ELECTRICAL DISTRIBUTION SYSTEMS, OVERHEAD LINE CONSTRUCTION AND PROTECTION

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ABSTRACT

This paper will present and discuss the selection, design, construction, and protection of several different types of oilfield-oriented overhead electrical power distribution systems. This information will assist in choosing, installing, and/or modifying the overhead distribution system most suitable for a particular project.

INTRODUCTION

During 1965 Shell installed in the Wasson Water Supply System near Denver City, Texas, over 150,000 ft of 12,500-V overhead distribution lines to serve the 50 source wells of the System. Construction was the conventional industry-standard flat-top design. Electrical availability turned out to be approximately 55% due to an abnormally high number of lightning incidents. Overhead shield wires were installed in 1966, but due to high soil resistivities they were of minimal benefit.

In 1967 the decision was made to convert the West Texas Water Supply System near Kermit, Texas to electrified lift, which would require the construction of a totally new system of approximately 60,000 ft of overhead lines. Two very significant characteristics of this geographical region were known:

1. Surrounding operators and utility companies both knew this to be a notoriously high lightning incident area.
2. Soil resistivities were high: 6,000 to 12,000 ohm-cm.

An electrical availability approaching 99% was requested. After considerable investigation, it was felt the most lightning-resistant construction to utilize would be a modified high-impulse level "nonshielded"[1] design similar to that under study by the Transportation and Distribution Committee of the Edison Electrical Institute.

In 1971 after experiencing three years of excellent performance from this "nonshielded" design, it was decided to conduct an in-depth study of the Wasson System shielded construction to raise its 65% electrical availability to a more acceptable figure. The results of that study led to redesigning the existing system for an electrical availability well in excess of 90% (higher availability was economically unjustifiable).

The following discussion will present and discuss the basic design criteria for all three types of construction.

CHARACTERISTICS OF LIGHTNING

A detailed treatment of lightning phenomena will not be covered in this presentation, as it is covered quite thoroughly in several good reference books;[1,2,3] however, a few condensed basic characteristics will be presented to assist in explaining the different types of construction:

A. Lightning strikes have a voltage rise rate of 1,000 to 10,000 KV/microsecond; a good average is 4,000 KV/microsecond.[1]
B. The maximum direct strike voltage ever recorded is 5,000 KV. Induced voltages (from nearby strikes) generally range from line voltage to about 300 KV.[1]
C. Stroke time length ranges from 100 to 1,000,000 microseconds; a good average is 200 microseconds (0.012 A.C. cycles).[1]
D. Direct-strike currents run from 1,000 to 200,000 amps. Induced currents run from 100

to 10,000 amps.[1] Luckily, half of all strokes contain less than 1,500 amps and only one out of ten is over 6,000 amps.

E. Direct strikes will generally average one per mile of overhead line per year, in regions having annual isokeraunic levels from 25 to 40 (thunderstorm days per year).[1]

F. Crest magnitude is higher and duration is longer in high-resistance installations or high-resistance ground regions, i.e., greater than 5 ohms.[1] This signifies greater heat generation (hot lightning), therefore, greater overall damage potential.

G. Typical 9-13 KV (RMS rated) distribution class lightning arrestors flash over at approximately 40 KV. Their discharge capability is 30,000 to 40,000 amps (at a rise rate of approximately 3,200 amps/microsecond).[1,2]

From these aforementioned characteristics, it is reasonable to state that high-availability, lightning-resistant construction should include several features:

1. Direct-strike design for probable high crest values and prolonged tails. (The majority of induced stresses can be adequately drained by the system lightning arrestors.)
2. Protective devices must reliably respond and function in fractions of a microsecond in order to keep crest values and currents as low as possible in order to avoid structure and equipment damage.
3. The lowest resistance device-to-ground path must be attained.

CHARACTERISTICS OF DESIGN

First, there are two characteristics of basic design that must be defined:

A. "Cone of Protection"[1,3] - This theory states that any *well*-grounded object throws a protective "shadow" over any object below it, and lightning will not usually enter this shadow zone. Laboratory and field tests have shown that on level terrain this cone is 45° each side of center, with increasing effectiveness as this angle decreases. (On the side of a hill, the 45° angle should be decreased by the angle of the slope of the hill.)

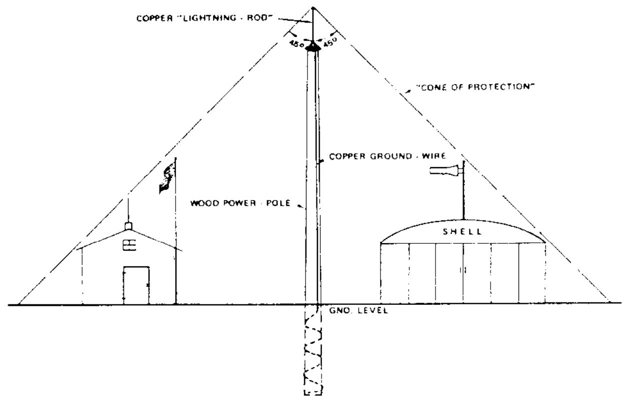
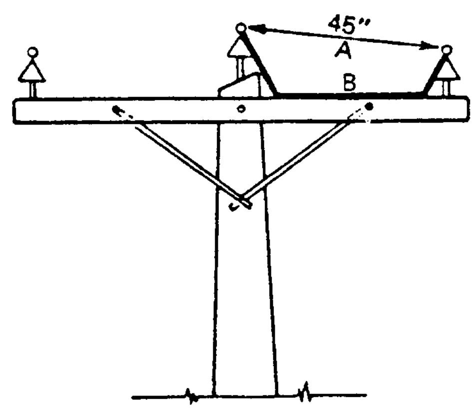


FIGURE 1

For an illustration, in the above facility all objects under the hypothetical 45° "cone of protection" would have 99% protection from a direct lightning.

B. "Basic Impulse Level (BIL)"[1,6] - This is simply the impulse voltage level at which high-voltage flashover will occur on a structure or device; it can be thought of as the breakdown point of the procelain, air, and wood insulation paths on a pole top. For calculating BIL, the following impulse flashover values are commonly accepted:

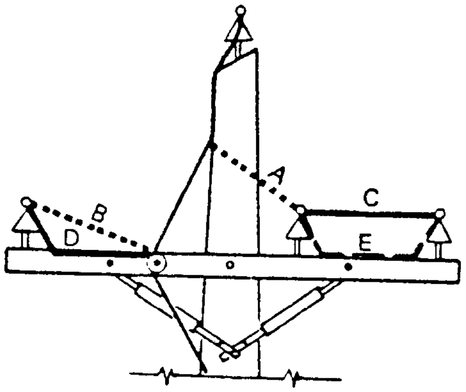
AIR, AVG	= 200 KV/FT
WOOD, CONTAMINATED AND WET, AVG	= 60 KV/FT
PINTYPE INSULATORS, 9-13 KV, TYPICAL	= 110 KV



A $\frac{45}{12} \times 200$ = 750 KV

B $110 + 110 + (\frac{45}{12} \times 60)$ = 445 KV ←BIL

FIGURE 2—STANDARD "FLAT-TOP" CONSTRUCTION



A $\frac{8}{12} \times 60 + \frac{17.5}{12} \times 200 = 332$ KV ←BIL

B $\frac{24.5}{12} \times 200 = 408$ KV

C $\frac{28}{12} \times 200 = 467$ KV

D $110 + 110 + \left(\frac{26}{12} \times 60\right) = 350$ KV

E $110 + 110 + \left(\frac{28}{12} \times 60\right) = 360$ KV

FIGURE 3—TYPICAL "SHIELDED" CONSTRUCTION

The BIL of a typical structure is determined as follows:

1. Calculate the BIL of each logically possible phase-to-ground and phase-to-phase path.
2. Select the lowest impulse flashover value as the BIL of the structure.

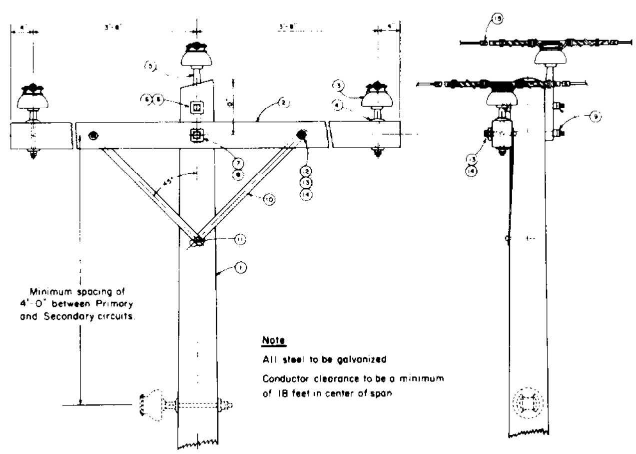
A flashover creates a sufficiently ionized (conductive) path to support 60 Hz "power follow" up to a BIL of approximately 300 KV on 9-13 KV systems (330 KV on 22-25 KV systems). Above this "critical BIL," the degree of ionization is usually insufficient to support 60 Hz current flow. When designing structures for protection from direct lightning strikes, a voltage just above the critical BIL is selected. This limits the stress buildup to a minimal value; at the same time it eliminates power interruptions (single phasing) caused by the 60 Hz current leaving the conductors.

TYPES OF CONSTRUCTION

Conventional "Flat-Top" Construction

This is the most commonly used type of overhead power line construction. It is generally considered satisfactory in low lightning incident regions. Direct strikes on these structures, however, have only one path to ground; at 445 KV a phase-to-phase flashover occurs through the crossarm wood via the steel insulator pins and through-pole mounting bolts. Considerable pole-top damage occurs with accompanying carbon tracking, 60 Hz power follow, conductor damage, breaker tripping, fuse blowing, and system outage.

Once constructed, it is generally quite costly to modify this type construction to effectively handle direct lightning strikes. In order to add overhead shield wires, mid-span clearances make it necessary to extend pole heights by adding on 4 in. x 4 in. x 6 ft treated *wood* bayonets. An alternate modification (and one that merits consideration) is the addition of distribution-class lightning arrestors on all three phases at each pole (± 50 arrestors, ± $1,000 per mile of three-phase line).[5] A recent study by a task force committee of the IEEE[4] predicts this method to provide a relatively high degree of electrical availability in both low and intermediate resistivity installations; it does, however, incur some additional system maintenance.



Item	Qnty	Description	Graybar No.
1	1	35' class 6, creosoted pine pole, 8 lb. final retention, with 15° one-way slope roof.	
2	1	Crossarm, treated, 3-1/2" x 4-1/2" x 8'-0"	
3	3	Wet process porcelain pin insulator	38149
4	2	Forged steel pin, with lock washer, square washer and nut 5/8" x 10"	981
5	1	Pressed steel pin, 1" thread x 15" straight base	3162
6	1	Machine bolt with nut, 5/8" x 10"	9810
7	1	Machine bolt with nut, 5/8" x 14"	9814
8	2	Square washer, 2-1/4" x 2-1/4" x 11/16"	7813
9	2	Locknut, 5/8"	4512
10	2	Crossarm brace, 1/4" x 1-1/4" x 28"	8128
11	1	Log screw, 1/2" x 4"	9754
12	2	Carriage bolt with nut, 3/8" x 4-1/2"	9634 1/2
13	2	Round washer, 1/4" x 9/16"	7802
14	2	Locknut, 3/8"	4510
15	3	Aluminum alloy preformed armor rods and tie wires	

MINIMUM SAG FOR NEW No. 4 ACSR 7/1

SPAN	TEMPERATURE °F 32°	60°	90°	120°
200'	6"	8"	10"	15"
250'	10"	12"	16"	21"
300'	15"	18"	24"	32"
350'	20"	24"	32"	40"

FIGURE 4—STANDARD FLAT-TOP CONSTRUCTION

A detailed construction drawing of this type construction is presented in Figure 4.

"Shielded" Construction

All three phase conductors are within the "cone of protection" of the overhead shield wire. Lightning strikes are directed to this uppermost line, then taken to ground by the copper ground wire that should be installed on *every* pole in the system using butt-wrapping, terminating in a full diameter copper pole ground (butt) plate. *Properly constructed,* with a BIL of not less than 300 KV *and* an overall installation resistance of less than 5 ohms, this popular configuration will generally perform as intended.

An extensive lack of understanding exists among design engineers and field construction personnel regarding proper design criteria for this type construction. A detailed proper dimensional and layout drawing for this construction is presented in Figure 5. Many installations have been, *and are still being,* built with improper geometry, hardware, and spacings as shown in Figure 6; any one of the violations of proper design illustrated in this figure will appreciably lower the BIL of the structure and is guaranteed to produce a significant decrease in the electrical availability of the system.

Performance of this type construction in high and intermediate resistance installations is quite poor; slowed draining action results in a buildup of the flux field surrounding the ground wire that, combined with the phase field, can exceed the BIL of

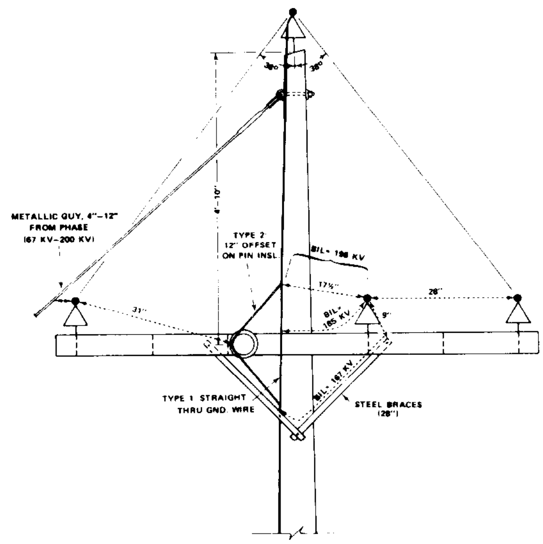
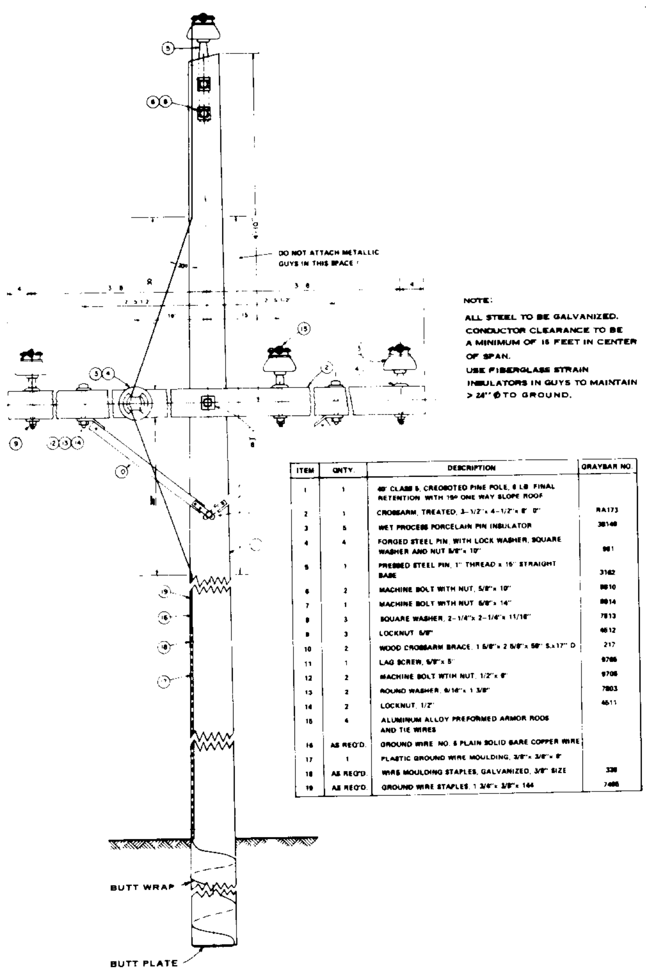


FIGURE 6—OVERHEAD SHIELDED CONSTRUCTION-IMPROPER CONSTRUCTION

the structure, producing damaging flashover through the pole wood; the accompanying damage is much the same as that covered earlier for flat-top construction. The effectiveness of this construction in marginal soil conditions can sometimes be enhanced by pretreating the soil in the lower portions of the pole hole with low-resistance chemical additives, such as magnesium sulfate or copper sulfate. (Rock salt should not be used because of its much greater corrosion activity on the relatively small masses of the copper ground wire and butt plate.)



ITEM	QNTY.	DESCRIPTION	GRAYBAR NO.
1	1	40' CLASS 5, CREOSOTED PINE POLE, 8 LB FINAL RETENTION WITH 15° ONE WAY SLOPE ROOF	
2	1	CROSSARM, TREATED, 3-1/2" x 4-1/2" x 8' 0"	RA173
3	5	WET PROCESS PORCELAIN PIN INSULATOR	38140
4	4	FORGED STEEL PIN, WITH LOCK WASHER, SQUARE WASHER AND NUT 5/8" x 10"	961
5	1	PRESSED STEEL PIN, 1" THREAD x 15" STRAIGHT BASE	3142
6	2	MACHINE BOLT WITH NUT, 5/8" x 10"	8810
7	1	MACHINE BOLT WITH NUT 5/8" x 14"	8814
8	3	SQUARE WASHER, 2-1/4" x 2-1/4" x 11/16"	7813
9	3	LOCKNUT 5/8"	4612
10	2	WOOD CROSSARM BRACE, 1 5/8" x 2 5/8" x 58" S x 17" D	217
11	1	LAG SCREW, 5/8" x 5"	9706
12	2	MACHINE BOLT WITH NUT, 1/2" x 8"	9708
13	2	ROUND WASHER, 9/16" x 1 3/8"	7803
14	2	LOCKNUT, 1/2"	4611
15	4	ALUMINUM ALLOY PREFORMED ARMOR RODS AND TIE WIRES	
16	AS REQ'D.	GROUND WIRE NO. 6 PLAIN SOLID BARE COPPER WIRE	
17	1	PLASTIC GROUND WIRE MOULDING, 3/8" x 3/8" x 8'	
18	AS REQ'D.	WIRE MOULDING STAPLES, GALVANIZED, 3/8" SIZE	338
19	AS REQ'D.	GROUND WIRE STAPLES, 1 3/4" x 3/8" x 144	7486

FIGURE 5—STANDARD SHIELDED CONSTRUCTION

"Hi-Impulse, Nonshielded" Construction

It is felt that this type construction, with a comparable new installation cost to shielded construction (which is approximately two times the cost of flat-top construction), has the more outstanding performance in *both* low and high resistance installations. Over 14 miles of this type line in the aforementioned West Texas Water Supply have given slightly in excess of 99% electrical availability over the past nine years. Detailed construction drawings of this type of construction are presented in Figures 7 and 8.

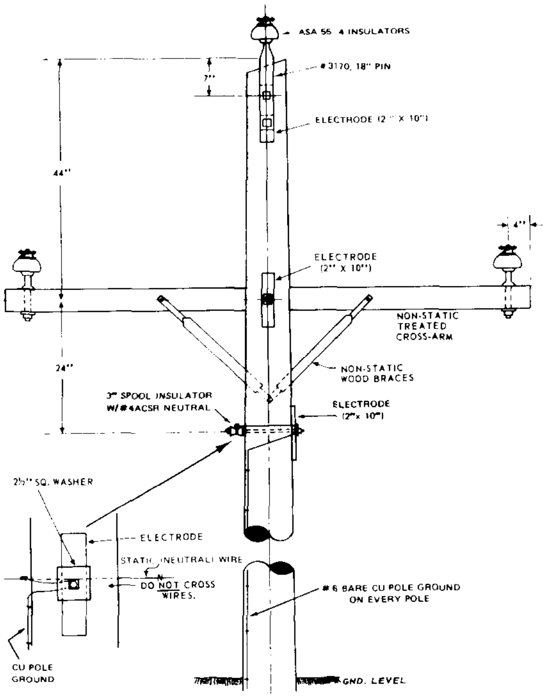


FIGURE 7 -HIGH-IMPULSE CONSTRUCTION

The two lower-phase conductors are within the "cone of protection" of the top phase, and their BIL to ground is maintained well above that of the top phase. Lightning strikes are directed to the uppermost phase, then taken to ground through a unique electrode path along the outer surface of the pole.

As the overvoltage stress builds up on the structure following a lightning strike, corona discharges appear from every sharp-edged metallic object within the stress area. As soon as the pole surfaces and the air surrounding them are sufficiently ionized by this corona, the flashover of the high impulse voltage begins down the lowest BIL path which, as shown in Figure 9, is down the pole electrode path at 300 KV. Use of the surface-mounted electrodes enables a considerable amount of control to be maintained over the path of the flashover. This path is directed along the surface of the pole

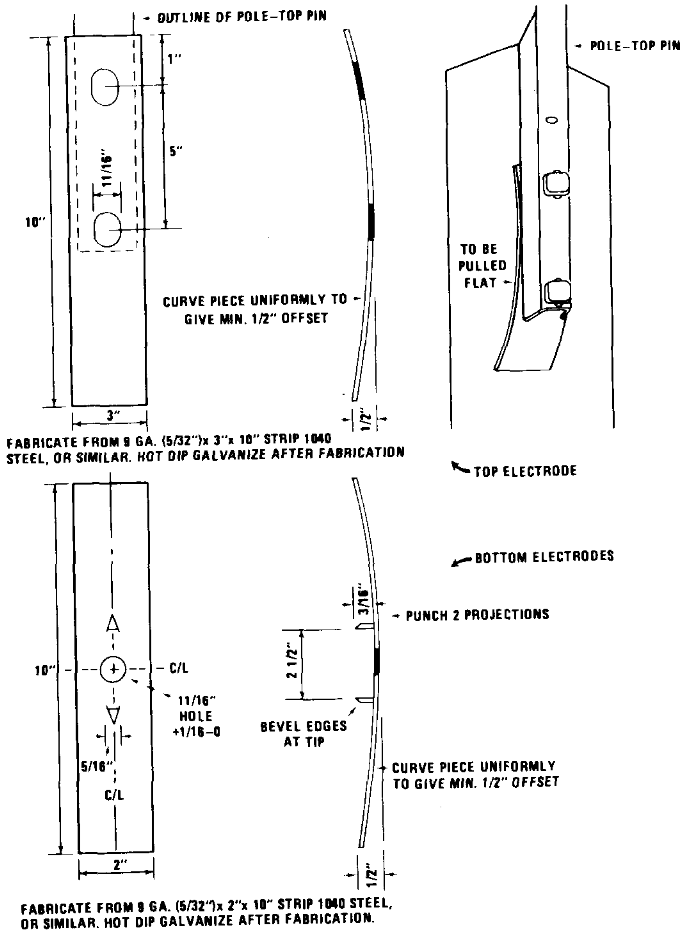


FIGURE 8—"HI-IMPULSE" ELECTRODE CONSTRUCTION

through the immediately adjacent air by the electrodes, instead of through the pole wood by the through-pole mounting bolts. The residual moisture on the surface of the pole is converted to steam by the flashover which "kicks" the arc straight out, away from the pole. The resulting lengthening path rapidly cools and quenches the flashover. A considerable amount of resistance and delay in transit time is created within this path so a "stiff" 5-ohm pole grounding system is no longer mandatory. By bonding all the system bottom electrodes together with a No. 4 ACSR conductor (which parallels all the butt-wrapped pole grounds), satisfactory operation has been possible in 12,000 ohm-cm soil (54 ohm equivalent ground).

As many as 15 strikes have been recorded on this type construction in the West Texas Water Supply System during a typical thunderstorm. These strikes and their subsequent flashovers do *not* normally trip oil circuit reclosers (O.C.R.'s) or blow sectionaliz-

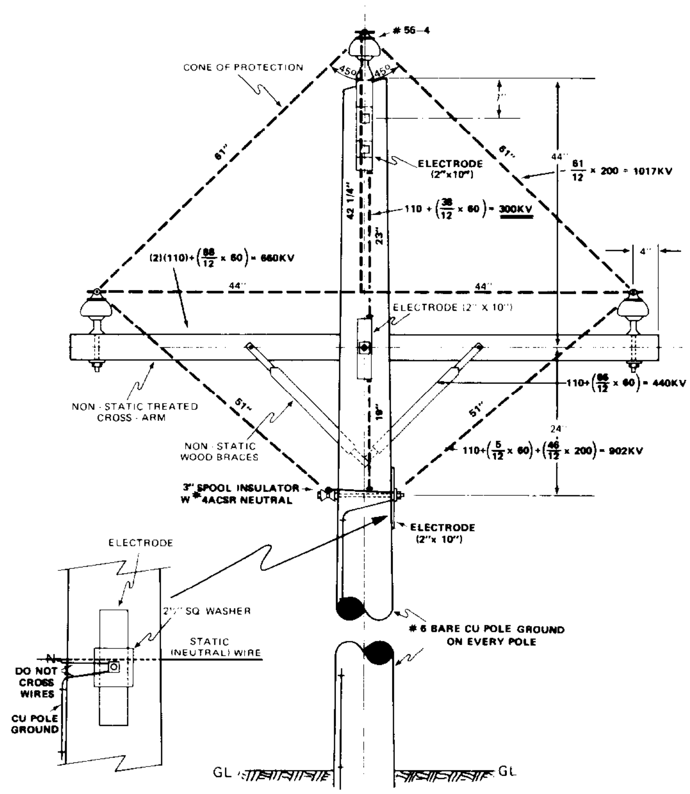


FIGURE 9—"HIGH-IMPULSES" POLE-LINE CONSTRUCTION
12-15 KV, BIL = 300 KV

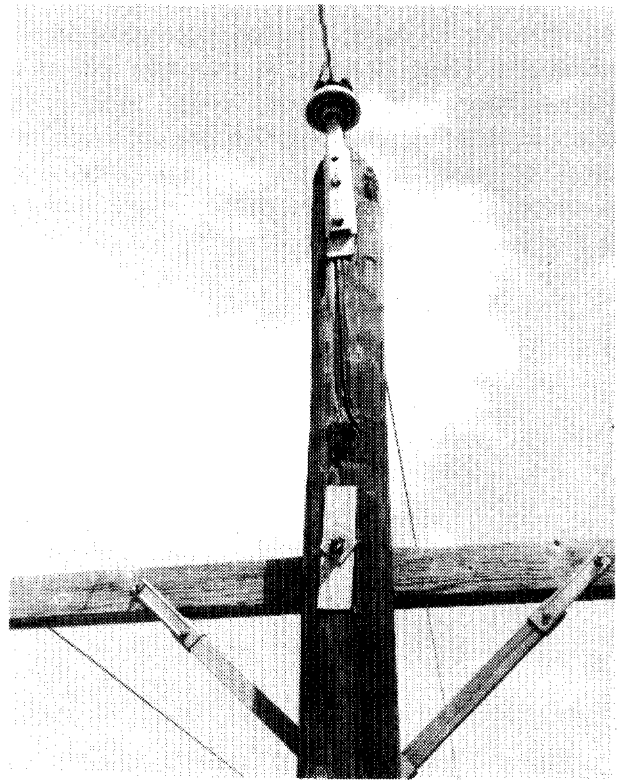


FIGURE 10

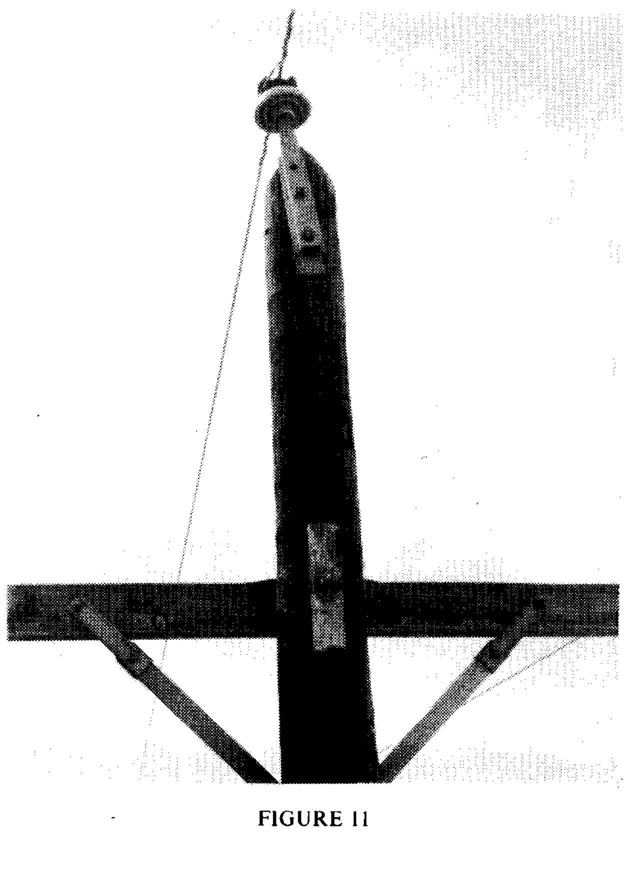


FIGURE 11

ing fuses; therefore, they do not create system interruptions or outages. Photographs (Figures 10 and 11) clearly demonstrate the electrode action of this construction during flashovers on poles that were hit by unusually high current strokes. (After nine years, this is the most typical degree of pole damage that has been observed in the system.) Note in both photographs that the depth of splinter removal decreases as the flashover proceeds downward confirming a definite cooling and quenching action. Note also that the flashover occurs in a definite counterclockwise direction. It has been repeatedly observed that power pole flashover paths travel one and one-half counterclockwise turns per 25 ft, or 90° in 50 in., which is the approximate overall length from the bottom of the top electrode to the top of the bottom electrode; therefore, the bottom electrode should always be located 90° from the top electrode in this counterclockwise direction.

Transition Between Different Types of Construction

It is often desirable to upgrade only those portions of an existing system that are experiencing

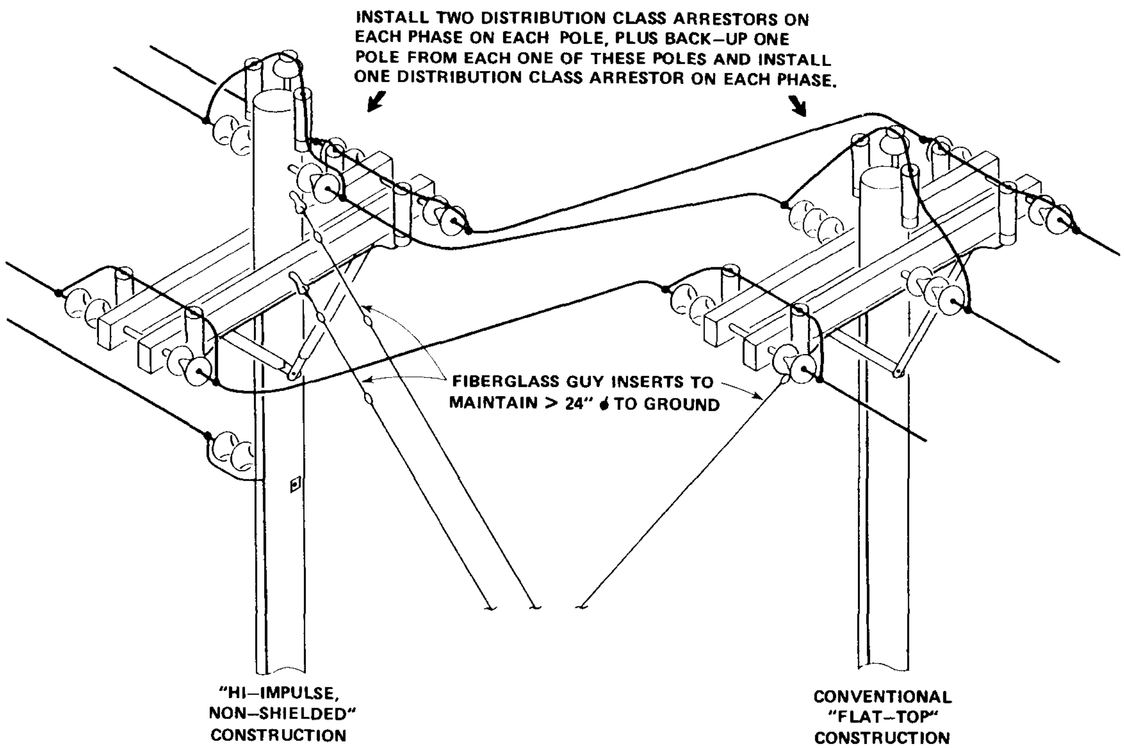


FIGURE 12—TRANSITION INTERFACE FOR ANY COMBINATION

problems. In those cases it becomes necessary to join together flat-top and overhead shielded, flat-top and high-impulse, or high-impulse and overhead shielded construction. These three distinctively different types of construction are decidedly incompatible without a transitory interface as shown in Figure 12. This transition minimizes induced interference problems that can occur through the junction.

Protection at Terminations and Taps; Arrestor Applications

The Arrestors and "Ground" - Regardless of the type of overhead construction used, the point is eventually reached where lightning arrestors must be installed to protect problem structures with inadequate BIL, tranformer banks, loads, etc. Without arrestors, the ± 300 KV impulse voltage levels which are reached during lightning incidents would destructively flash over in these installations. Fifteen KV transformer banks, for example, are usually rated at 95 KV BIL so an impressed impulse voltage of 300 KV would puncture and destroy the insulation.

The protection offered by the arrestors, and any associated protective equipment, is no better than the grounding system to which they are connected. A common misconception of system grounds is that they should be equivalent to a massive salt block or be the same potential as the oceans. This is not necessarily true. The objective is to achieve a good low-resistance connection to the earth, that will be at the ground potential of the particular earth located beneath the device, regardless of the characteristics of the soil that makes up this earth. The problem is achieving an effective hard-wired connection to this potential through the ground rod and this soil. The oil industry has a highly efficient device available to solve this problem—the oil well, with its mile or two of steel pipe passing through layers of highly conductive clays and salts. However, what if one of these expensive "ground rods" is located too far from the arrestor installation to be an effective ground connection? Conventional ground rods must then be relied upon and somehow "made" effective. Two major obstacles must be overcome: (1) the contact resistance between the ground rod and the adjacent soil, and (2) the resistance of the immediately surrounding soil. Component (1) is a matter of clean bare copper-clad rods and adequate compaction of the soil around them. Component (2) presents a little more of a problem. A ground rod radiates current in all directions. It can be thought of as being surrounded by discrete layers of earth, all of equal thickness. The layer of earth nearest the ground rod naturally has the smallest surface area and so offers the greatest resistance. The next layer is somewhat larger in area and offers less resistance, and so on. Finally, a distance from the ground rod will be reached where the inclusion of additional layers does not add significantly to the resistance of the earth surrounding the rod; if sufficient conductivity can be established in these layers, out to this distance, earth potential has been achieved for all practical purposes.

Figure 13 shows a method that has been very effective in achieving this goal without the great expense associated with grids, counterpoises, and deep-well grounds. The success of this "Chemical Ground" is based on the three chemicals used: (1) bentonite, a sodium aluminum silicate clay-drilling mud additive which swells to several times its original volume when wet; (2) gypsum ($CaSO_4 \cdot H_2O$), used in manufacturing sheetrock and plaster of paris, which remains in a stable condition by holding water; and (3) rock salt, the low-resistance additive. (The corrosive action is offset by using large mass rods.) Following activation with saturated brine, the bentonite swells and maintains

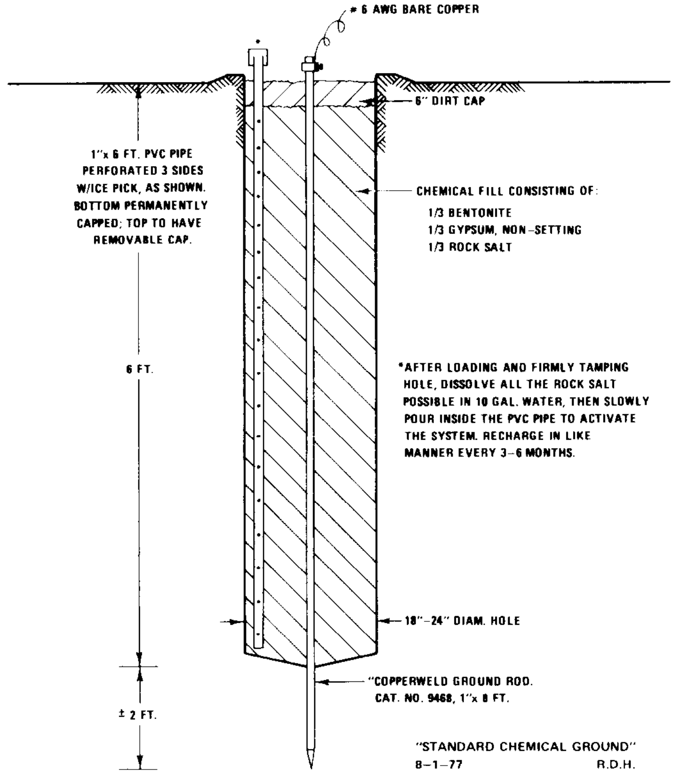


FIGURE 13—STANDARD CHEMICAL GROUND

the hole under sufficient pressure to assure low contact resistance; the gypsum retains the water to prevent loss of conductivity in the hole, due to drying out, from absorption and regional drought conditions; the rock salt, in addition to its high

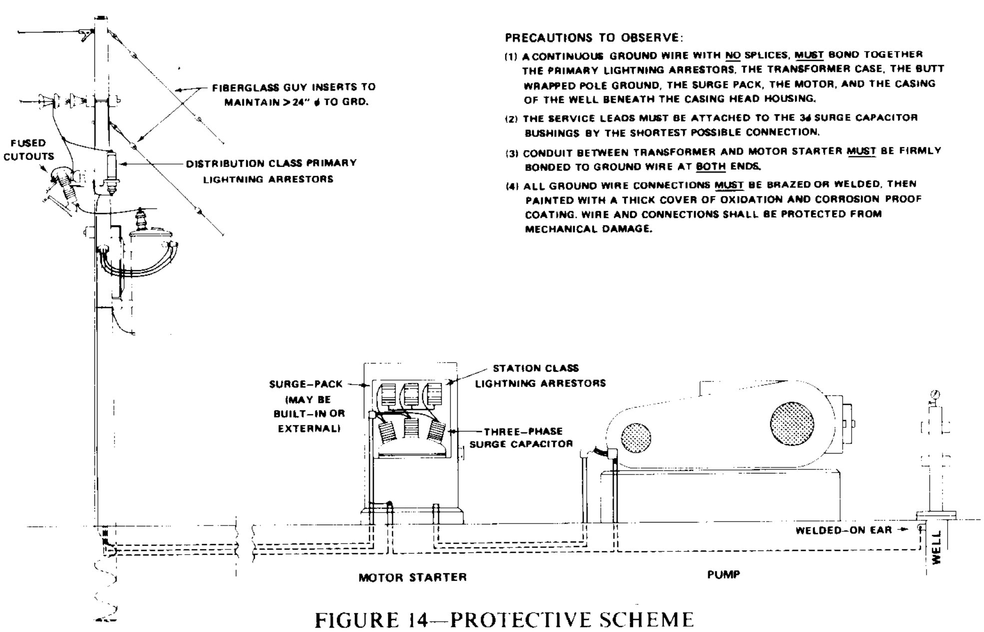


FIGURE 14—PROTECTIVE SCHEME

conductivity, leaches into the surrounding soil over the years, continually including more and more earth layers and adding to the installation's efficiency. Two to six of these grounds in parallel can effectively lower and maintain installation resistance to a fraction of an ohm.

Selecting and Installing the Arrestors - The final item to worry about in achieving a lightning-resistant system is the placement of the lightning arrestors, plus any associated protective equipment, where they'll be of greatest benefit. Years of experience have produced the more or less standard protective scheme shown in Figure 14.

First, a discussion of the three different types of autovalve distribution and equipment lightning arrestors available. In order of cost, overall protective quality, and durability, they are: (1) the Station Class arrestor, (2) the Intermediate Class arrestor, and (3) the Distribution Class arrestor. The Station Class arrestors offer three times the current rating of the Distribution Class arrestors at roughly 10 times the cost. The Intermediate Class arrestors offer one and one-half times the current rating of the Distribution Class arrestors at roughly seven times the cost. The Distribution Class arrestor's greatest asset is economy. They have been found to be wholly satisfactory for protecting an overhead system from induced currents, for protecting transformer primary (and secondary), and for protecting any problem overhead structure where sufficient BIL cannot be obtained due to line or equipment congestion. The most important precaution during arrestor installation is to observe a 40-50 KV BIL between the arrestor and surrounding objects to avoid flashover to these objects before the arrestor can internally flash over.

The Station Class arrestors are used at the loads or in their switchgear as the "last line of defense." For protecting large, expensive investments they are a "must." Generally they are used in parallel with a surge capacitor to form what is referred to as a "Surge Pack." The arrestors protect against major insulation-to-ground flashovers; the surge capacitors protect turn insulation from steep wavefront puncture. Correct installation of these surge packs is difficult. The most effective location for these devices would be as close to the motor terminals as possible; however, most of them have been installed on the line side of the switchgear with obviously satisfactory performance. To assure that the surge capacitor is effective, the connecting leads *must* be one ft or less in length. If the inductance in these leads is greater than $1/4$-μH., i.e., greater than 12 in., it will appear as an open circuit to the high-impulse discharge and the capacitor will have no effect in shaping the wavefront. The length of the arrestor leads is not quite as critical. It is recommended that the service leads be brought directly into the capacitor bushings for a zero lead length with the arrestor leads connected to this same point with minimum length leads.

Failure after Completion - After selecting the best overall system for a given installation and installing and double-checking it with great care, the availability falls short of that required. What next? Generally, the incidents that lower availability can be confined to a readily identifiable portion of the system. The protection in those portions can almost always be sufficiently increased by performing a few additional simple tasks:

1. Install a second Distribution Class arrestor in parallel with the existing ones on each phase at the transformers, then back up one span from the transformer bank and install a Distribution Class arrestor on each phase at this pole.
2. Install Intermediate or Station Class arrestors on each phase on the secondary of the transformers.
3. Check the drop-out characteristics of the magnetic contactor assembly in relation to the control relays, particularly in Size 4, 5, and 6 starters. If necessary convert the A.C. holding coil to D.C. operation.
4. Implement system O.C.R. and fuse coordination.[5,6]
5. Check for insufficient single-phase protection.

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