SESSION 504

OVERHEAD VERSUS UNDERGROUND ANALYSIS

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ABSTRACT

Underground transmission cable usage in the United States is small: less than one percent of overhead line mileage. The higher cost of underground cables is of course the major impediment to their installation, but there are many technical differences between the two transmission types that affect cable usage as well.

In terms of utility system design and operation, cables tend to hog load when installed in parallel with overhead lines, their ampacity ratings are substantially different, outage times can be very much longer, capacitance effects are much higher, surge arrester duty is higher, dielectric losses can be high, reactive compensation may be required, etc. Sophisticated analysis is required to accurately quantify these effects.

Installation requires trenching (or boring) every foot of the route. Although long-term impact may be lower than for an overhead line, construction impact is often higher. In many cases, specialized equipment and specially trained personnel are required which are available from only a few sources.

This paper briefly describes issues that should be addressed in an overhead / underground analysis, and provides references for more detailed analysis.

UTILITY SYSTEM DESIGN

Applying an underground cable as an alternate to an overhead line is not simply a case of calculating equivalent power transfer capabilities and installing a suitable cable system. Several important considerations must be addressed in the initial planning stage. Principal issues are:

- Electrical characteristics
- Differences in steady-state loading
- Major differences in short-term overload characteristics
- Effects on power flows
- Reactive compensation requirements
- Effects on short-circuit currents
- Effects on switching devices
- Effects on surge-protective devices
- System losses
- Restoration procedures and times
- Reliability issues

Many of these issues can be evaluated using equations given in Reference 1, which may be adequate for an initial evaluation of an underground cable versus an overhead line. However, the detailed analysis which should be part of design for an actual cable system, requires computer analysis using load flow, transient-stability, short-circuit, and overvoltage programs – in additional to cable-system design programs such as ampacity, pulling tension, etc.

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Electrical Characteristics

Electrical characteristics of underground cables are significantly different from those of overhead lines, as summarized in Table 1. XLPE-insulated cables have lower charging current and dielectric losses than do paper-insulated high-pressure pipe-type cable, so they operate a little more like an overhead line.

Table 1
Typical Electrical Characteristics, 230-kV Overhead Line and Underground Cables

Parameter	Overhead Line	Underground XLPE	Underground HPFF
Shunt capacitance, µf\F/mi	0.15	0.26	0.43
Series inductance, mH/mi	2.0	0.90	0.70
Series Reactance, ohm/mi	0.77	0.34	0.26
Charging current, A/mi	1.4	13.1	21.7
Dielectric loss, kW/mi	0+	1.1	21.4
Reactive charging power, MVA/mi	0.3	5.2	8.6
Capacitive energy kJ/mi	0.26	2.3	7.6
Surge impedance, ohms	375	40	40
Surge impedance loading, MW	141	1300	1300

Figure 1 shows a cable equivalent circuit, taken from a paper addressing the system implications of underground cables[1].

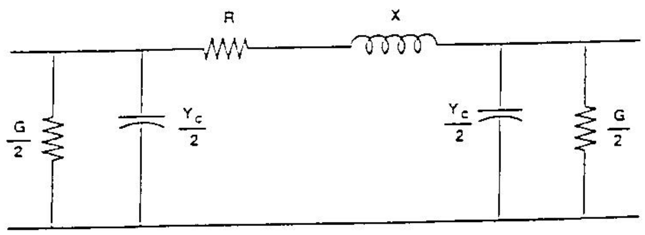


Figure 1. Cable equivalent circuit

The series impedance consists of the conductor resistance and inductive reactance, while the shunt impedance consists of capacitive reactance and dielectric losses. Capacitance is the major concern for underground cables, but we will address each of the components of the figure.

Series resistance R affects ampacity and losses, as will be described later. In addition, it will affect system voltages and angles in load flow studies and transient stability studies.

Series inductance, X_L, affects load sharing among transmission lines, fault current levels, voltage regulation, and system stability.

Shunt Resistance, G, represents dielectric losses in the underground cable.

Capacitive Reactance, Y_c, accounts for the cable system capacitance and affects inrush current, charging current, voltage profile, and surge impedance.

Although each of these impedances must be taken into account when performing detailed cable system design, we will only address the more important items.

Differences in steady-state loading

Figure 2 shows the electrical equivalent of the thermal circuit for an underground cable, which is much more complex than the circuit for overhead lines. Most of the terms can be calculated with good accuracy using the Neher-McGrath[2] procedure in the United States, and the equivalent IEC 287[3] elsewhere. Several PC-based ampacity programs are available.

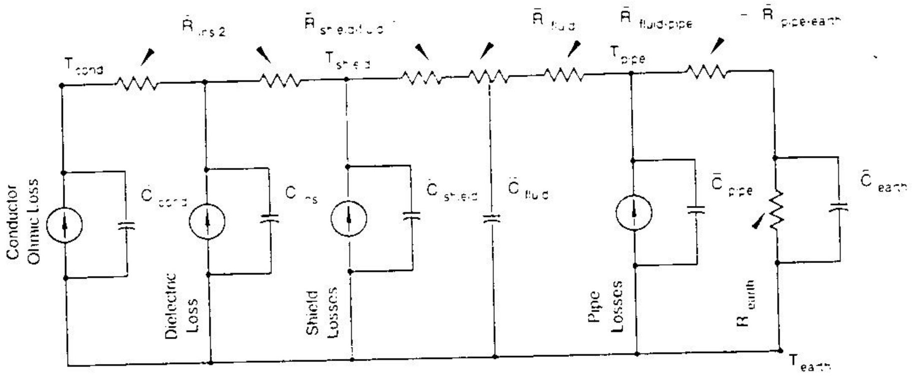


Figure 2. Electrical equivalent of cable thermal circuit

The thermal rating of an underground cable is much lower than that for an overhead transmission line. In an overhead line, heat generated in the conductors transfers directly to the air, and ampacities can be very high. In contrast, all of the heat generated in an underground cable must pass through the thermal resistance of the various cable system components and the earth before reaching the ultimate heat sink which is the air at the earth's surface. The earth thermal resistivity is by far the largest, accounting for more than half the total. It is also the most variable, changing both with distance along the cable and with time (because of changes in soil moisture content which strongly affects thermal properties.) Soil thermal resistance can easily vary by a factor of four over the cable length.

The thermal time constant for an overhead conductor is 10 - 20 minutes, which is far shorter than the duration of a daily load peak. Ratings are therefore based on peak loads. For underground cables, the earth's large thermal capacitance damps the temperature swings due to by changes in hourly loads, and the ampacity is based upon the average daily heat input, rather than the peak. (Since heat input is a function of losses – which vary as the square of load – cable rating is actually based upon a daily loss factor, which is defined as the load factor of the losses. An empirical equation relates load factor and loss factor).

Table 2 shows the effect of load/loss factor on allowable peak loadings for a 230-kV extruded-dielectric cable

Table 2
Effect of Load/Loss Factor on Allowable Peak Loadings

Load Factor per unit	Calculated Loss Factor, per unit	Allowable Peak Loading Amperes
0.5	0.33	1125
0.6	0.43	1085
0.7	0.55	1035
0.8	0.69	990
0.9	0.84	947
1.0	1.0	905

The disparity in ratings between overhead lines and underground cables results in one of the difficult issues a planner must face when evaluating the cable requirements for an underground line that might replace part or all of an overhead circuit. Utilities never want to limit capacity. The cable might therefore be required to match the thermal rating of the overhead line, even though the overhead line may never be operated near its thermal rating. Cost implications for the underground cable are very high.

Short-term overload characteristics

The insulated cables themselves have a large thermal mass compared to overhead lines, and the earth has a huge thermal mass. The internal thermal time constant for a cable system (time constant for the cable itself, commonly applied for transient ampacities) is 1 - 3 hours, and the external time constant, (including the earth near the cable, commonly applied for emergency ampacities) is more than a week.

In addition to the large heat-absorbing capabilities of the cable/earth system, industry specifications permit the cable conductor temperatures to increase for short periods. For XLPE cables, the normal 90°C allowable conductor temperature can rise to 105 - 130°C during emergency loadings. For paper-insulated cables, the normal 85°C allowable conductor temperature can rise to 100 - 105°C

Between the heat storage capacity of the cable/earth system and the higher allowable temperature during emergencies, the underground cable system is capable of substantial currents for short periods. Figure 3 shows the allowable short-time ampacities for a 230-kV XLPE cable.

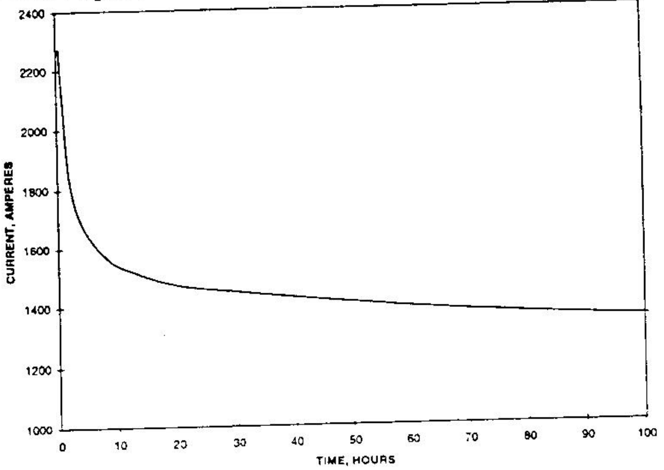


Figure 3. Transient/emergency ampacities for 230-kV XLPE cable

Cable preload has a large effect on allowable transient/emergency ampacities. Ampacities shown in Figure 3 are for a 100% preload – the cables are assumed to have been carrying full load for many weeks prior to the contingency. In reality, most cables are loaded to less than 50% of their rating. The two-hour ampacity for an extruded-dielectric cable at 100% preload is 1640 amperes, while that number rises to 2050 amperes if the cable was operating at 50% of rated load prior to the contingency.

Uprating can produce ampacity improvements of as much as 20 - 40% on underground cables. Uprating approaches generally take advantage of the large thermal mass of the cable/earth system and the ability to reduce some of the thermal resistances. Uprating approaches include:

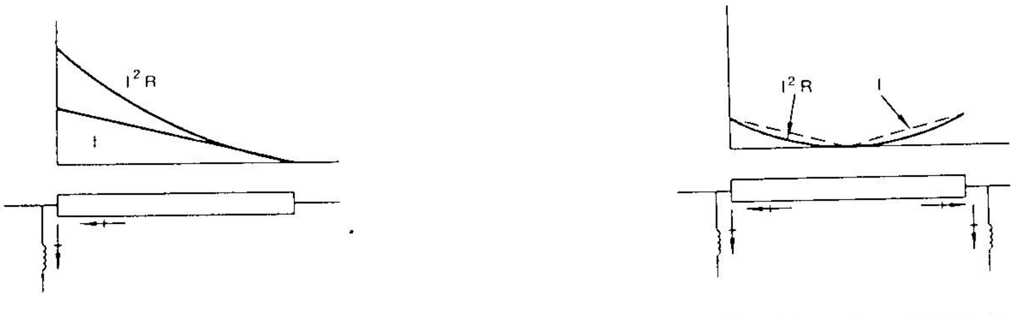
- Ampacity audits of actual field conditions. Recent introduction of distributed fiber optic temperature monitoring has benefited this approach.
- Dynamic rating systems
- Locate and mitigate hot spots
- Accept occasional loss of life
- Add cooling
- Reconductor cable in ducts or pipe.

Surge Impedance Loading

At surge impedance loading (SIL), the VARs generated in line capacitance are canceled by the VARs absorbed in line inductance. SIL is a useful tool for estimating the relative loading capabilities of transmission lines. At 230 kV, surge impedance loading for an overhead line is about 140 MW (Table 1) while that for an underground cable is about 1300 MW. Cables are thermally limited to operate below surge impedance loading, while overhead lines can operate below or above SIL – and short lines typically operate at several times SIL.

Capacitance Effects

A cable is a long, distributed capacitor. **Charging current** supplied by the utility system is required to charge and discharge the capacitor sixty times per second. If all charging current is supplied from one end of the circuit, the charging current and charging current losses will be distributed as shown in Figure 4a If charging current is supplied equally from each end – e.g. if shunt reactors are installed – charging current and losses will be distributed as shown in Figure 4b.



a. Flow from one end

b. Equal flow from both ends

Figure 4. Charging current and losses

Charging current has several effects on cable system operation:

Cable ampacity is reduced. Even though the charging current is in quadrature with the real current, it generates I^2R losses. With the 21.7 A/mile charging current for HPFF cable shown in Table 1, a 15 mile line would have a 325 ampere total charging current If all current flowed from one end, allowable real-power ampacity for a 1000 ampere cable rating would be 945 amperes: $\sqrt{(1000^2 - 325^2)}$. If charging current flowed equally at each end, allowable real-power ampacity would be 985 amperes. **Critical length** is defined as the length at which the charging current accounts for all the available I^2R losses. For the HPFF cable rated 1000 amperes, that length is 45 miles. For the XLPE cable in Table 1, the 13.1 amperes/mile charging current gives a critical length of 75 miles for a 1000-ampere rated circuit.

Voltage rise. Charging current flowing through the series inductance of other transmission lines or transformers can cause a voltage rise on the cable. This is not usually a problem, but should be checked during detailed design.

Shunt reactors. If the utility system cannot accommodate the cable charging current without excessive voltage rise, shunt reactors may be needed. This is especially true in major urban areas where large numbers of paper-insulated cables are installed, or on especially long EHV ac submarine cables where reactors are required to permit a reasonable real-power transfer.

Surge arresters and switching devices. The cable capacitance can cause the energy in surges to be significantly greater than those for overhead lines. Detailed analysis using a transient network analyzer or digital switching surge program is required for cable circuits longer than several miles.

Restoration after a blackout can be impeded if a large number of cables is present. Significant energy is required to charge the cable capacitance, and reactive currents can cause system overvoltages. The presence of shunt reactors helps restoration efforts for utility systems containing large amounts of transmission cables.

Dielectric Losses

Dielectric losses are due to the real (in phase) component of charging current flow through the cable insulation. These losses vary as the square of voltage, and can reduce ampacity by more than 25% for EHV paper-insulated cables. XLPE insulation is less lossy, and dielectric loss effects on ampacity are minimal. Table 1 shows they are 1.1 kW per mile (0.07 W/ phase foot) for a 230-kV XLPE cable, and 21.4 kW/mile (1.4 W/ phase foot) for a 230-kV HPFF cable. These losses are present whenever the cable is energized, so must be considered when evaluating cost of losses.

Power flows

Cables have a much lower series reactance than overhead lines. With an overhead and underground circuit in parallel – or even with an underground circuit in a network – the cable will carry a much greater load than the overhead line. The cable may be overloaded while the overhead line is very lightly loaded. Phase angle regulators are used to control cable loadings.

System Losses

Calculation procedures losses and cost of losses for an underground cable are the same as those for an overhead line. Differences in losses themselves are:

Dielectric losses in underground cables operate at a 100% load factor. They should be evaluated for XLPE cables even though dielectric losses have little effect on ampacity.
Charging current losses in underground cables operate at 100% load factor, and these losses need to be integrated over the cable length. In the example of Figure 4a, charging current losses are zero for the first foot of cable, and they are maximum for the last foot of cable.
Ohmic losses consist of shield/sheath losses in addition to conductor losses. Pipe-type cables, and even extruded-dielectric cables installed in steel casings, can have significant hysterisis losses.
Auxiliary Equipment Pressurizing pumps for pressurized cable system have minimal energy usage, but intensive forced-cooled systems can have high annual energy usage, especially if refrigeration units are used.

A detailed cost-of-losses analysis should be performed using the procedures developed by an IEEE Insulated Conductors Committee group[4]. In recent studies, cost of losses for underground cables were about 40 - 60% of those for an equivalent overhead line carrying the same loads. The present worth of lifetime cost of losses can be 50% of the total installed cost of the cable system.

Reliability, Restoration Procedures and Times

Transmission cable **reliability** is generally excellent. A recent CIGRE review[5] showed 1.25 faults per 100 km per year for underground cables 110-220 kV, and 3.1 faults per 100 km per year for overhead lines.

Restoration procedures and times can be lengthy, however. Durations vary substantially depending upon time it takes to locate the fault, whether cable replacement is required, the length of time to make a splice, etc. Durations of 7 - 21 days are not uncommon, and outages can be much longer if replacement cable has
to be ordered. Fluid-filled cables generally have longer repair and restoration times than extruded-dielectric cables because of handling the dielectric liquid and need to insure the line is properly pressurized before re-energizing.

Because of these long restoration times, some utilities provide 100% redundancy: two circuits are installed, each capable of carrying full load for the duration of repairs on the companion circuit. The cable system's long thermal time constant is helpful in permitting the overloads without excessive temperature rise.

Other Analytical Issues

Since cable systems are more complex than overhead lines, additional analytical studies often must be performed. Extruded-dielectric and self-contained fluid-filled (SCFF) cables have induced shield/sheath currents and voltages which must be carefully evaluated. Elaborate sheath cross-bonding schemes with attendant equipment are often employed for longer circuits. Hydraulic calculations are required for both SCFF and pipe-type cables, and cathodic protection system design is required for pipe-type cables. Pulling tension calculations must be performed for extruded-dielectric and SCFF cables in duct, and for pipe-type cables. Short-circuit analyses should be performed, since cables tend to have higher short-circuit currents.

ENVIRONMENTAL ISSUES

Underground cables of course have less visual impact than overhead lines, and they have no external electric fields. Magnetic fields from underground cables can be higher or lower than those from overhead lines, depending upon the cable type, bonding mode, number of circuits, phase positions, depth, etc. Figure 5 shows calculated values for a 700-ampere load..

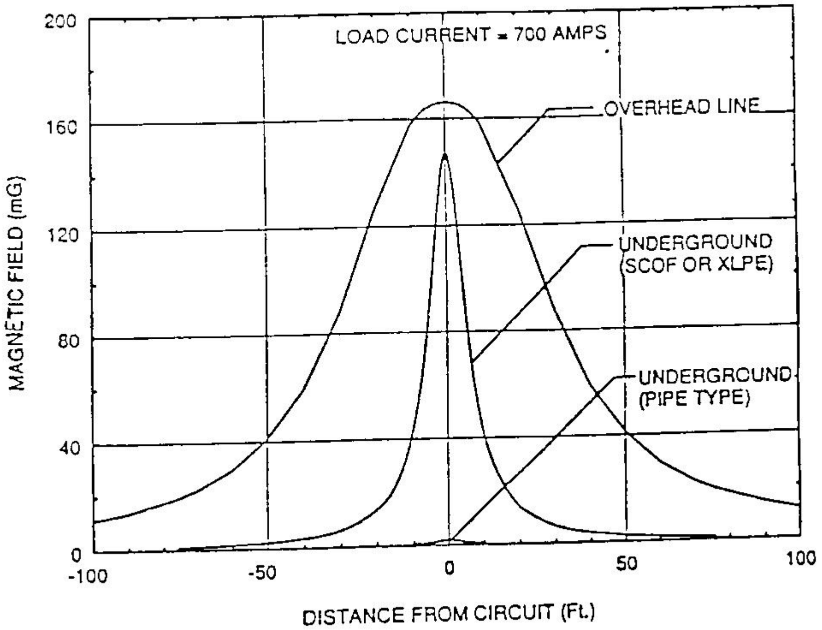


Figure 5. Magnetic fields for overhead line and underground cables

Some utilities are concerned about the lead sheath that is present in many XLPE and SCFF cables, even though newer cables have a thick polyethylene jacket, and jacket integrity tests are performed every couple of years.

The dielectric liquid in SCFF and high-pressure fluid-filled cables is a major concern for many U.S. utilities because of the possibility of leaks. Rapid leak detection and location methods have been developed. Nevertheless, new SCFF cable installations are almost non-existent in the U.S., and XLPE cable is replacing high-pressure fluid-filled cables at voltages to 138 kV. Several U.S. utilities are currently installing 115-kV and 138-kV high-pressure gas-filled cables to take advantage of the long history, ruggedness, and low magnetic fields of pipe-type cables.

The earth surface above a buried cable can be one or two Centigrade degrees warmer than the surrounding earth. The only reported effect was premature germination of seeds in fields.

Since every foot of a cable circuit must be excavated, chances are greater that contaminated soil will be found. At least one utility is using guided boring at major intersections, to bore below possible gasoline plumes from abandoned service stations – or at least minimize the amount of contaminated soil that must be removed and taken to approved disposal areas.

VOLTAGE LEVELS

Cable voltages typically lag voltages on overhead lines by a decade or more. Overhead lines are in service at 765 kV, and there are a great many miles of 500-kV lines. The highest underground cable voltage commonly used in this country is 345 kV , and the great majority is high-pressure fluid-filled pipe-type cable. 500 kV HPFF cable has been successfully completed long-term tests at EPRI's Waltz Mill test facility, and one of the cables was also tested successfully for 765 kV operation. Several 525-kV SCFF cables are in service in the U.S. and Canada, and at least one SF_6 bus system has operated at 525 kV. Extruded-dielectric cables are commonly used at 138 kV in the United States, and there are a few 230-kV installations. 400 kV extruded-dielectric cables are in service overseas, and 500 kV cables are considered feasible.

COSTS

Underground cables are almost always more costly than overhead lines. It is not possible to make general statements about the ratio of costs for the two approaches. Route considerations, cable type and cable system design, actual loadings, etc. must be evaluated on a case-by-case basis. Significant economies - perhaps as much as 20%, can be achieved by carefully designing the cable system and its installation, versus simply assuming a "typical cable system." Detailed studies conducted within the last several years have shown ratios as low as 3:1 and as high as 20:1. The denominator as well as the numerator must be analyzed. Some of the lower cost ratios are actually due to requirements for very expensive overhead structures.

SUMMARY

Underground cables are different from overhead lines in several important respects. A series of engineering analyses is required to properly evaluate the underground alternative. Simple statements such as "the cable alternative is too expensive" are not adequate as siting commissions and others become more sophisticated in evaluating alternatives.

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