Thermal Overload Protection of Cables

1. Introduction

Failure of underground cables can be costly and time consuming to repair. Protection systems are designed to protect cables from the high current levels present under fault conditions. However, the temperature rise due to extended overload conditions is just as likely to cause cable failure. As the trend in power system operations is to utilize equipment as close to operating limits as possible, the importance of protecting equipment against thermal overloads becomes more critical.

Thermal overload protection calculates the temperature of the conductor based on specific conductor data and the current present in the circuit, and is used to protect conductors from damage due to extended overloads. In this application example thermal overload protection of underground cables only is described.

Thermal overload protection is normally used in an alarm mode to notify system operators of the potential for cable damage. However, thermal overload protection can be used to trip a circuit-breaker as well. In either case, the presence of thermal overload can be detected and removed before cable failure occurs.

2. Thermal overload protection

Thermal overload protection with total memory calculates a real time estimate of the temperature rise of the cable, Θ, expressed in terms of the maximum temperature rise, $\Delta\Theta_{max}$. This calculation is based on the magnitude of currents flowing to the load, and the maximum continuous current rating of the conductor. The calculation uses the solution to the first order thermal differential equation:

$$\tau \frac{d\Theta}{dt} + \Theta = I^2$$

$$\underline{\text{with}} \; = \Theta = \frac{\Delta\Theta}{\Delta\Theta_{max}}$$

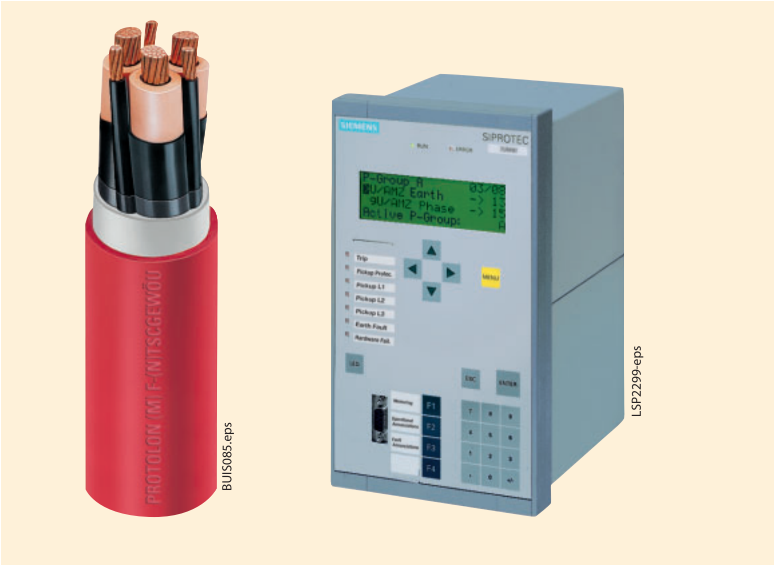

Fig. 1

$\Delta\Theta$ = temperature rise above ambient temperature
$\Delta\Theta_{max}$ = maximum rated temperature rise corresponding to maximum current
τ = thermal time constant for heating of the conductor
I = measured r.m.s. current based on the maximum rated overload current of the protected conductors: I_{meas}/I_{max}.

The solution to the thermal differential equation is:

$$\Theta_{op} = \Theta_{amb} + \Delta\Theta_{max}\left(1 - e^{\frac{-t}{\tau}}\right)$$

The initial value is Θ_{amb}, the ambient temperature of the cable, and the steady state value is $\Theta_{amb} + \Delta\Theta$, where $\Delta\Theta$ is determined by the magnitude of I. The initial value, Θ_{amb}, is assumed to be that temperature on which the cable ratings are based. The steady state value is achieved when the temperature has reached its final value due to the heating effects of I. At this point, the value of $\tau d\Theta/dt$ in Equation 1 is zero. Therefore, at steady state, $\Delta\Theta = \Delta\Theta_{max} I^2$, where $I = I_{meas}/I_{max}$. The transition between the initial value and the steady state value is governed by the exponential expression, $1 - e^{\frac{-t}{\tau}}$. τ is a constant of the cable to be protected.

Fig. 2 shows the operating temperature of the cable as a function of time and overload. With no load, the conductor is at its ambient temperature. If an overload equivalent to the maximum rated current is added at some time, the temperature of the cable will approach Θ_{max} following the exponential

$$1 - e^{\frac{-t}{\tau}}.$$

The conductor temperature due to a current overload, starting from no-load conditions, has the same characteristic as shown in Fig. 2, with Θ_{max} becoming Θ_{op}, and I_{MAX} becoming I_{Load}. However, when the conductor already has some load present, the characteristic of the operating temperature changes. The conductor will heat up the cable to some steady state temperature. When an overload is added, the final temperature of the cable is calculated as if the cable was at normal operating temperature. However, the starting point of the second (overload) characteristic will coincide with the steady state temperature of the normal load. This is illustrated in Fig. 3.

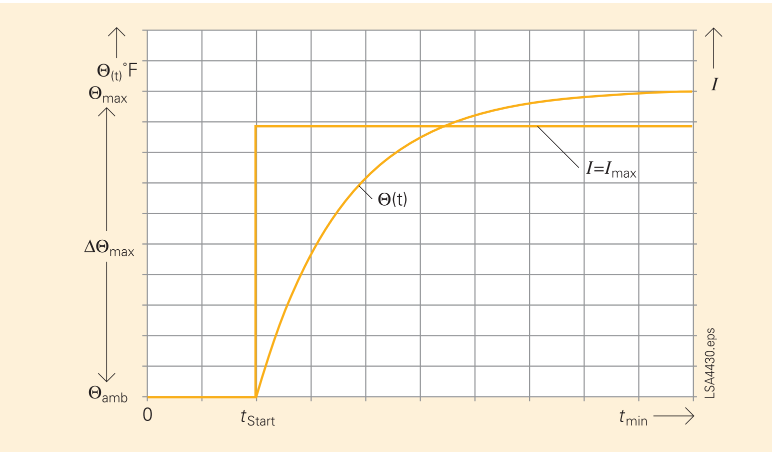

Fig. 2 Temperature vs. time for an overload of I_{max}

3. Calculation of settings

There are two required settings for thermal overload protection, the k factor, and the thermal time constant τ. τ is specific to the properties of the cable. The k factor relates the maximum continuous current rating of the cable to the relay.

3.1 Maximum continuous current of cable

The maximum continuous current rating of the cable is used in determining the k factor setting, and may be used in determining the setting for τ. This current depends on the cross-section, insulating material, cable design, and conductor configuration. Cable manufacturers may specify the maximum continuous current rating of their cable. If the rating is not available, it is possible to estimate a maximum continuous current based on conductor ampacity information. The ampacity of conductors is specified based on circuit configurations, conductor temperature, and ambient temperature. Also specified is the maximum operating temperature of the conductor, and correction factors for various conductor operating temperatures and ambient earth temperatures.

To determine the maximum continuous current rating of a cable, use the ampacity at the emergency overload operating temperature, and not that of the maximum conductor operating temperature. According to ICEA specifications, [1] *emergency overloads* are permitted for only a total of 100 hours per 12 month period, only for no more than five such periods in the life of the cable. Therefore, it is desirable to trip or alarm for any situation when the thermal overload reaches this level. To determine the maximum continuous current, remember that the conductor configuration and ambient temperature effect the current rating.

Example:

Circuit voltage:	12.47 kV
Cable size:	500 MCM shielded copper cable
Conductor temperature:	90 °C
Ambient temperature:	20 °C
Configuration:	3 circuits duct bank

From conductor tables, the ampacity for 90 °C copper conductor at 20° ambient temperature with 3 circuits in duct bank is 360 amps. The emergency overload operating temperature for 90 °C-cable is 130 °C. From Table 1, at 20 °C ambient temperature, the ampacity rating factor is 1.18.

Therefore,
360 A x 1.18 = 424.8 A maximum continuous current

3.2 Calculating the k factor

The k factor relates the operating current to the relay to permit overload detection. The k factor is defined as the ratio of the maximum continuous current I_{max} to the rated relay current I_N:

Example:

$$k = \frac{I_{max}}{I_N}$$

Circuit voltage	12.47 kV
Cable size	500 MCM shielded copper cable
Conductor temperature	90 °C
Ambient temperature	20 °C
Configuration	3 circuits in duct bank
Maximum continuous current (I_{max})	424.8 A primary
Current transformer ratio	800/5
Rated relay current (I_N)	5 A secondary

$$k = \frac{\frac{424.8}{(800/5)}}{5} = 0.53$$

3.3 Thermal time constant τ

The thermal time constant τ is a measure of the speed at which the cable heats up or cools down as load increases or decreases, and is the time required to reach 63 per cent of the final temperature rise with a constant power loss. The thermal time constant is the determining factor for calculating the operating temperature as a percent of the maximum permissible overload temperature, as shown in Equation 2. τ may be available from the cable manufacturer. If no specification for τ is available, it may be estimated from the permissible short-circuit rated current of the cable, and the maximum continuous current rating. It is common to use the 1 second rated current as the permissible short-circuit current. τ is calculated by the following equation:

$$\tau(\text{min}) = \frac{1}{60} \cdot \left| \frac{I_{1\ \text{second}}}{I_{max}} \right|^2$$

If the short-circuit current at an interval other than one second is used, the equation is multiplied by this interval. For example, if the 0.5 second rating is used:

$$\tau(\text{min}) = \frac{0.5}{60} \cdot \left| \frac{I_{0.5\ \text{second}}}{I_{max}} \right|^2$$

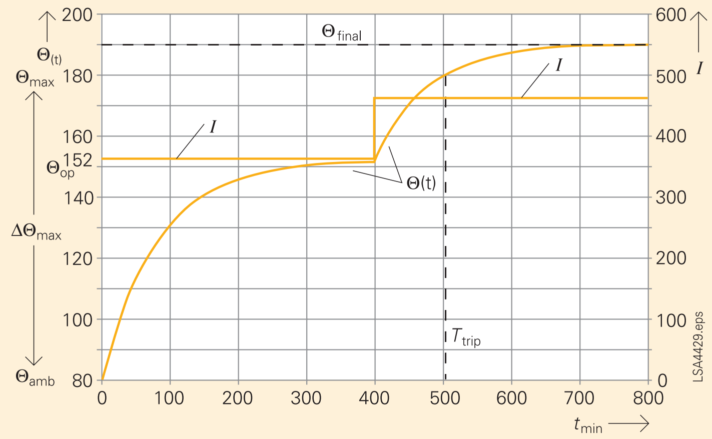

Fig. 3 Temperature vs. time with an existing overload

Example for calculating the thermal constant τ:

Circuit voltage	12.47 kV
Cable size	500 MCM shielded copper cable
Conductor temperature	90 °C
Ambient temperature	20 °C
Configuration	3 circuits in duct bank
Maximum continuos current (I_{max})	424.8 A primary
Maximum current oür 1 second	35,975 A primary

$$\tau(\text{min}) = \frac{1}{60} \cdot \left| \frac{35{,}975}{424.8} \right|^2 = 119.5\ \text{min}$$

Conductor size	Ampacity	Max. continuous current	Short-time withstand capability (1 sec)	τ (minutes)
1/0	160	189	7 585	27
2/0	185	218	9 570	32
3/0	205	242	12 065	41
4/0	230	271	15 214	52
250 MCM	255	301	17 975	59
350 MCM	305	360	25 165	81
500 MCM	360	425	35 950	119
750 MCM	430	507	53 925	188
1000 MCM	485	572	71 900	263

Table 1 Shielded copper conductor, 5001 - 35000 volts, 90 °C, three-conductor cable, three circuits in duct bank

Conductor temperature	Ambient earth temperature				
°C	10 °C	15 °C	20 °C	25 °C	30 °C
75	0.99	0.95	0.91	0.87	0.82
85	1.04	1.02	0.97	0.93	0.89
90	1.07	1.04	1.00	0.96	0.93
100	1.12	1.09	1.05	1.02	0.98
105	1.14	1.11	1.08	1.05	1.01
110	1.16	1.13	1.10	1.07	1.04
125	1.22	1.19	1.16	1.14	1.11
130	1.24	1.21	1.18	1.16	1.13
140	1.27	1.24	1.22	1.19	1.17

Table 2
Correction factors for various ambient earth temperatures

Short-circuit rated current for copper

- $$\left(\frac{I}{A}\right)^2 \cdot t = 0.0297 \cdot \log\left(\frac{T_2 + 234}{T_1 + 234}\right)$$

I = Short-circuit current - Amperes [A]
A = Conductor area - circular mils (0,001" diameter; convert to mm^2 where necessary)
t = time of short-circuit, seconds
T_1 = Operating temperature 90 °C
T_2 = Maximum short-circuit temperature 250 °C

Short-circuit current for aluminium

- $$\left(\frac{I}{A}\right)^2 \cdot t = 0.0125 \cdot \log\left(\frac{T_2 + 234}{T_1 + 234}\right)$$

Table 1 lists calculated values of τ for common conductors and configurations. Below Table 2 are the formulas to calculate the short-circuit rating of conductors

3.4 Analysis of relay settings

Combining the examples in Sections 3.1, 3.2, and 3.3, the cable information leads to the following relay settings:

k factor: 0.53

τ: 119.5 minutes

The operating temperature at a given moment in time can be calculated using Equation 2.

Θ_{amb} = the conductor operating temperature = 90 °C.
$\Delta\Theta_{max}$ = the maximum overload temperature minus the initial operating temperature = 130 °C - 90 °C = 40 °C.

As shown in Section 2 above, to determine the steady state temperature, the exponential term can be replaced by I^2, where $I = I_{meas}/I_{max}$. Based on these settings, and a load current of 400 A,

$$\Theta_{op} = \Theta_{amb} + \Delta\Theta_{max}\left(\frac{I_{meas}}{I_{max}}\right)^2 = 90° + 40°\left(\frac{400}{424.8}\right)^2$$

$$= 125\ °C$$

Thus, for a load of 400 A, the conductor will heat up to 125 °C.

4. Implementing thermal overload protection

Thermal overload protection in SIPROTEC relays calculates the temperature for all three phases independently, and uses the highest of the three calculated temperatures for tripping levels. Besides the k factor and the thermal time constant, there are two other settings for thermal overload protection. As seen in Figure 3, these are the "thermal alarm stage" and the "current overload alarm stage".

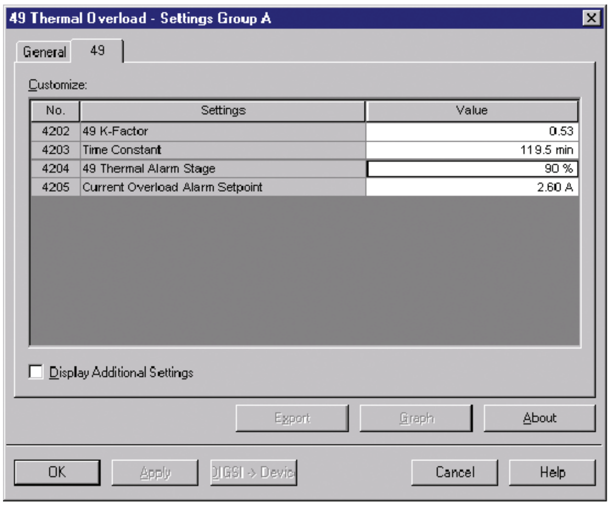

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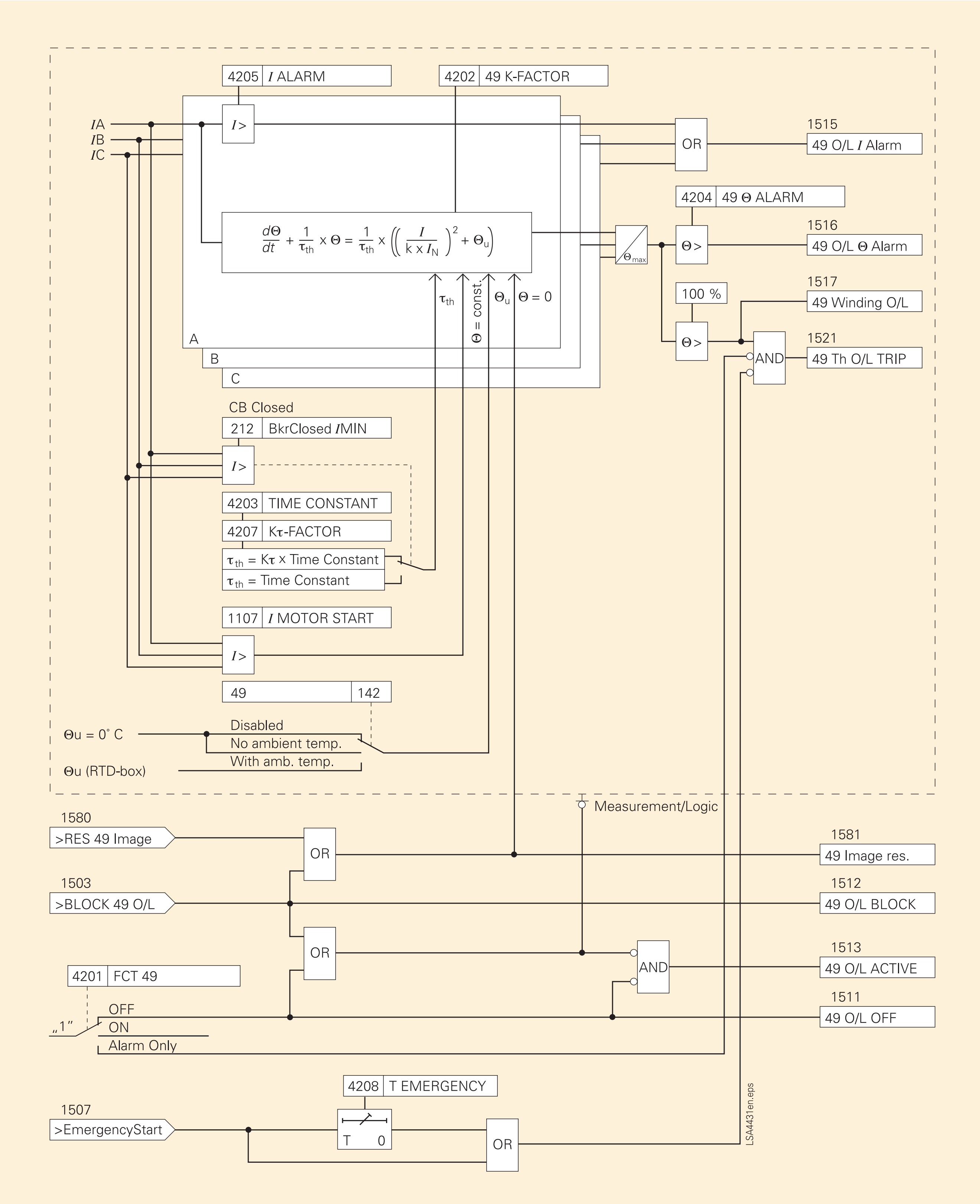
Fig. 4 Thermal overload protection settings

4.1 Thermal alarm stage

The thermal alarm stage sends an alarm signal before the relay trips for a thermal overload condition. The thermal alarm stage is also the dropout level for the thermal overload protection trip signal. Therefore, the calculated temperature must drop below this level for the protection trip to reset. This stage is set in percent of the maximum temperature. A setting of 90 % will meet most operating conditions.



$$\frac{d\Theta}{dt} + \frac{1}{\tau_{th}} \times \Theta = \frac{1}{\tau_{th}} \times \left(\left(\frac{I}{k \times I_N}\right)^2 + \Theta_u\right)$$

Fig. 5 Logic diagram of the overload protection

4.2 Current overload alarm stage

The current overload alarm stage sends an alarm when the load current exceeds the value of the setting. This setting should be set equal to, or slightly less than, the maximum continuous current rating of the cable.

4.3 Thermal overload protection as an alarm or tripping function

Thermal overload protection may be configured to either "ON" (tripping) or "Alarm only" for overload conditions, and is normally set to "Alarm only". Configuring thermal overload protection to "ON" makes this a tripping function, meaning it asserts the *0511 Relay TRIP* function. The factory default configuration of the relay has the *0511 Relay TRIP* function set to close a contact that trips the circuit-breaker.

"Alarm only" means thermal overload protection does not assert the *0511 relay trip* function. Thermal overload protection may still be programmed to operate a binary output for tripping purposes. this configuration allows the thermal overload function to be used to warn operators of potential cable failure due to overloads.

4.4 Adjusting settings for differences in ambient temperature

The ambient temperature of the earth has a significant effect on the maximum continuous current rating of the cable. In most applications, it is best to assume one ambient earth temperature to perform relay setting calculations. However, in some areas, there may be large seasonal differences in ambient earth temperature. Using multiple settings groups allows the relay to adapt the thermal overload protection settings to large changes in the seasonal temperature.

Changing the settings group can be accomplished via binary input, remote command, or function key, all of which require operator intervention to accomplish the change. Another possibility is to have the relay change settings groups based on system conditions. Wiring the output of a temperature sensor into an optional transducer input on the 7SJ63 relay will permit the changing of settings groups when the earth temperature passes a threshold for a specified period of time.

5. Summary

The failure of underground cables due to heating caused by long term overload conditions is easily prevented by using thermal overload protection. Based on information provided by cable manufacturers, circuit configuration, and operating conditions, it is simple to determine settings for thermal overload protection. Thermal overload protection is normally used to alarm for overload conditions, to allow system operators to make informed decisions on how to handle an overload to prevent cable damage. A thermal overload alarm, when combined with a SCADA system, can be used to track the amount of time the cable is exposed to overload, allowing for estimates of the remaining life of the cable.

6. References

Insulated Cable Engineers Association Standard P32-382-1994, "Short Circuit Characteristics of Insulated Cable", 1994, South Yarmouth, MA.

"Engineering Handbook", The Okonite Company, 1999, Ramsey, NJ.

H. Pender and W. Del Mar, "Electrical Engineer's Handbook", 4th Edition, Wiley & Sons, New York, NY.