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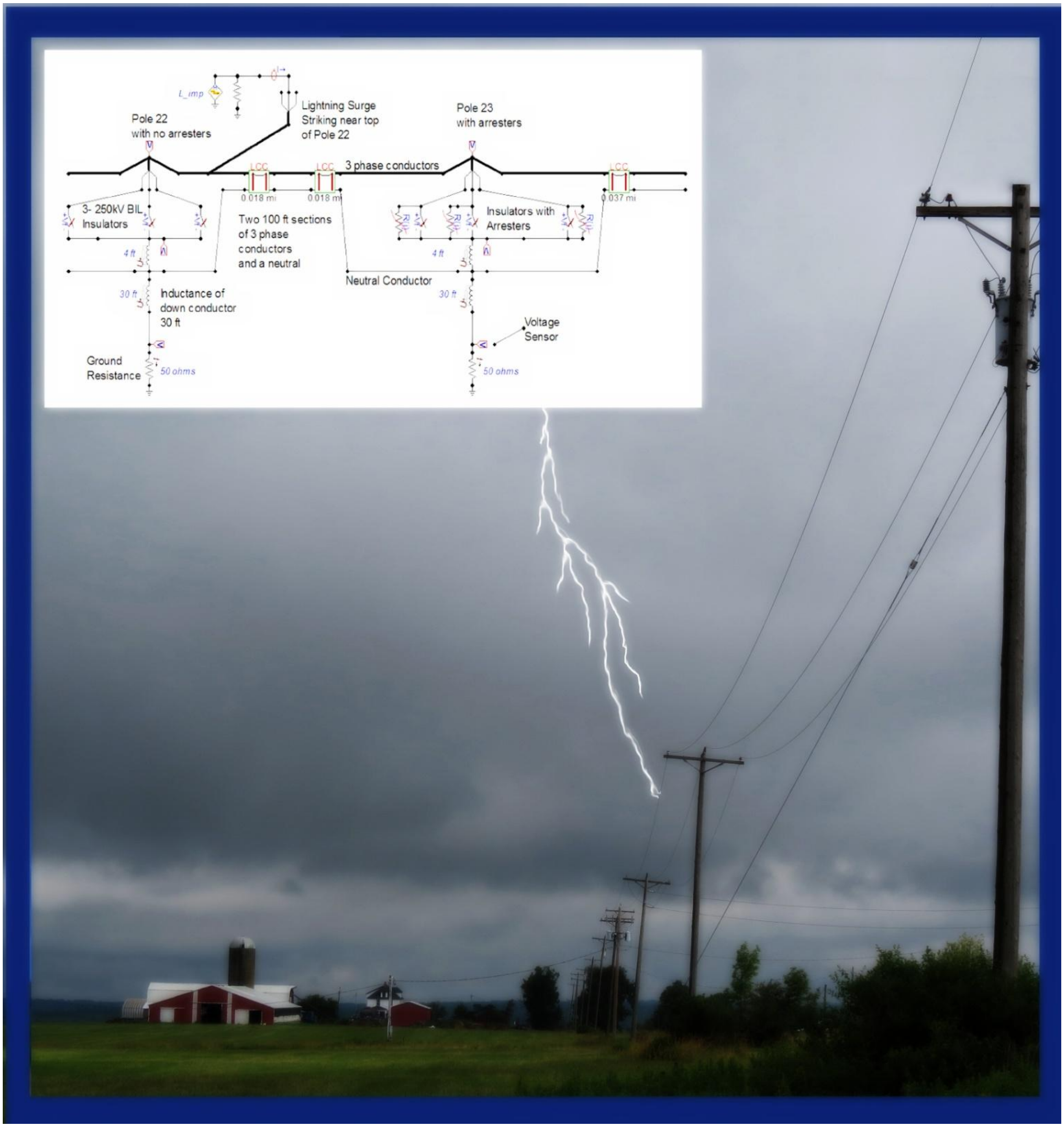
Distribution System Responses to Lightning Strikes



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Distribution lines that run through the open countryside are very likely targets for lightning strikes. Once the line is hit, a surge is generated that travels in both directions down the line seeking a low impedance path to ground. In its travels, it can result many electrical events. The purpose of this article is to give the reader better insight into what happens on a distribution power system when struck by lightning and explain how and where it goes once on the system.

After the strike, a surge is created and very often, reaches a pole, it will flashover the insulator. To better understand this, let's look at a distribution system commonly used in the US. The system is referred to as a four wire solidly grounded wye, and it consists of three conductors and a neutral. For this discussion, the system is a 34.5kV system, with wooden poles that are 34 ft tall with a neutral at 30 ft. For the sake of simplification, there are no distribution transformers on the system. The phase conductors are at 34 feet with no shield wire on this system. The physical configuration can be seen in Figure 1. This system has its neutral conductor grounded at every pole.

The following case studies were executed using the popular transient analysis program ATP. ATP is an open-source software suite that is used throughout the world for this very type of analysis. A typical ATP circuit used in this analysis can be seen in Figure 2

Before we analyze the strike to the full system, let's take a closer look at the voltages and currents when lightning arrives at just one pole. Figure 3 shows a one pole ATP model.

Cloud to ground lightning strokes are a well studied phenomenon, but after it makes contact with earth,

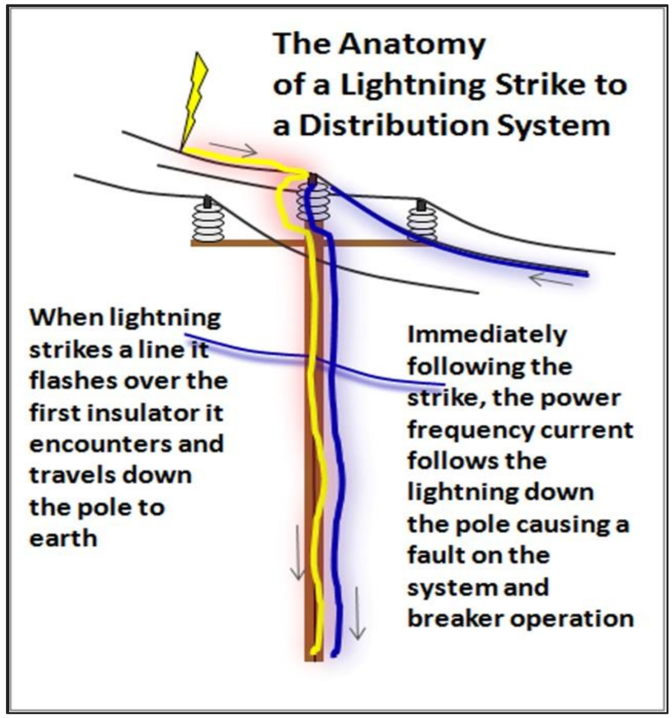

Figure 1: Typical four wire multi-grounded distribution system.

the data becomes scarcer. For this single pole analysis studied herein, the lighting strikes phase conductor B near the top of the pole and immediately the voltage begins to rise. Since the surge impedance of a distribution line is in the order of 300 ohms the voltage at the top of the tower for a 10, 000 amp lightning stroke would reach about 3,000,000 volts (Figure 4). Typically the Basic Insulation Level (BIL) of the insulators is 250kV, as soon as the voltage across the insulator exceeds this value, it flashes over. At the beginning of the strike, the voltage at the base of the insulators will be close to earth level therefore the entire voltage from the strike is across the insulators.

After the insulator flashes over, it is commonly thought that the voltage at the top of the pole will then go to

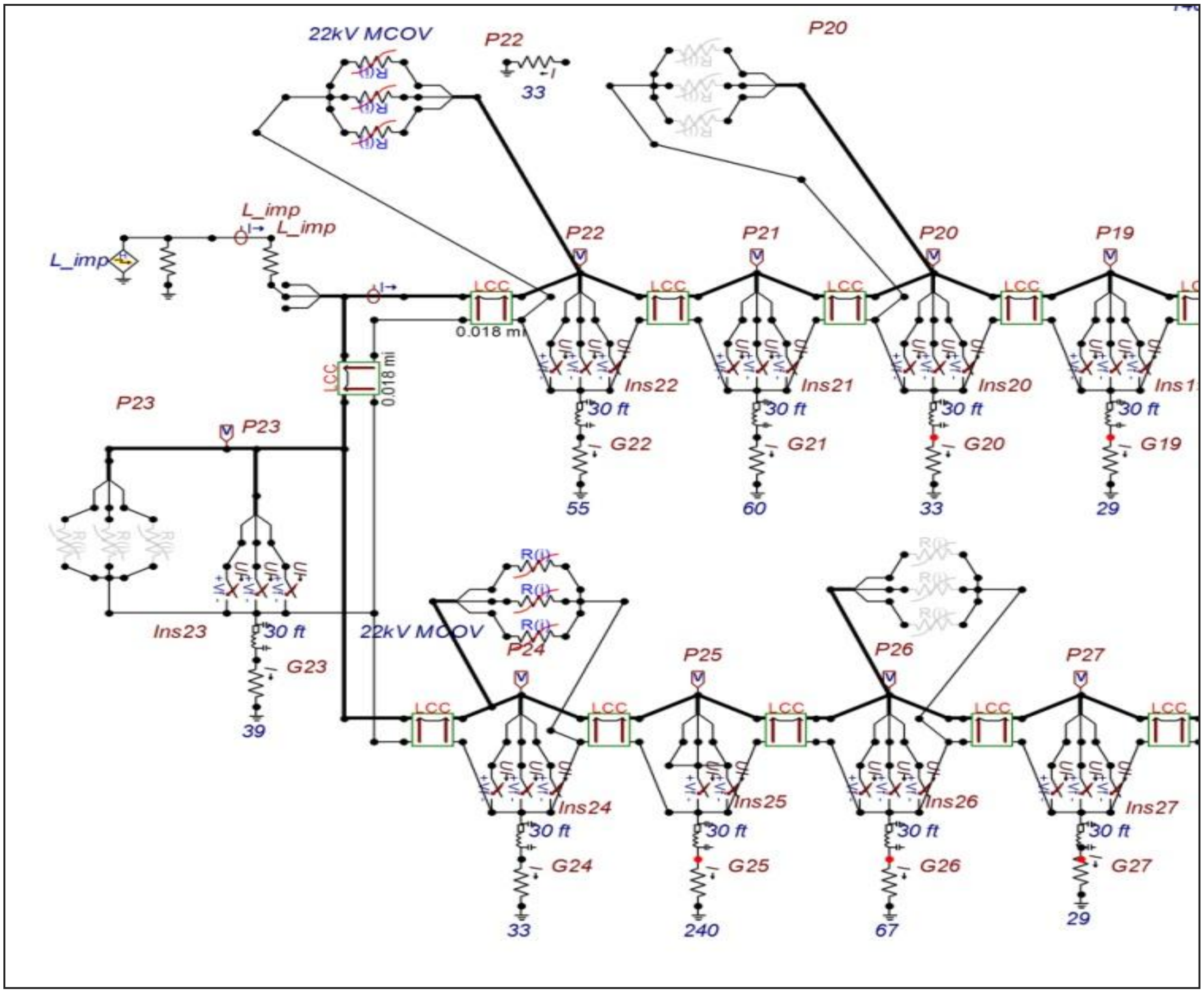

Figure 2: Typical ATP Model of a Distribution Line

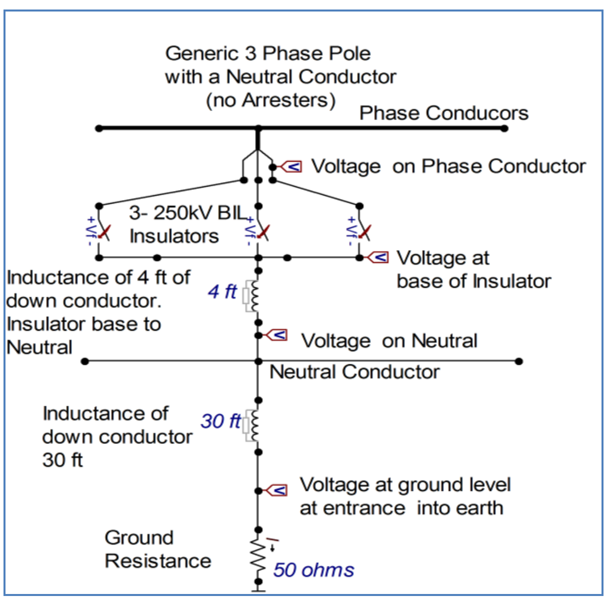

Figure 3: ATP Model of a Distribution pole similar to that seen in Figure 1.

earth levels, however this is not true. Figure 5 shows that after the flashover, the voltage at the top of the pole continues to rise. This is due to the fact that the pole down conductor has resistance at its interface to earth. The voltage level at the top of a pole during a lightning strike is a strong function of the current of the stroke and the pole ground resistance. In this case earth resistance is 50 ohms and the current down the pole is just under 6000 amps. Simple ohms law tells us that the

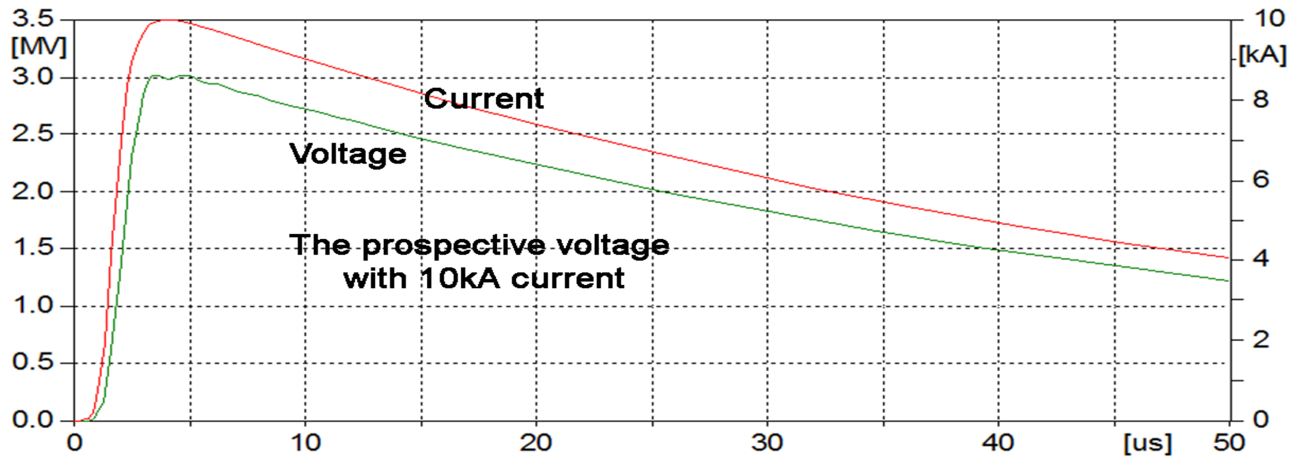

Figure 4: Surge voltage on the line created by stroke current and line surge impedance

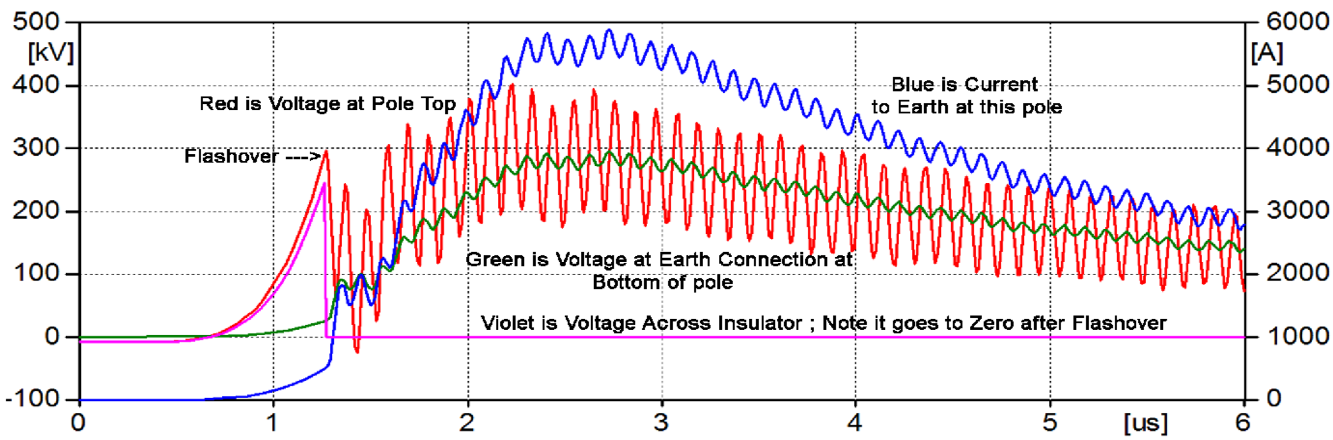

Figure 5: Voltage a various points on a distribution pole during a lightning event

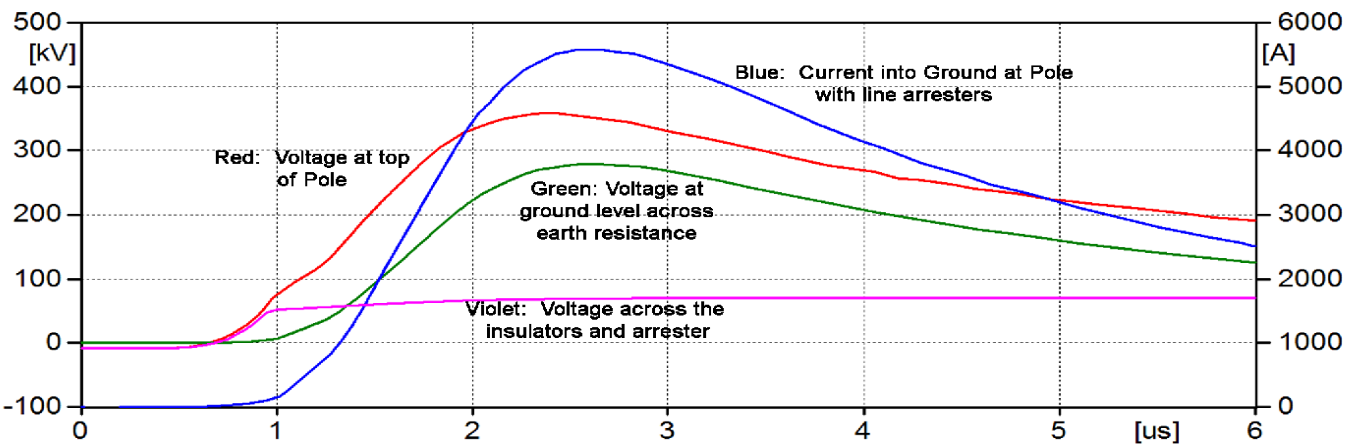

Figure 6: Same pole as in Figure 4, but with an arrester installed across the insulator

voltage across the earth resistance will be a minimum of 300kV plus the voltage drop along the inductance of the down conductor.

When running the same simulation with arresters on the pole (Figure 6), the voltage levels are very similar. The only major difference is that the insulator does not flashover. Table 1 shows the various voltages and currents on two identical poles, one with arresters and one without.

Comparison of Pole Voltages and Currents							
		Pole 22 without Arresters			Pole 23 with Arresters		
Lightning Current Level-→		**10kA**	**30kA**	**50kA**	**10kA**	**30kA**	**50kA**
Voltage at Top**	25 ohm ground	380kV*	875kV	1.4MV	246kV	620kV	940kV
Voltage across Ins		Flashover at all currents			71kV	79lV	87kV
Voltage at Gnd		285kV	808kV	1.28MV	169kV	490kV	766kV
Current into Gnd		5.7kA	16.5kA	26kA	6.2kA	19kA	30kA
Voltage at Top	50 ohm ground	400kV*	875kV	1.37MV	350kV	900kV	1.4MV
Voltage across Ins		Flashover at all currents			70kV	79kV	86kV
Voltage at Gnd		285kV	818kV	1.33MV	270kV	780kV	1.3MV
Current into Gnd		5.7kA	16.5kA	26kA	5.6kA	15kA	26kA
Voltage at Top	100 ohm ground	409kV*	867kV	1.38MV	493kV	1.25MV	2.02MV
Voltage across Ins		Flashover at all currents			69kV	78kV	84kV
Voltage at Gnd		307kV	847kV	1.37MV	419kV	1.14MV	1.9MV
Current into Gnd		5.7kA	16.5kA	27kA	4.2kA	11.5kA	19kA
*Significant Oscillations Peak Value taken see Fig 5 **Locations of measurement points can be seen in Figure 2							

Table 1: Voltage Profile along a pole struck by lightning

What becomes obvious from this exercise shown in Table 1 is:

1. The voltage at the top of the pole is a strong function of the lightning current. In every case, the higher the stroke current, the higher the voltage at the pole top. This is the case whether the insulator flashes over or the arrester conducts and inhibits the flashover.
2. The voltage at the pole top is also a strong function of the down conductor's resistance at its interface to ground (ground resistance).
3. The voltage potential experienced at the ground level is nearly as high as the voltage at the top of the pole during a lightning strike.

Response of Complete System to a Strike

A very common question in the industry, is how often should arresters be installed on a line (one without equipment) to give it protection from lightning. In North America, there is a common rule that says install 4 sets of arresters per mile or every 4 or 5 spans to improve lightning performance. This practice appears to have been around since antiquity in power systems. Let's explore this further with the circuit as shown in Figure 2.

For this analysis, a 31 pole circuit is used with various ground resistances. The span distance is constant at 200 ft. The location of the stroke is always near the top of pole 23 on the B phase but the arresters are located at various locations. Keep in mind that when arresters are connected to all phase on a pole, the insulators on that pole will not flashover. Table 2 shows the results.

Conclusions from Cases of Table 2

From these eight cases shown in Table 2, several conclusions can be drawn about the arrester location and the protection they provide to the system.

1. If arresters are mounted on every other pole and
   a. the lightning strikes near the top of the pole with arresters, there is no flashover of the protected pole, but both adjacent poles can flashover with lightning currents as low as 50kA (Case 3). At even higher currents, flashover can be experienced on all three phases even when the strike is only to one phase.
   b. The lightning strikes phase B near the unprotected pole, it will flashover the struck phase for currents as low as 10kA (perhaps

Pole Location			Pole 18	Pole 20	Pole 22	Pole 23	Pole 24	Pole 26	Pole 28
Distance from Pole 23 (ft)			1000	600	200	0	200	600	1000
Pole Ground Resistance Ohms			33	33	55	39	33	67	33
Case	Stroke Current to 23B	Phase			Surge is alwayon Pole 23 Phase B				
1	20kA	A	Arr	No FO	No FO	FO	No FO	No FO	Arr
		B	Arr	No FO	No FO	FO	No FO	No FO	Arr
		C	Arr	No FO	No FO	FO	No FO	No FO	Arr
2	20kA	A	Arr	No FO	No FO	Arr	No FO	No FO	Arr
		B	Arr	No FO	No FO	Arr	No FO	No FO	Arr
		C	Arr	No FO	No FO	Arr	No FO	No FO	Arr
3	50kA	A	Arr	No FO	No FO	Arr	No FO	No FO	Arr
		B	Arr	No FO	FO	Arr	FO	No FO	Arr
		C	Arr	No FO	No FO	Arr	No FO	No FO	Arr
4	70kA	A	Arr	No FO	FO	Arr	FO	No FO	Arr
		B	Arr	No FO	FO	Arr	FO	No FO	Arr
		C	Arr	No FO	FO	Arr	FO	No FO	Arr
5	70kA	A	No FO	Arr	FO	FO	FO	Arr	No FO
		B	No FO	Arr	FO	FO	FO	Arr	No FO
		C	No FO	Arr	FO	FO	FO	Arr	No FO
	30kA	A	No FO	Arr	No FO	No FO	No FO	Arr	No FO
		B	No FO	Arr	FO	FO	FO	Arr	No FO
		C	No FO	Arr	No FO	No FO	No FO	Arr	No FO
7	10kA	A	No FO	Arr	No FO	No FO	No FO	Arr	No FO
		B	No FO	Arr	No FO	FO	No FO	Arr	No FO
		C	No FO	Arr	No FO	No FO	No FO	Arr	No FO
8	10kA	A	No FO	No FO	Arr	No FO	Arr	No FO	No FO
		B	No FO	No FO	Arr	FO	Arr	No FO	No FO
		C	No FO	No FO	Arr	No FO	Arr	No FO	No FO

Table 2 Case study results showing various system responses to stroke at pole 23 B phase

c. lower). The adjacent protected poles do not flashover.

2. With arresters 5 spans apart, and lightning strikes a protected pole, that pole will not experience a flashover, but both adjacent poles may flashover depending on the current.
3. With arresters located 6 spans apart, (200 ft per span) and lightning strikes to center pole, it will flashover for currents as low as 10kA (Cases 5,6,7)

Mid-Span Strike Analysis

For the last example in this arrester spacing study, the strike is directed to the center of the span between poles 22 and 23. Pole 23 is protected with arresters while pole 22 is not protected (see figure 2). As predicted from the earlier cases, the voltage at the top of the poles will rise to very high levels even if they flashover or have arresters installed. This is a perfect example of how an arrester protected pole does not experience a flashover but the voltage on the system rises to significant levels and moves the flashover to the unprotected pole . In this case, at 30kA strike causes flashovers occur at pole 23 and 20. For a 50kA strike to the same circuit, only poles on either side of the protected pole (22) flashover. of the poles will rise to very high levels even if they flashover or have arresters installed.

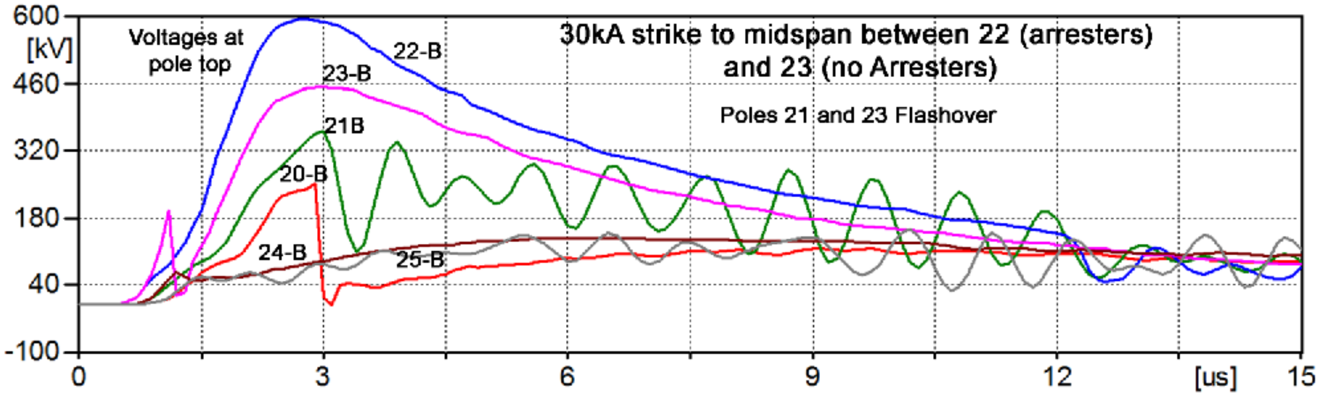

Figure 7: Voltages on phase B along the line with a 30kA strike to midspan between Pole 22 and 23

The voltages on B phase along the line as shown if Figure 7 is a perfect example of how an arrester protected pole does not experience a flashover but the voltage on the system rises to significant levels and moves the flashover to the unprotected pole . In this case, at 30kA strike causes flashovers occur at pole 23 and 20.

For a 50kA strike to the same circuit, only poles on either side of the protected pole (22) flashover.

Overall Conclusions

1. It can be seen from the above examples that a lightning stroke has multiple paths once it enters the power system.
2. The ground resistance of a pole and the magnitude of the lightning stroke determine the voltage level at the pole top. For even low lightning currents and normal ground resistances, the voltage at a pole top can reach several million volts.
3. The main lesson learned herein is that if lightning strikes a phase conductor near a pole that is protected by arresters and the adjacent poles are not protected, the protected pole will not experience a flashover but for average current levels, the flashover will move to a nearby-unprotected pole.
4. If arresters are installed using the four per mile rule, the pole with the arresters will not flashover, but the flashover will generally move to the first unprotected pole. Unfortunately, it is quite possible that on a system with high ground resistance, arresters using this rule will result in no improvement in outage rate.
5. It appears that the only effective way to protect an unshielded line as configured here is to install arresters at every pole, anything less than that has a very low return on the investment. (This conclusion is corroborated in IEEE 1410 section 7.3, “Guide for Improving the Lightning Performance of Distribution Lines”.)

Summary

Once the charge from a lightning strike enters a distribution system, it has many options on how to act. The line configuration however is the master of the surge destiny and fortunately, for us, the surge can be effectively managed. Insulators do not have to flashover and lines do not need to fault during a storm if line configurations are selected appropriately.

About ArresterFacts

Thanks for using ArresterWorks as your source of Arrester and Surge Understanding.

If you ever have any questions about this or other arrester issues, contact Jonathan Woodworth at jonathan.woodworth@arresterworks.com

Visit www.arresterworks.com for all you surge protection needs.