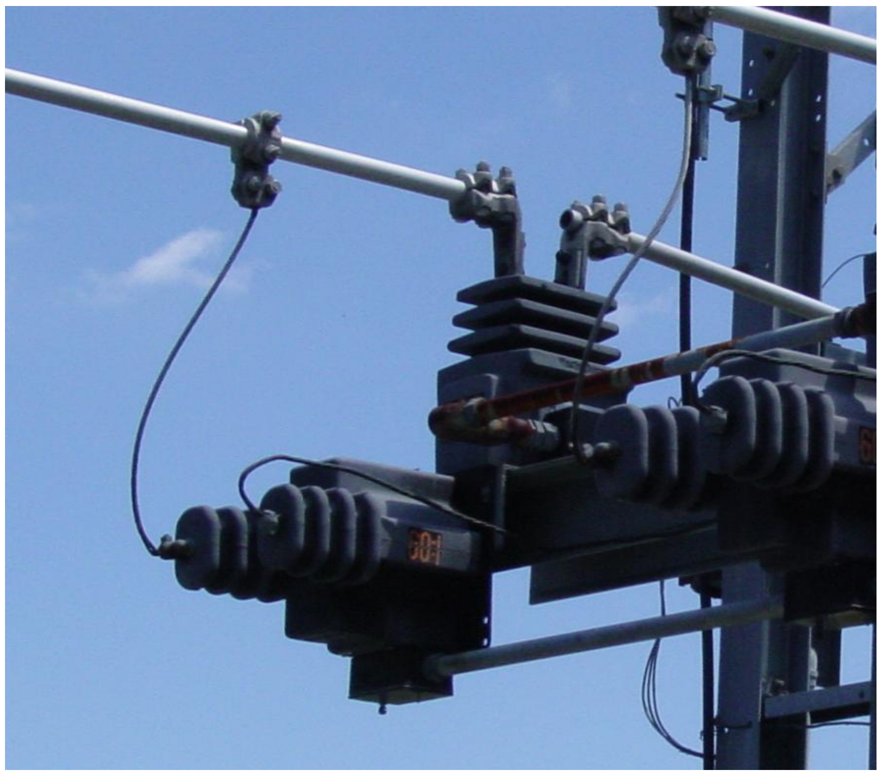
1. When steep front incoming surges would break down insulation near the line entrance or on the bus (station arresters may be far too distant to provide adequate protection);
2. When part of the station insulation is isolated from protective influence of the station arresters by switching; and
3. When the station arrester has been damaged or otherwise removed from service so that its protection is not available

Note that the operation of a gap places a fault on the system that has to be cleared by a circuit breaker, recloser, or fuse, remote from the line end in question. The engineer, along with operations personnel, should evaluate the suitability of this type of operation.

Chapter 3
Instrument Transformers

This chapter discusses current and inductively coupled voltage transformers of types generally used in the measurement of electricity and in the control of equipment associated with the transmission and distribution of alternating current.

The primary function of an *instrument transformer* is defined as a transformer that is intended to reproduce in its secondary circuit, in a definite and known proportion, the current or voltage of its primary circuit with the phase relations substantially preserved. Instrument transformers also provide insulation between the primary and secondary circuits and thus simplify the construction of measuring devices and provide safety for personnel using those devices.



Occasionally, instrument transformers serve another duty as bus supports, especially at the higher voltages where the cost of extra bus supports becomes significant. The manufacturer should always be consulted in such applications to determine what externally applied forces the product can withstand.

If necessary, a voltage transformer may be used for supplying power rather than for measurement. In such situations, it is usually possible to place burdens higher than the volt-ampere rating on the secondary circuit without excessive heating and consequent shortening of life. The limit of such burden is known as the *Thermal Burden Rating*, which is the volt-ampere output that the transformer will supply continuously at rated secondary voltage without causing the specified temperature limits to be exceeded. The voltage transformer's accuracy of transformation will not be maintained for this type of use.

The primary national standard applicable to current and voltage transformers is ANSI/IEEE Std. C57.13, "IEEE Standard Requirements for Instrument Transformers." This standard covers all-important aspects, including terminology, general requirements, ratings, burdens, accuracy, construction, and test code.

Service Conditions

The standard ratings of instrument transformers are based on operation at the thermal rating of the instrument transformer for defined ambient temperature conditions provided the altitude does not exceed 3,300 feet. Instrument transformers may be used at higher ambient temperatures, at altitudes higher than 3,300 feet, or for other unusual conditions if the effects on performance are considered. Consult the manufacturer for specific applications.

Altitude

Table 12 in shows the altitude correction factors to be used to account for the adverse effect of decreased air density on the insulation withstand capability.

Table 12
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

These correction factors modify the standard insulation classes shown in Table 13. A higher standard BIL may be required at high altitudes in order to obtain the insulation required for the voltage used. The decreased air density at higher altitudes also affects heat dissipation and the permissible loading on instrument transformers. Current transformers may be operated at altitudes greater than 3,300 feet if the current is reduced below rated current by 0.3 percent for each 325 feet the altitude exceeds 3,300 feet.

Table 13
Current Transformer
BIL and Dielectric Tests

Max System Voltage (kV)	Nominal System Voltage (kV)	BIL & Full Wave Crest (kV)	Chopped Wave Min time to Crest Flashover		Power Frequency Applied Voltage test (kV/RMS)	Wet 60 Hz 10sec Withstand (kV/RMS)	Min Creepage Distance (in)
			(kV)	(µs)			
0.66	.6	10	12	-	4	-	-
1.2	1.2	30	36	1.5	10	6	-
2.75	2.4	45	54	1.5	15	13	-
5.6	5	60	69	1.5	19	20	-
9.52	8.7	75	88	1.6	26	24	-
15.5	15	95	110	1.8	34	30	-
15.5	15	110	130	2	34	34	11
25.5	25	125	145	2.25	40	36	15
25.5	25	150	175	3	50	50	17
36.5	34.5	200	230	3	70	70	26
48.3	46	250	290	3	95	95	35
72.5	69	350	400	3	140	140	48
121	115	450	520	3	185	185	66
121	115	550	630	3	230	230	79
145	138	650	750	3	275	275	92
169	161	750	865	3	325	315	114
242	230	900	1035	3	395	350	140
242	230	1050	1210	3	460	445	170
362	345	1300	1500	3	575	-	205
550	500	1675	1925	3	575	-	318
550	500	1800	2070	3	800	-	318
800	765	2050	2360	3	920	-	442

Temperature

Table 14 provides the limits of temperature rise for instrument transformers, including the average winding temperature and hottest-spot winding temperature rises.

For 30C average ambient temperature conditions, the temperature of the cooling air (ambient temperature) does not exceed 40C, and the average temperature of the cooling air for any 24-hour period does not exceed 30C.

Instrument transformers may also be rated for 55C ambient temperature for use inside enclosed switchgear, provided the ambient temperature of the cooling air on the inside of enclosed switchgear does not exceed 55C.

Table 14
Instrument Transformers Temperature Limits

Type of Instrument Transformer	30C Ambient		55C Ambient	
	Average Winding Temperature Rise	Hot Spot Winding Temperature Rise	Average Winding Temperature Rise	Hot Spot Winding Temperature Rise
55C	55C	65C	30C	40C
65C	65C	80C	40C	55C
80C (Dry-Type)	80C	110C	55C	85C

Current transformers designed for 55C temperature rise above 30C ambient temperatures are given a *continuous-thermal-current rating factor* (RF). The RF is multiplied by the rated current to indicate the current that can be carried continuously without exceeding the standard temperature limitations. Figure 9 shows the permissible loading for given average cooling air temperatures and RFs. As an example, a current transformer with an RF of 1.5 could be used at 150 percent of rated current at 30C average ambient temperature and 100 percent at 60C average ambient temperature without exceeding the temperature limitations of the current transformer. Voltage transformers can be operated at higher ambient temperatures only after consultation with the manufacturer.

55C Rise Current Transformer Basic Loading Characteristics

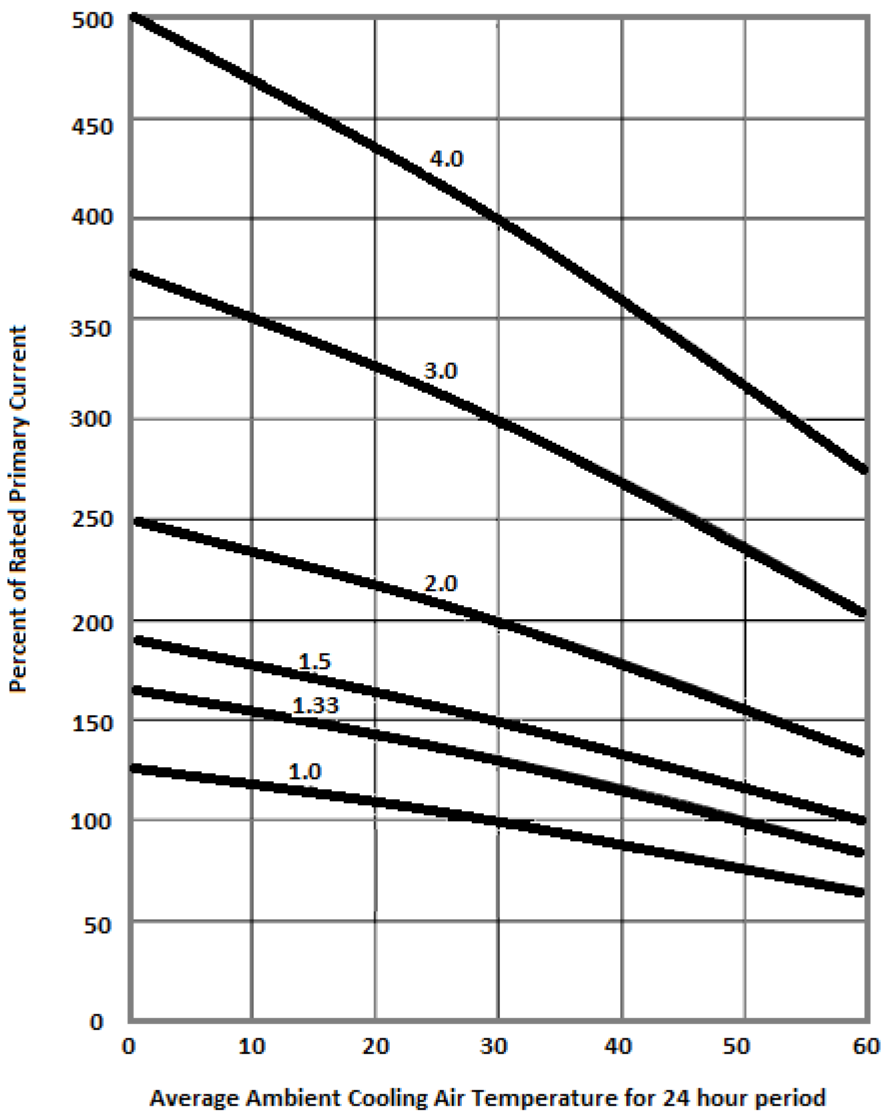


Figure 9

Accuracy

To be a useful part of a measurement system, instrument transformers have to change the magnitude of the voltage or current that is being measured without introducing any unknown errors of measurement into the system. The accuracy of transformation should, therefore, be either a known value so that the errors can be included in the computation of the overall measurement, or the errors have to be within the limits of a specified small value so they may be disregarded.

The accuracy obtainable with an instrument transformer depends on its design, circuit conditions, and the burden imposed on the secondary. Accuracy is measured in terms of its true value and phase angle under specified operating conditions.

Accuracy Classes for Metering Service

Accuracy classes for metering service have been established that limit the *transformer correction factor* (TCF) to specified values when the metered load has a power factor of 0.6 lagging to 1.0. The standard accuracy classes for metering service and corresponding TCF limits for current and voltage transformers are shown in Table 15.

Table 15
Accuracy Class for Metering and Correction Factors

Metering Accuracy Class	**Voltage Transformers (Rated Voltage)**		**Current Transformers**			
			100% Rated Current		**10% Rated Current**	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**
0.3	0.997	1.003	0.997	1.003	0.994	1.006
0.6	0.994	1.006	0.994	1.006	0.988	1.012
1.2	0.988	1.012	0.988	1.012	0.976	1.024

The *transformer correction factor* for a current or voltage transformer is the *ratio correction factor* (RCF) multiplied by the phase angle correction factor for a specified primary circuit power factor.

The *ratio correction factor* is the ratio of the true ratio to the marked ratio.

The *phase angle correction factor* is the ratio of the true power factor to the measured power factor. It is a function of both the phase angles of the instrument transformers and the power factor of the primary circuit being measured. The phase angle correction factor corrects for the phase displacement of the secondary current or voltage, or both, due to the instrument transformer phase angles. Phase angle of an instrument transformer is the phase displacement, in minutes, between the primary and secondary values.

Secondary Burdens

The *burden* for an instrument transformer is that property of the circuit connected to the secondary winding that determines the active and reactive power at the secondary terminals. The burden is expressed either as total ohms impedance with the effective resistance and reactive components, or as the total volt-amperes and power factor at the specified value of current or voltage, and frequency.

The burden on the secondary circuit of an instrument transformer affects the accuracy of the device. Accordingly, the burdens of the various meters and other instruments on the secondary have to be known. This information is usually obtained from data sheets issued by the manufacturers.

For many purposes, such as when the burdens are known to be well within the rated burden capability of the transformer, or when accuracy is not a concern, it is sufficient to add arithmetically the volt-ampere burden of the individual devices. If the burden is expressed as an impedance value, the volt-ampere burden can be calculated from the relationship expressed in by,

$$\mathbf{VA = E^2 / Z_b}$$

Where:
E = Voltage drop across the burden
Z_b = Burden impedance

For more accurate purposes, and when the actual burdens approach the limits of the burden rating, the total burden should be determined by adding the individual burdens vectorially (taking power factors into account).

Construction

All instrument transformers have external terminals or leads to which the high-voltage or primary circuit and the secondary circuits are connected. These terminals are marked to indicate the polarity of the windings.

When letters are used to indicate polarity, the letter H shall be used to distinguish the terminals of the primary winding. The letters X, Y, Z, W, V, and U are used to identify the terminals of up to six secondary windings, respectively. In addition to the letters, each terminal is numbered (e.g., H1, H2, X1, X2). Letters followed by the same number are of the same polarity.

If multiple primary windings are provided, the H terminals are numbered with consecutive pairs of numbers (H1-H2, H3-H4, etc.). The odd-numbered terminals are of the same polarity. When taps are provided in the secondary windings, the terminals of each winding are numbered consecutively (X1, X2, X3, etc.). The lowest and highest numbered terminals indicate the full winding with intermediate numbers indicating the taps. When the X1 terminals are not in use, the lower number of the two terminals used is the polarity terminal.

Current Transformers

A current transformer is an instrument transformer intended to have its primary winding connected in series with the conductor carrying the current to be measured or controlled. The ratio of primary to secondary current is roughly inversely proportional to the ratio of primary to secondary turns and is usually arranged to produce either five amperes or one ampere (IEC Standard) in the full tap of the secondary winding when rated current is flowing in the primary.

Current transformers can be included in two general categories: *metering service* and *relay service*. As a rule, current transformers designed for metering service should not be used for relay applications or system protection. Likewise, current transformers designed for relay service should not be used for high-accuracy metering applications.

Current transformers designed for relay service are fabricated with large cores, which allows the current transformer to replicate the primary current during fault (high primary current) conditions. The large core requires a high exciting current, which limits the accuracy of the current transformer, especially for low primary currents.

Current transformers designed for metering service have smaller cores with small or negligible exciting currents, which enables the current transformer to be highly accurate at normal load currents. However, the smaller core saturates (secondary current is not a replica of the primary current) at currents slightly above rated current. A current transformer designed for metering service may not reliably operate protective devices during fault conditions.

Current transformers can be supplied with single-ratio, dual-ratio, or multi-ratio secondary windings. A multi-ratio current transformer is one from which more than one ratio can be obtained by the use of taps on the secondary winding.

Types

Various types of current transformers are available.

A *bar-type current transformer* is one that has a fixed, insulated straight conductor in the form of a bar, rod, or tube that is a single primary turn passing through the magnetic circuit and that is assembled to the secondary, core, and winding.

A *bushing-type current transformer* is one that has a round core and a secondary winding insulated from and permanently assembled on the core but has no primary winding or insulation for a primary winding. This type of current transformer is for use with a fully insulated conductor as the primary winding.

A *double-secondary current transformer* is one that has secondary coils each on a separate magnetic circuit with both magnetic circuits excited by the same primary winding. *Multiple-secondary* (three or more) current transformers are also manufactured.

A *window- or donut-type current transformer* is one that has a secondary winding insulated from and permanently assembled on the core, but has no primary winding as an integral part of the structure. Complete or partial insulation is provided for a primary winding in the window through which one or more turns of the line conductor can be threaded to provide the primary winding.

A wound-type current transformer is one that has a fixed primary winding mechanically encircling the core; it may have one or more primary turns. The primary and secondary windings are completely insulated and permanently assembled on the core as an integral structure.

Other types are available in addition to those listed. Descriptions can be found in manufacturers' literature.

Ratings

Ratings are used to specify the operating characteristics and construction of the current transformer. The following paragraphs provide the terms used to express the ratings for current transformers. Basic impulse insulation levels (BILs) in terms of full wave test voltages, nominal system voltages, and maximum line-to-ground system voltages are shown in Table 13. Current ratings are shown in Table 16 (for other than bushing type) and Table 17 (multi-ratio bushing type).

Table 16
Current Transformers
Ratings for One or Two Ratios

Single Ratio		Current Ratings (Amps)	
		Double Ratio with Series-Parallel Primay Windings	Double Ratio with Taps in Secondary Widning
10:5	800:5	25 x 50:5	25 / 50:5
15:5	1200:5	50 x 100:5	50 / 100:5
25:5	1500:5	100 x 200:5	100 / 200:5
40:5	2000:5	200 x 400:5	200 / 400:5
50:5	3000:5	400 x 800:5	300 / 600:5
75:5	4000:5	600 x 1200:5	400 / 800:5
100:5	5000:5	1000 x 2000:5	600 / 1200:5
200:5	6000:5	2000 x 4000:5	1000 / 2000:5
300:5	8000:5	-	1500 / 3000:5
400:5	12000:5	-	2000 / 4000:5

Table 17
Multi-Ratio Current Transformers

Current Rating (amps)	Secondary Taps	Current Rating (amps)	Secondary Taps
600:5		3000:5	
50:5	X2-X3	300:5	X3-X4
100:5	X1-X2	500:5	X4-X5
150:5	X1-X3	800:5	X3-X5
200:5	X4-X5	1000:5	X1-X2
250:5	X3-X4	1200:5	X2-X3
300:5	X2-X4	1500:5	X2-X4
400:5	X1-X4	2000:5	X2-X5
450:5	X3-X5	2200:5	X1-X3
500:5	X2-X5	2500:5	X1-X4
600:5	X1-X5	3000:5	X1-X5
1200:5		4000:5	
100:5	X2-X3		
200:5	X1-X2	500:5	X1-X2
300:5	X1-X3	1000:5	X3-X4
400:5	X4-X5	1500:5	X2-X3
500:5	X3-X4	2000:5	X1-X3
600:5	X2-X4	2500:5	X2-X4
800:5	X1-X4	3000:5	X1-X4
900:5	X3-X5	3500:5	X2-X5
1000:5	X2-X5	4000:5	X1-X5
1200:5	X1-X5		
2000:5		5000:5	
300:5	X3-X4	500:5	X2-X3
400:5	X1-X2	1000:5	X4-X5
500:5	X4-X5	1500:5	X1-X2
800:5	X2-X3	2000:5	X3-X4
1100:5	X2-X4	2500:5	X2-X4
1200:5	X1-X3	3000:5	X3-X5
1500:5	X1-X4	3500:5	X2-X5
1600:5	X2-X5	4000:5	X1-X4
2000:5	X1-X5	5000:5	X1-X5

Standard burdens for current transformers are shown in Table 18. The first five burdens listed are burdens for which metering accuracy classes have been assigned, and the last four are for relay accuracy.

Accuracy ratings are given for each standard burden for which the current transformer is designed. Table 15 lists the accuracy classes and corresponding limits for transformer correction factors for current transformers for metering service. For example, the accuracy rating of a current transformer for metering service might be 0.3B-0.1 and B-0.2, and 0.6B-0.5. Based on these ratings, the transformer will maintain 0.3 accuracy class limits for standard burdens of B-0.1 and B-0.2 and maintain 0.6 accuracy class limits for a standard burden of B-0.5. The standard metering burdens, with the characteristics shown by Table 18, are 0.1, 0.2, 0.5, 0.9, and 1.8.

Table 18
Standard Burdens for Current Transformers
(5 amp Secondary)

Burden Designation	Resistance (ohms)	Inductance (mH)	Impedance	VA	Power Factor
Metering Burdens					
B-0.1	0.09	0.116	0.1	2.5	0.9
B-0.2	0.18	0.232	0.2	5.0	0.9
B-0.5	0.45	0.580	0.5	12.5	0.9
B-0.9	0.81	1.04	0.9	22.5	0.9
B-1.8	1.62	2.08	1.8	45.0	0.9
Relay Burdens					
B-1	0.5	2.3	1.0	25	0.5
B-2	1.0	4.6	2.0	50	0.5
B-4	2.0	9.2	4.0	100	0.5
B-8	4.0	18.4	8.0	200	0.5

Relay accuracy ratings (or classes) are designated by a classification and a secondary voltage terminal rating as follows:

- C or K classification means the true ratio of the transformer (primary current to secondary current) can be readily determined for each application using the marked ratio and typical excitation curves.

- T classification means the transformer ratio have to be determined by test. The manufacturer has to supply test data to determine performance.

- The secondary terminal voltage rating is the voltage that the transformer will deliver to a standard burden listed in Table 18 at 20 times normal secondary current (and also at any current from 1 to 20 times rated current at any lesser burden) without exceeding 10 percent ratio error.

For example, relay accuracy class C400 means that the ratio can be calculated and that the ratio error will not exceed 10 percent at any current from 1 to 20 times normal secondary current if the burden does not exceed 4.0 ohms (4.0 ohms * 5 amperes * 20 times normal current = 400 volts). Standard secondary terminal voltage ratings are 10, 20, 50, 100, 200, 400, and 800 volts.

For current transformers with tapped secondaries or multi-ratio secondaries, the accuracy class applies only to the full secondary winding unless specifically stated otherwise. Performance on lower taps may be significantly reduced and limited. Use of the lower taps should be avoided if possible. Continuous thermal current rating factors shall be 1.0, 1.33, 1.5, 2.0, 3.0, or 4.0, based on 30C ambient temperature.

The ratings represent the short-time (typically 1 second) primary current the current transformer can withstand with the secondary windings short circuited without damage or exceeding temperature limitations. Dangerously high voltages (more than 3500 volts for Class 1) can exist at the open circuit of current transformer secondary circuits, and appropriate measures have to be taken for safety and insulation withstand capability. Always short the secondary windings of current transformers when not in use.

The following information has to be available for calculating the performance of current transformers for metering service:

- Typical ratio correction factor and phase angle curves for the standard burdens for which accuracy ratings are assigned
- Mechanical and thermal short-time ratings

The following information has to be available for calculating the performance of current transformers for relaying service:

- Relaying accuracy classification
- Mechanical and thermal short-time ratings
- Resistance of secondary winding to determine value for each published ratio
- For Class C and K transformers, typical excitation curves
- For Class T transformers, typical overcurrent ratio curves

Voltage Transformers

A voltage transformer or potential transformer is an instrument transformer intended to have its primary winding connected in shunt with a power supply circuit, the voltage of which is to be measured or controlled.

Types:
There are several types of voltage transformers available.

A *cascade-type voltage transformer* is a single high-voltage line terminal voltage transformer with the primary winding distributed on several cores with the cores electromagnetically coupled by coupling windings and the secondary winding on the core at the neutral end of the high-voltage winding. Each core of this type of transformer is insulated from the other cores and is maintained at a fixed potential with respect to ground and the line-to-ground voltage.

A *double-secondary voltage transformer* is one that has two secondary windings on the same magnetic circuit insulated from each other and the primary. Either or both of the secondary windings may be used for measurements or control.

A *grounded-neutral, terminal-type voltage transformer* is one that has the neutral end of the high-voltage winding connected to the case or mounting base.

An *insulated-neutral, terminal voltage transformer* is one that has the neutral end of the high-voltage winding insulated from the case or base and connected to a terminal that provides insulation for a lower voltage insulation class than required for the rated insulation class of the transformer.

A *single high-voltage line, terminal voltage transformer* is one that has the line end of the primary winding connected to a terminal insulated from ground for the rated insulation class.

A *two-high-voltage line, terminal voltage transformer* is one that has both ends of the high-voltage winding connected to separate terminals that are insulated from each other, and from other parts of the transformer, for the rated insulation class of the transformer.

Ratings
The standard voltage transformers are divided into five groups, appropriately named, Groups 1, 2, 3, 4, and 5.

- Group 1: Designed for 100 percent of rated primary voltage across the primary winding when connected line-to-line, line-to-ground, or line-to-neutral.

- Group 2: Designed for line-to-line service, but may be used line-to-ground or line-to-neutral at a voltage across the primary winding equal to the rated line-to-line voltage divided by 3. This restriction is due to insulation limitations from line to ground.

- Group 3: Designed for line-to-ground service only and having two secondaries. The neutral terminal may be an insulated or grounded type.

- Group 4: Designed for line-to-ground service in indoor applications only. The neutral terminal may be an insulated or grounded type.

- Group 5: Designed for line-to-ground service only in outdoor applications. The neutral terminal may be an insulated or grounded type. Similar to Group 3 except single ratio and includes lower voltage classes.

Group 1 voltage transformers are for application with 100 percent of rated primary voltage across the primary winding when connected line-to-line or line-to-ground. These transformers shall be capable of operation at 125 percent of rated voltage on an emergency basis (this capability does not preclude the possibility of ferroresonance), provided the burden, in volt-amperes at rated voltage, does not exceed 64 percent of the thermal burden rating, without exceeding the following average winding temperatures: 105C for 55C rise types, 115C for 65C rise types, and 130C for 80C rise types. This will result in a reduction of life expectancy.

Group 2 voltage transformers are primarily for line-to-line service, and may be applied line-to-ground or line-to-neutral at a winding voltage equal to the primary voltage rating divided by the square root of three (1.732).

Group 3 voltage transformers are for line-to-ground connection only and have two secondaries. They may be insulated-neutral- or grounded-neutral-terminal type. Ratings through 161,000 Grd Y/92,000 shall be capable of the 1.732 times rated voltage (this does not preclude the possibility of ferroresonance) for one minute without exceeding 175C temperature rise for copper conductor or 125C rise for EC aluminum. Ratings 230 000 Grd Y /138 000 and above shall be capable of operation at 140 percent of rated voltage with the same limitation of time and temperature. Group 3 transformers shall be capable of continuous operation at 110 percent of rated voltage, provided the burden in volt-amperes at this voltage does not exceed the thermal burden rating.

Group 4 voltage transformers are for line-to-ground connection only. They may be insulated-neutral or grounded-neutral-terminal type. These voltage transformers shall be capable of continuous operation at 110 percent of rated voltage, provided the burden, in volt-amperes at this voltage, does not exceed the thermal burden rating. Group 4A voltage transformers shall be capable of operation at 125 percent of rated voltage on an emergency basis (this capability does not preclude the possibility of ferroresonance), provided the burden, in volt-amperes at rated voltage, does not exceed 64 percent of the thermal burden rating, without exceeding the following winding temperatures: 105C for 55C rise types, 115C for 65C rise types, and 130C for 80C rise types. (This will result in a reduction of normal life expectancy.) The manufacturer may be consulted for information about a possible higher rating.

Group 5 voltage transformers are for line-to-ground connection only, and are for use outdoors on grounded systems. They may be insulated-neutral- or grounded-neutral-terminal type. They shall be capable of operation at 140 percent of rated voltage for 1 min. without exceeding 175C temperature rise for copper conductor or 125C rise for EC aluminum conductor (this will result in a reduction of normal life expectancy). These voltage transformers shall be capable of continuous operation at 110 percent of rated voltage, provided the burden, in volt-amperes at this voltage, does not exceed the thermal burden rating. This capability does not preclude the possibility of ferroresonance.

A voltage transformer shall be assigned an accuracy class rating for each of the standard burdens for which it is designed. For example, an accuracy rating may be 0.3W and X, 0.6Y, and 1.2Z. The values 0.3, 0.6, and 1.2 indicate the accuracy class and represent the percent deviation (maximum and minimum) from the rated voltage. The designations W, X, Y, and Z are standard burdens. Standard burdens for voltage transformers for accuracy rating purposes are given in Table 19. The burdens are expressed in volt-amperes at a specified power factor at either 120 or 69.3 volts.

Table 19
Voltage Transformers
Standard Burdens

Characteristics			Characteristics 120V Basis			Characteristics 69.3V Basis		
Designation	VA	PF	Resistance (Ohms)	Inductance (H)	Impedance (Ohms)	Resistance (Ohms)	Inductance (H)	Impedance (Ohms)
W	12.5	0.10	115.2	3.04	1152	38.4	1.01	384
M	25	0.70	403.2	1.09	576	134.4	0.364	192
X	35	0.20	82.3	1.07	411	27.4	0.356	137
Y	75	0.85	163.2	0.268	192	54.4	0.0894	64
Z	200	0.85	61.2	0.101	72	20.4	0.0335	24
ZZ	400	0.85	30.6	0.0503	36	10.2	0.0168	12

Notes for Table 19: For rated secondary voltages from 108 V through 132 V or from 62.4 V through 76.2 V, the standard burdens for accuracy tests within ±10% of rated voltage are defined by the characteristic burden impedances at 120 V or 69.3 V respectively. For other rated secondary voltages, the standard burdens for accuracy tests within ±10% of rated voltage are defined by the characteristic burden volt-amperes and power factor. The characteristic volt-amperes apply at rated secondary voltage and appropriate impedances are required. When transformers with rated secondary volts from 108 V through 132 V are tested at secondary voltages within ±10% of one-half times rated voltage, the standard burdens for accuracy tests are defined by the characteristic burdens impedances at 69.3 V. When transformers with other rated secondary volts are to be tested at secondary voltages within ±10% of 1/13 times rated voltage, the standard burdens for accuracy tests are defined by the characteristic burden volt-amperes and power factor. The characteristic volt-amperes apply at 1/13 times rated voltage, for a given standard burden; the burden impedances are lower and the changes in accuracy resulting from burden current are greater than at rated voltage.

Accuracy classes are based on the requirement that the transformer correction factor shall be within specified limits when the power factor of the metered load has any value from 0.6 lag to 1.0, from zero burden to the specified standard burden and at any voltage from 90 to 110 percent of the rated transformer voltage. Accuracy classes and corresponding limits of TCF are shown in Table 15.

The thermal burden rating of a voltage transformer shall be specified in terms of the maximum burden that the transformer can carry at rated secondary voltage without exceeding the temperature rise above 30C ambient permitted by Table 14.

Application Data

The following information has to be obtained from the manufacturer to accurately determine operating characteristics and limits:

- Typical ratio and phase angle curves for rated primary voltage, plotted for the standard burdens and for the same numerical burdens with unity power factor, from zero burden to the maximum standard burden volt-amperes of the transformer
- Accuracy ratings for all standard burdens up to and including the maximum standard burden rating of the transformer
- Thermal burden rating

Combination Units

Combined instrument transformers, sometimes called metering units, include a voltage transformer and current transformer in a single free-standing unit. These units are used primarily in metering applications where a dedicated voltage transformer and current transformer are used for revenue metering. Each instrument transformer in the combined instrument transformer has to meet the requirements and ratings of ANSI/IEEE Std. C57.13 for the application. Ratings are provided for each instrument transformer in the combined unit.

These units have the advantage of cost savings by eliminating a set of support structures and foundations and reducing substation space requirements. A disadvantage of the combined instrument transformers is a failure of one component requires the entire unit to be removed from service and repaired or replaced.

Another type of combination unit called a *power voltage transformer* combines an auxiliary power transformer with instrument voltage transformers. A common primary winding is included with multiple secondary windings in a single free-standing unit. One or more of the secondary windings are rated for power application, typically 10 kVA to 100 kVA. Additional secondary windings are also included and can be rated either metering or relay accuracy classes with standard burdens as given in Table 19.

The advantage of these devices is cost saving by eliminating a set of support structures and reducing space requirements. The devices are also useful at remote switching stations or high-voltage substations where no local distribution service is available for station service. One disadvantage of the power voltage transformer is the loss of accuracy in the metering or relaying secondary windings when the power secondary winding is loaded. Consult the manufacturer to determine the effects of power winding load on the performance of the voltage transformer.

Tests

ANSI/IEEE Std. C57.13 lists the minimum routine tests an instrument transformer receives at the factory to ensure the instrument transformer meets the specified requirements. The routine tests include applied potential dielectric tests, induced potential tests, accuracy tests, and polarity checks. Additional tests are performed by the manufacturer for each transformer design (type tests) and are not performed on every transformer.

The Standard also describes the methods recommended for testing an instrument transformer. Although most of these tests are usually performed only in the factory, there may be occasions when the user will perform some of them in the user's own testing facility or in the field.

Chapter 4
Coupling Capacitors &Coupling Capacitor Voltage Transformers

Both coupling capacitors and coupling capacitor voltage transformers are single-phase devices that utilize one or more capacitor units, usually mounted on a base, to couple a communication signal to a high-voltage power line.

Coupling capacitors (CCs) are used in conjunction with line traps and line tuners for power line carrier (PLC) communication over high-voltage power lines. A CC with an electromagnetic unit is called a *Coupling Capacitor Voltage Transformer* (CCVT). CCVTs can be used to supply voltage for metering and protection applications similar to a voltage transformer.

The ANSI Standard applicable to the power line coupling capacitors is ANSI Std. C93.1, "Power Line Coupling Capacitors and Coupling Capacitor Voltage Transformers (CCVT) Requirements." This standard covers such items as definitions, service conditions, ratings, testing, and manufacturing requirements.

Coupling Capacitors

Coupling capacitors are primarily used for coupling power line carrier communication equipment to a high-voltage power line. A coupling capacitor used for power line carrier coupling will usually consist of the following equipment and accessories:

- An assembly of one or more capacitor units. The capacitor units are enclosed in an oil-filled, sealed porcelain shell and typically mounted on a supporting base.
- A supporting enclosure beneath the capacitor stack that may include accessories for functional or protective purposes.
- An inductor connected between the low-voltage terminal and the ground terminal to provide low impedance to the 60 Hz frequency current and high impedance to the carrier frequency current.
- The grounding switch is connected across the low-voltage and ground terminals and is used to bypass the drain coil during inspection or maintenance. It is operated externally by hook stick from ground elevation. It does not interrupt the operation of the high-voltage line or, when used, the voltage transformer components; however, closing the carrier grounding switch may affect the accuracy of the voltage transformer components.
- Spaced electrodes connected between the low-voltage and ground terminals for limiting transient overvoltages.
- The terminal to which the coaxial cable from the power line carrier line tuning equipment is connected.
- The terminal connected to the high-voltage power line. This terminal may also be connected on the line side of a line tram. Fusing of the high-voltage terminal is not necessary.
- The terminal at the lower end of the capacitor stack located within the base.

- The terminal on the exterior of the base connected directly to the ground grid.
- A space heater may be provided in the base for prevention of condensation.
- Provisions may be supplied for installing the electromagnetic unit for future conversion to a CCVT.

Coupling Capacitor Voltage Transformers

Coupling capacitor voltage transformers, commonly termed capacitor voltage transformers (CVTs), are devices used for coupling to a power line to provide low voltages for the operation of relays and metering instruments. Power line carrier accessories or provisions for future installation of carrier accessories may be included in the base. The photo on the right shows a typical CCVT.

Coupling capacitor voltage transformers are commonly supplied without carrier accessories, especially at voltages above 115 kV, as a more economical alternative to inductive voltage transformers. Coupling capacitor voltage transformers can be provided with the same ratings and accuracy as inductive voltage transformers.

However, because of the energy-storage capability of capacitors, sudden reductions in the power line voltage may result in momentary distortion of the CCVT secondary voltage. The amount of distortion is related to CCVT capacitance and the burden (secondary load) value and configuration. Modern CCVT designs are available to minimize this problem.

In addition to the carrier coupling accessories described above for a coupling capacitor, a CCVT may include the following equipment and accessories:

- In the capacitor stack, the units are divided to form two capacitances connected in series. The point between the two capacitances is tapped to provide a voltage proportional to the power line voltage. The tapped connection is brought to a terminal in the base designated as the intermediate-voltage terminal. The electromagnetic unit is connected between the intermediate-voltage terminal and the ground terminal.

- The transformer is the portion of the electromagnetic unit that provides a reproduction of the power line voltage at the secondary terminals of the transformer. Transformers commonly have two or more secondary windings. Each secondary winding is typically rated 120 volts line-to-neutral with a tap rated 69.3 volts line-to-neutral.

- The secondary terminals of the voltage transformer are connected for metering, protection, and control functions. The secondary circuits are typically fused although a common practice is to not fuse critical protection circuits when reliability is the key consideration. Some manufactures provide CCVTs that are designed to withstand a secondary short circuit continuously and do not require fusing; however, never intentionally short circuit the secondary of any CCVT. Also, the secondary windings of

CCVTs should not be connected in a closed delta because excessive current may circulate in the delta.

- The transformer is connected to the intermediate-voltage terminal through the choke coil or carrier blocking impedance. The choke coil prevents carrier frequencies from entering the electromagnetic unit. A protective gap is provided across the choke coil to limit voltage surges.

- A series reactor may be included in the electromagnetic unit to increase the inductive reactance of the electromagnetic unit to approximately equal the capacitive reactance of the CCVT at the power frequency.

- The potential grounding switch is connected between the capacitor divider intermediate-voltage terminal and the ground terminal. When closed, the potential grounding switch removes the electromagnetic unit from service. Closing the switch does not interrupt the operation of the high-voltage line or the carrier equipment. Like the carrier grounding switch, the potential grounding switch is located externally on the base and operated from elevation by hook stick.

- Protective gaps or other means are provided to limit overvoltages in the transformer. Older CCVTs may contain additional accessories for adjusting the voltage and capacitance of the unit. These accessories may be located in a separate cabinet mounted close to the base, usually on the same supporting structure. The accessories were required because, as the capacitors age, the voltage and capacitance values of the CCVT drift and require periodic calibration. Modern CCVT designs and materials have eliminated the need for these adjustments.

Different manufactures may use different components and arrangements to obtain secondary voltages representative of the power line voltage at the required accuracy. Manufacturers may also be able to provide specialty CCVTs for unusual applications.

Service Conditions

ANSI Std. C93.1 defines the usual service conditions for which CC and CCVT manufacturers are required to design their equipment. Consult the manufacturer when service conditions are unusual or exceed the limits stated below.

Coupling capacitors and CCVTs are designed for outdoor service at ambient temperatures from –40C to +45C. The maximum mean temperature for a one-hour period is +45C. Other limits are +40C mean over 24 hours and +30C mean over one year. Maximum altitude is 3,300 feet. Dielectric strength is decreased at higher altitudes approximately 5 percent for each 1,600 feet above 3,300 feet. The power frequency is 60 Hz. The carrier frequency range is 30 to 500 kHz.

The service condition is considered unusual if the equipment will be exposed to damaging or explosive fumes; excessive, abrasive, or explosive dust; steam; or salt spray. Applications that require special consideration by the manufacturer include use in high-voltage power cable systems and gas-insulated substations.

Ratings

The standard voltage ratings and associated insulation levels for CCs and CCVTs includes system voltage ratings, insulation withstand voltage levels for impulse and switching surges, power frequency withstand voltages, and minimum leakage distance of the capacitor porcelain.

The thermal burden rating of a CCVT is expressed in terms of the maximum burden a CCVT can supply at maximum voltage without exceeding the temperature limitations of the CCVT. The burden, expressed in volt-amperes, is given for each secondary winding. For CCVTs with multiple secondary windings, a total thermal burden (primary winding thermal burden) is also provided. If a single thermal rating is provided, it is applicable to any distribution of secondary volt-amperes.

Accuracy ratings are a means of expressing the conformity of the values obtained at the CCVT secondaries to the values calculated using the marked ratios. Accuracy classes have been established that define accuracy limits, in terms of *ratio correction factor* (RCF) and phase angle. The RCF is the ratio of the true ratio to the marked ratio. Standard accuracy classes include 0.3, 0.6, and 1.2 classes. Each secondary winding is assigned an accuracy class for the standard burden for which it was designed. Burdens for accuracy rating are expressed in volt-amperes at a specified lagging power factor and given a letter designation, as shown in Table 20. These values are applicable at either 120 or 69.3 volts.

Table 20
Burdens for Accuracy Ratings of Instrument Transformers

Charateristics on Standard Burdens			Characteristics 120V Basis			Characteristics 69.3V Basis		
Designation	VA	PF	Resistance (Ohms)	Inductance (H)	Impedance (Ohms)	Resistance (Ohms)	Inductance (H)	Impedance (Ohms)
M	35	0.20	82.3	1.07	411	27.4	0.356	137
W	12.5	0.10	115.2	3.04	1152	38.4	1.01	384
X	25	0.70	403.2	1.09	576	134.4	0.364	192
Y	75	0.85	163.2	0.268	192	54.4	0.0894	64

Z	200	0.85	61.2	0.101	72	20.4	0.0335	24
ZZ	400	0.85	30.6	0.0503	36	10.2	0.0168	12

CCVTs are classified for either relaying service or metering service. Metering service CCVTs has to maintain the stated accuracy for primary voltages between 90 percent of the performance reference voltage and maximum rated voltage. Metering service CCVTs shall be assigned an accuracy class of 0.3, 0.6, or 1.2 for each winding.

Relaying service CCVTs are always assigned an accuracy class of 1.2R. Relaying service CCVTs have additional requirements for maintaining accuracy limits under varying frequency conditions and low-voltage conditions.

CCs and CCVTs are usually classified as *high capacitance* or *extra-high capacitance*, depending on the value of the high-voltage capacitance. The high-voltage capacitance C1 is the capacitance between the high-voltage and intermediate-voltage terminals. Available ratings are listed in manufacturers' catalogs.

The typical *high-capacitance* unit can be equipped for broadband carrier coupling, and some units can be furnished for one- or two-frequency carrier coupling. High-capacitance CCVTs can be supplied with an accuracy class of 0.3, 0.6, or 1.2. Burden capability ranges up to 200 VA. They are not suitable for revenue metering, but can be used for relaying and SCADA systems.

The typical *extra-high capacitance* device is particularly applicable on the higher voltage systems, 115 kV and above, where the increased capacitance rating is desired to provide a low impedance path for carrier signals. It is also the only type of CCVT suitable for revenue metering, when specified with an accuracy class of 0.3. Burden capability ranges up to 400 VA.

The higher capacitance devices are generally more expensive than the lower capacitance devices. However, capacitance can usually be equated to performance. In general, the higher the capacitance of the device, the better its performance characteristics will be. The extra-high capacitance CCVT is particularly applicable at high-voltage and extra-high-voltage interconnections between two utilities where revenue metering from the primary transmission line is essential and where broadband coupling is desired between carrier transmitter–receiver equipment and the power line.

Tests

ANSI Std. C93.1 describes the various test conditions, routine tests, and design tests performed on CCs and CCVTs. Two routine production tests that are to be made on each completed capacitor unit (i.e., an assembly of capacitor elements in a single container with accessible connections) include *capacitance and dissipation factor measurements* and *dielectric tests*.

Capacitance and dissipation factor measurements up to rated maximum voltage and frequency before and after dielectric tests. Dissipation factor is the tangent of the angle delta by which the phase difference between the voltage applied to the capacitor and resulting current deviates from 90 degrees. The dissipation factor is usually expressed as a percentage.

Every capacitor is subjected to a power-frequency withstand voltage test, applied between the high-voltage and ground terminals.
Other routine tests include verification of the protective gap sparkover settings, accuracy, and polarity. For accuracy tests, ratio and phase angle measurements are made at the performance reference voltage and power frequency at the maximum burden for each rated accuracy class and at zero burden.

When testing a CCVT or during operation, never energize the CCVT from the secondary winding. The CCVT may be damaged by the voltages and currents that develop in the CCVT.

Summary

This course has covered the specification and application of some of the supporting major equipment found in electrical substations. This includes various types of electrical switches, arrestors, and instrument transformers including CT's, PT's, and CCVT's.

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