

ARCING FAULT 'RESISTANCE' (IT ISN'T)

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Abstract

Much has been written about the imperfection of distance relays when faced with arcing faults near the reach point on a transmission line when there is significant 'remote end infeed.' Warrington, in 1931, showed that there is not really a problem, if the arc is modeled correctly. Here, the benefits of modern computers are used to confirm Warrington's conjecture, and show that it is not physically correct to simply postulate arbitrary arc resistance values and assume linearity of the arc resistance. An arcing fault is shown to have a relatively small "apparent arc impedance" compared to the line impedance, for a variety of conditions.

INTRODUCTION

A transmission line arcing fault is often modeled as resistance, because the 60-hertz component of the current through the arc is essentially in phase with the 60-hertz component of the voltage across the arc. The first problem with this approach is that a particular arc's voltage/current ratio varies greatly with the current magnitude, and the second problem is that simply choosing a wide range of values for the arc resistance – to 'cover all the bases' – is not a valid approach, as it turns out. Warrington recognized this many years ago(1), (2).

This paper does not consider the 'high impedance arcing fault' phenomenon, as when a broken conductor falls to the ground. That too is a highly nonlinear situation, but requires a different approach to detection since the current is usually well below load current.

The situation addressed here is that of a lightning-induced or a pollution-induced 60-hertz arc across an insulator string. See Fig 1. A phase-to-phase arc induced by wind-blown conductors is not specifically considered, but the conclusions would be the same.

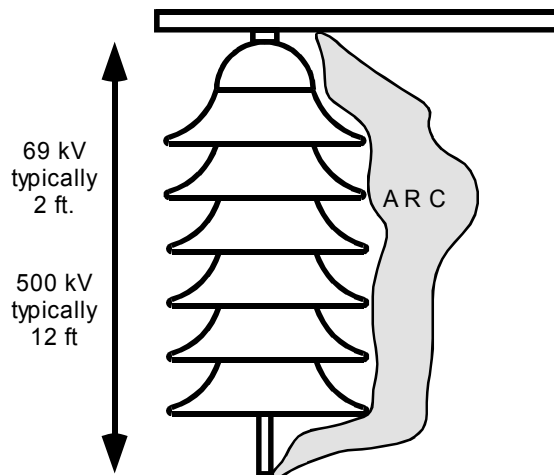


Fig. 1. Sixty hertz arcing fault across an insulator string.

The reason for examining this condition is the need to set distance relays such that they do not over- or under-reach because of the arcing fault component of the sensed distance, or the error in this perception caused by *remote end infeed*. If this effect were significant, it would have to be allowed for either in a compromised setting for the distance relay zone, or by changing the distance-measuring algorithm if that were deemed reasonable and feasible. The effect, and three commonly used distance relay characteristics are shown in Fig. 2.

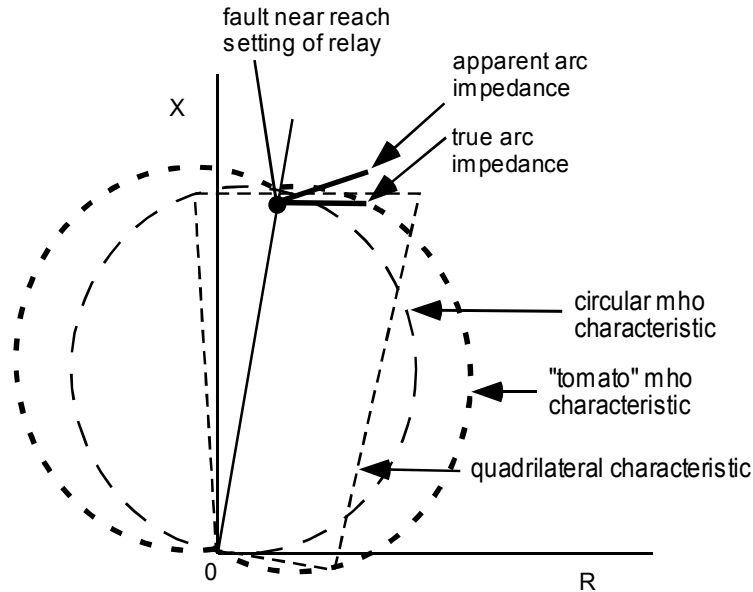


Fig. 2. Perception of the arc impedance in the distance relay plane.

THE NATURE OF A 60-HERTZ ARC

Examples of voltage-current measurements taken on actual 60-hertz arcs, under actual operating conditions are rare. One excellent recording was made during staged-fault tests on a 500kV Canada-USA interconnection transmission line, in 1982(3). The single-phase arc length was 3.8 meters, i.e. about 12 feet, typical of an insulator string length for a 500kV line.

Fig. 3 shows the arc voltage and current oscilloscope recordings. Zero time was the instant at which the fault was initiated, by the swinging of a very fine steel wire from ground to the conductor. The fault site was 48 km (30 miles) from the source end. Other details are available from the paper(3).

Fig. 4 shows that it is reasonable to use phasor analysis to study the effects of arcs on the 'big picture.' The sinusoidal fundamental components are quite accurate – certainly for the first few cycles where first-zone impedance elements are expected to operate correctly.

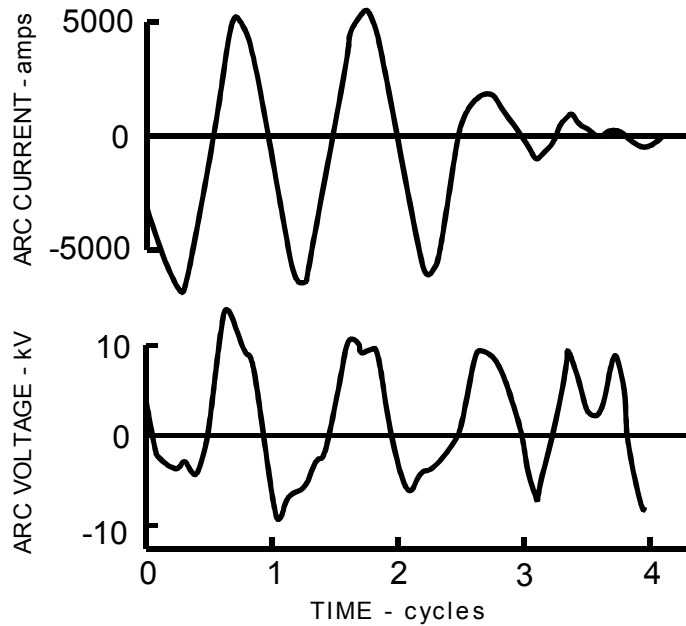


Fig. 3. Arc current and arc voltage from 500-kV line staged fault tests.

It is tempting to calculate a ‘resistance’ from the data of these curves. The rms voltage (in the first few cycles, and excluding the dc offset) is about 5400 volts, and the rms current is about 4400 amps. This gives an apparent resistance of 1.2 ohms. The trouble with actually using this figure is that it will vary wildly from this value at other fault locations. A key observation, though, is that it is low compared to the line impedance to the fault, and this will be shown to be almost always the case.

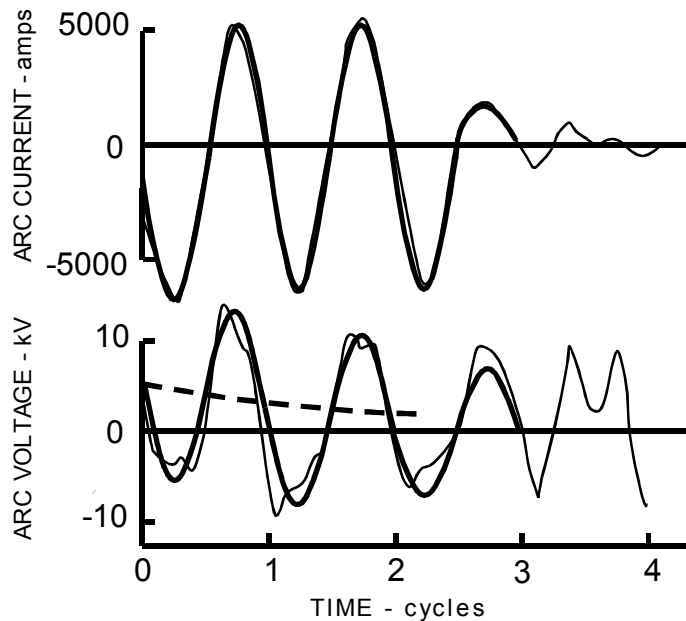


Fig. 4. Sixty-hertz sinusoidal approximations (heavy lines) superimposed on the waveforms of Fig. 3 (light lines).

ARC MODEL

Two commonly used 'models' are the Warrington(4) model and the Blackburn(5) model. In both of these, it is assumed that phasor analysis holds, in other words that 60-hertz sinusoidal analysis is close enough. Figures 3 and 4 seem to corroborate this assumption. However, both models postulate that *linear resistance* is not a proper model. The Warrington model, the Blackburn model and the Linear Resistance model can all be expressed by a common equation:

$$\text{Common equation:} \quad V = K \cdot L \cdot I^N$$

where V is the ac rms arc voltage in volts,
 I is the ac rms arc current in amps,
 K is a constant,
 L is the arc length in feet,
 N is a constant.

$$\text{Warrington:} \quad V = 8750 \cdot L \cdot I^{-0.4} \quad (1)$$

$$\text{Blackburn:} \quad V = 440 \cdot L \cdot I^0 \quad (2)$$

$$\text{Linear Resistance:} \quad V = K \cdot L \cdot I^1 \quad (3)$$

Fig. 5 shows a comparison of these models. The Linear Resistance model is shown in parentheses because it should not be used. It can only be considered valid at a point where it agrees with either the Warrington or Blackburn model, not at other arbitrary points on its locus.

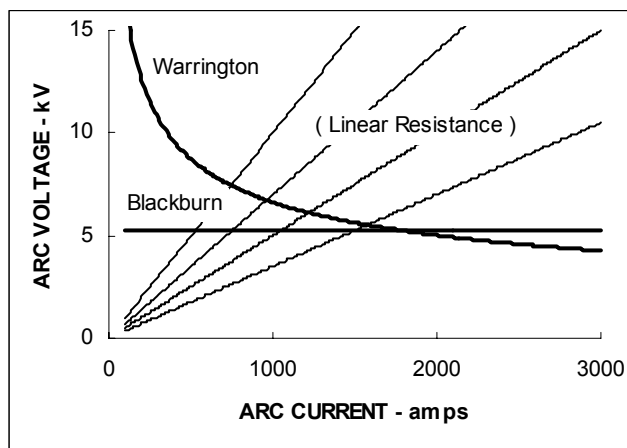


Fig. 5. Comparison of several 60-Hz arc models.

Incidentally, some recent work(6) in Germany re-examines Warrington's original 1931 data(1) which was limited to currents of 1000 A, and also draws conclusions following laboratory work at FGH-Mannheim with currents up to 20 kA. A careful reading of the paper, though, suggests that Warrington's formula or Blackburn's formula are not far off the mark.

For example, the paper suggests that Blackburn’s constant of 440 V/ft might be more accurate if changed to 366 V/ft or 412 V/ft or even 260 V/ft, but doesn’t say which. One conclusion might be that we should be using only one significant figure: say 400 V/ft.

It remains to more carefully specify the mathematics of the arc model, in phasor-usable form.

Equations (1) and (2) specify the *magnitude* of the (assumed sinusoidal) voltage as a function of the *magnitude* of the (assumed sinusoidal) current. The *phase* must be considered, and the model simply specifies that *the arc voltage is always in phase with the arc current* no matter what that phase may be with respect to some reference. See Fig. 6. The mathematical detail to accomplish this, is not presented here. It is one of the factors that makes the circuit solution ‘tricky.’

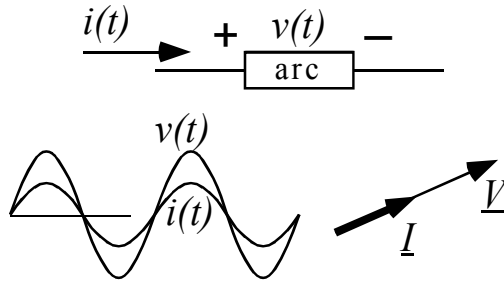


Fig. 6. Voltage-current relationship for Warrington or Blackburn model.

It is interesting that, in the case of the Blackburn model, the circuit element is an “ac constant voltage sink,” analogous to an ideal generator, which is an “ac constant voltage source.”

CIRCUIT ANALYSIS MODEL

Circuit analysis is here complicated by the fact that the arc model is nonlinear, even if it is assumed to be a phasor relationship. The single-phase fault case (assumed here) is shown in Fig. 7.

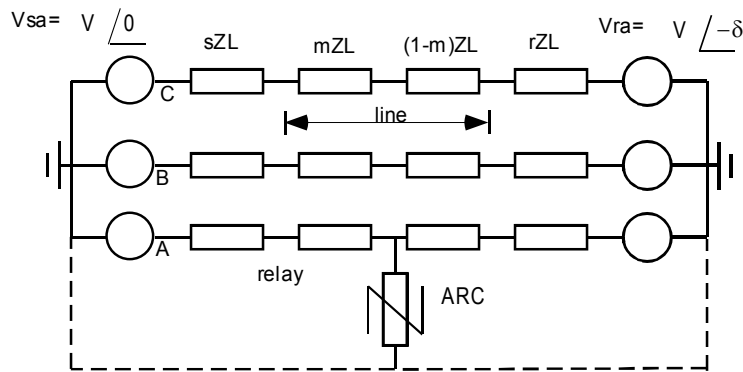


Fig. 7. Three-phase circuit and corresponding sequence network, for a phase-to-ground fault through an arc.

The symbols used in the figure are

δ	load angle	r	receiving end source impedance ratio for 100% of the line
ZL	line positive sequence impedance	V_{sa}	phase A voltage, sending end
m	relative distance to fault	V_{ra}	phase A voltage, receiving end
s	sending end source impedance ratio for 100% of the line	Z_{ratio}	zero-to-pos. sequence imp. ratio

Note that the effects of ground wires and tower footing resistance are already included by means of the zero-to-positive sequence impedance ratio, Z_{ratio} (which may be a complex number). See the Appendix for the sequence network used to solve the circuit.

CALCULATIONS AND RESULTS

Three examples are presented here. For each, the relay reach (m) is 80% of the line length; the remote end source impedance ratio (r) is 20%; and the Warrington arc model is used. The 500 kV line is that of reference (3); the 69 kV line is a hypothetical one representing the lower-voltage end of lines with distance relaying applied.

The 500 kV line is 334 miles long, has a positive sequence impedance Z_1 of $0.02+j0.498 \Omega/\text{mi}$, a zero sequence impedance Z_0 of $0.28+j1.674 \Omega/\text{mi}$, an assumed load angle of 30° , and an insulator string length of 12 feet.

The 69 kV line is 25 miles long, has a positive sequence impedance Z_1 of $0.3+j0.8 \Omega/\text{mi}$, a zero sequence impedance Z_0 of $0.9+j2.4 \Omega/\text{mi}$, an assumed load angle of 45° , and an insulator string length of 2 feet.

Three significant parameters were varied:

- | | |
|--------------------------------|--|
| Arc length | <ul style="list-style-type: none"> • length of arc = length of insulator string – the most probable case, • length of arc = 3 x length of insulator string – perhaps a wind-blown arc. |
| Source impedance | <ul style="list-style-type: none"> • 20% of the line length - the actual case for the 500 kV line, • 200% of the line length, since this has a noticeable effect. |
| Pre-fault power flow direction | <ul style="list-style-type: none"> • toward far end of line, • toward near end of line. |

Table 1. Details of Studied Cases with Abbreviated Results of Calculations

Results listed for reach point (m=0.8) only, and pre-fault load direction toward far end of line)

Case	Voltage kV	Arc length feet	Z _{source} % of line	(a)	(b)	Error (b)-(a)	Reactive reach error in %
				Actual Z ₁ to fault	Relay sees Z to fault		
1a	500	12	20 %	6.9+j145.9	9.4+j147.2	2.5+j1.3	0.9 %
1b	500	36	20 %	“	14.5+j149.8	7.5+j3.9	2.7 %
2a	69	2	20 %	6.0+j16	6.3+j16.2	0.3+j0.2	1.2 %
2b	69	6	20 %	“	6.9+j16.6	0.9+j0.6	3.8 %
3a	69	2	200 %	“	6.8+j16.7	0.8+j0.7	4.4 %
3b	69	6	200 %	“	8.5+j18.2	2.5+j2.2	13.8 %

Complete results are shown on R vs X diagrams in figures 8, 9, and 10. The fault was applied at every possible location along the entire length of the each line, that is, $0 < m < 1.0$.

The “tip-up” in the perceived impedance is for a pre-fault load current toward the far end of the line, i.e. ‘under-reach’. A “tip-down” effect occurs for pre-fault current in the reverse direction. For clarity, it is not included in the figures except as noted by the dashed lines in Fig. 10.

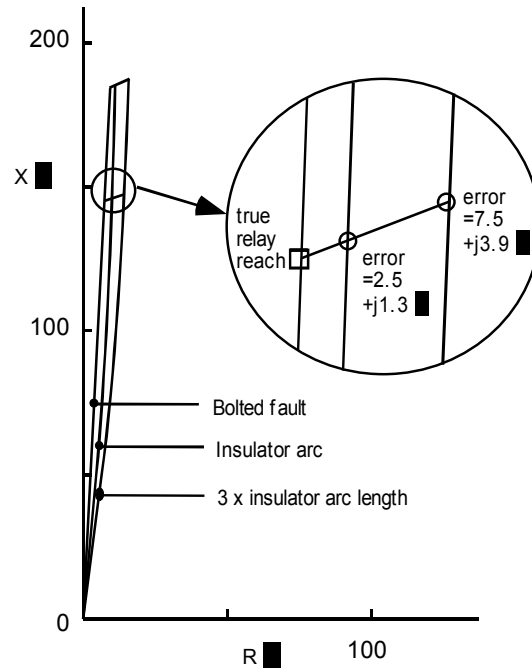


Fig. 8. Case 1: 500 kV line with no arc, 12-foot insulator arc, and 36-foot arc.

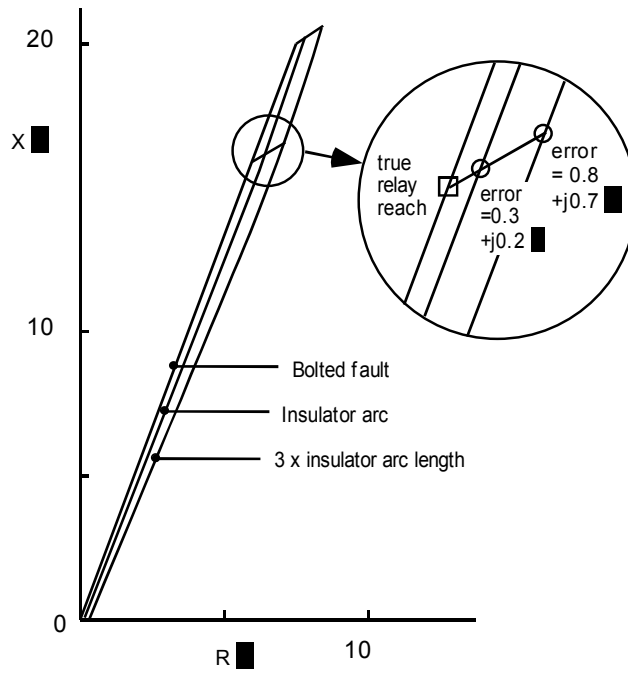


Fig. 9. 69 kV line.

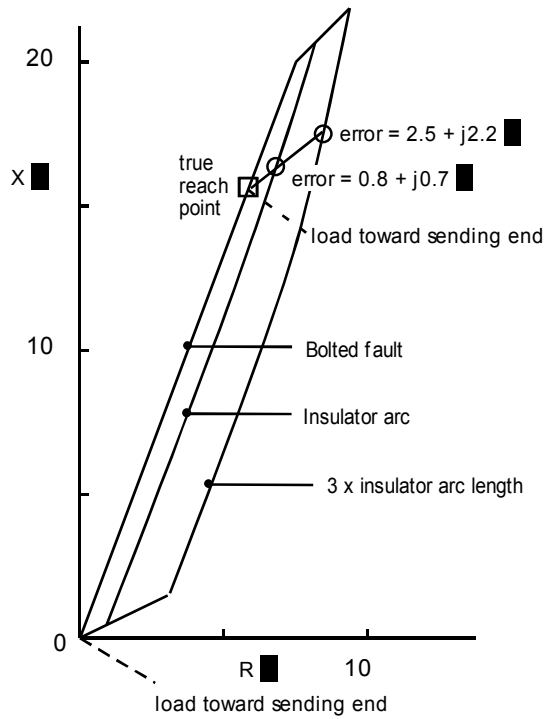


Fig. 10. 69 kV line with high source impedance.

CONCLUSIONS

For the representative cases studied, the error in reactive reach is less than five per cent, except under very unusual cases such as extra-long fault arc length and extra-high source impedance and for a relatively low voltage line. It is probable that errors in measurement or errors in other settings (e.g. $Z1/Z0$ ratio) will be greater than the error due to apparent arc impedance. Therefore, it is concluded that this factor need not be taken into account in setting distance relays.

Also, the additional resistance-direction reach to be covered by a distance relay – if intended to allow for apparent arc resistance - need not be as large as may have been assumed in the past.

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Appendix: Sequence Network

The circuit of Fig. 7 can be analyzed directly, using for example EMTP, or EMTDC, but the nonlinear arcing fault models of interest in this paper may not be available. Therefore, MathCad was used, for which it was decided that a *sequence component* network would be the most efficient way. Only the single phase to ground fault was considered since it is by far the most common.

In MathCad, it is quite convenient to use the *Given, Find* routine to solve nonlinear complex-number equations. The symmetrical component equivalent circuit used is shown below, as Fig. 8.

The solution is found by solving three equations in three unknowns (VF, IF, and I1).

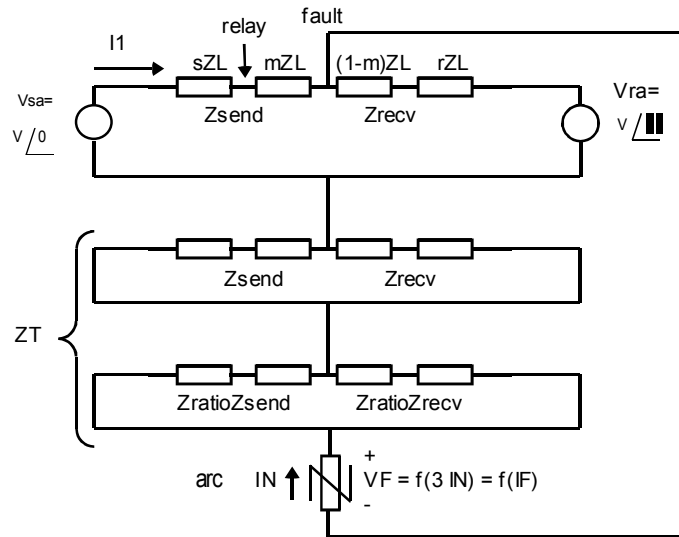


Fig. 11. Sequence network.

The symbols used in the figure are

δ	load angle	Z_{send}	total imp. to fault, sending. end
ZL	line positive sequence impedance	Z_{recv}	total imp. to fault, receiving end
m	relative distance to fault	V_{sa}	phase A voltage, sending end
s	sending end source imp. ratio	V_{ra}	phase A voltage, receiving end
r	receiving end source imp. ratio	Z_{ratio}	zero-to-pos. sequence imp. ratio

The details of the calculation are not presented here.

AUTHORS

Glenn Swift: Glenn graduated from the University of Alberta in 1953, and received the PhD degree from the Illinois Institute of Technology in 1968. He has worked for several firms including Metropolitan-Vickers in the UK, Canadian Westinghouse, Ontario Hydro and Federal Pioneer Ltd. After thirty-six years as a professor of Electrical Engineering, he helped establish a division of NxtPhase Corporation, a manufacturer of relays, recorders and optical current and voltage transformers.

Dave Fedirchuk: Dave graduated from the University of Manitoba in 1972. He has been a Professional Engineer for twenty-five years, with Manitoba Hydro, engaged in relay settings determination and disturbance analysis work. For the last 6 years he has been working for NxtPhase Corporation as Product Manager for their line of relays and disturbance recorders.

Tom Ernst: Tom graduated from the University of Minnesota in 1978 with a BSEE. He worked for Northern States Power Co. (Xcel energy) in Minneapolis, Minnesota for 18 years where he held various positions in substation relay engineering, and plant electrical and I&C engineering. In 1993, he left NSP to work as a utility consultant designing substation projects for Municipal, Cooperative and Investor Owned utilities. Tom moved to Duluth, Minnesota in 1997 to take his current position as Supervising Engineer - Relay Engineering for Minnesota Power.