BASIC CABLE CHARACTERISTICS

PART II

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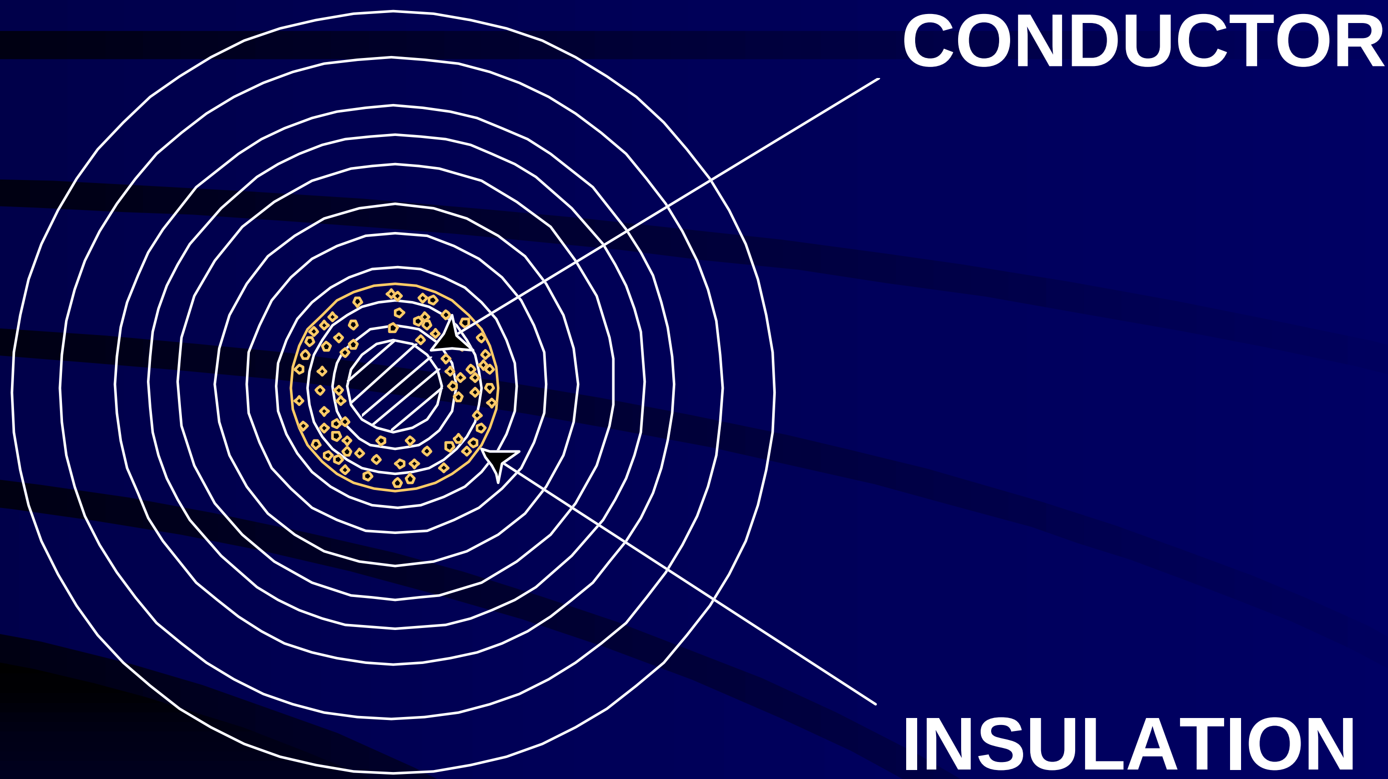
IN PART I WE REVIEWED THE FACT THAT A MAGNETIC FIELD ACCOMPANIED ELECTRIC CURRENT FLOW

A Cable Carrying Current Has a Magnetic Field Associated With the Current



MAGNETIC FIELD FLUX LINES EXTEND OUT TO INFINITY.
NOTE THAT ANY COVERING OR INSULATION DOES NOT ALTER THE MAGNETIC FIELD LINES.

CONDUCTOR SELF INDUCTANCE

The magnetic field associated with alternating current flow in a conductor is the source of self inductance.

The self inductance of a solid round conductor may be approximated by:

$$L = K_u \cdot l \cdot \left[\log_e\left(\frac{2 \cdot l}{r}\right) - \frac{3}{4} \right] \quad \text{per unit length } l$$

K_u is a constant dependent on dimensional units

r is the conductor radius. The smaller the conductor radius, the greater the self inductance.

CONDUCTOR SELF INDUCTANCE...

Results in lower impedance in the "outer rings" of the conductor when viewed as made up of concentric tubes

$X_L = 2pfL$ where f is ac frequency (hertz)

Causes the current to preferentially flow in the outer rings/tubes (lower impedance). This is commonly called skin effect

Results in an incremental increase in resistance when carrying ac current as compared with dc current of the same magnitude

SKIN EFFECT

In Part I, the term Y_{cs} in the formula

$$R_{ac} = R_{dc} \cdot (1 + Y_{cs} + Y_{cp})$$

is the incremental increase in resistance due to skin effect.

Steps taken to reduce skin effect include:

- Segmenting the conductor
- Making hollow core conductors
- Some strand coatings will effect skin effect

SKIN EFFECT AT 60 HERTZ

A commonly used approximation for Y_{cs} is:

$$Y_{cs} = \frac{11}{\left[\frac{R_{dc}@T_c}{K_s} + \frac{4 \cdot K_s}{R_{dc}@T_c} - 2.56 \cdot \left(\frac{K_s}{R_{dc}@T_c}\right)^2\right]^2}$$

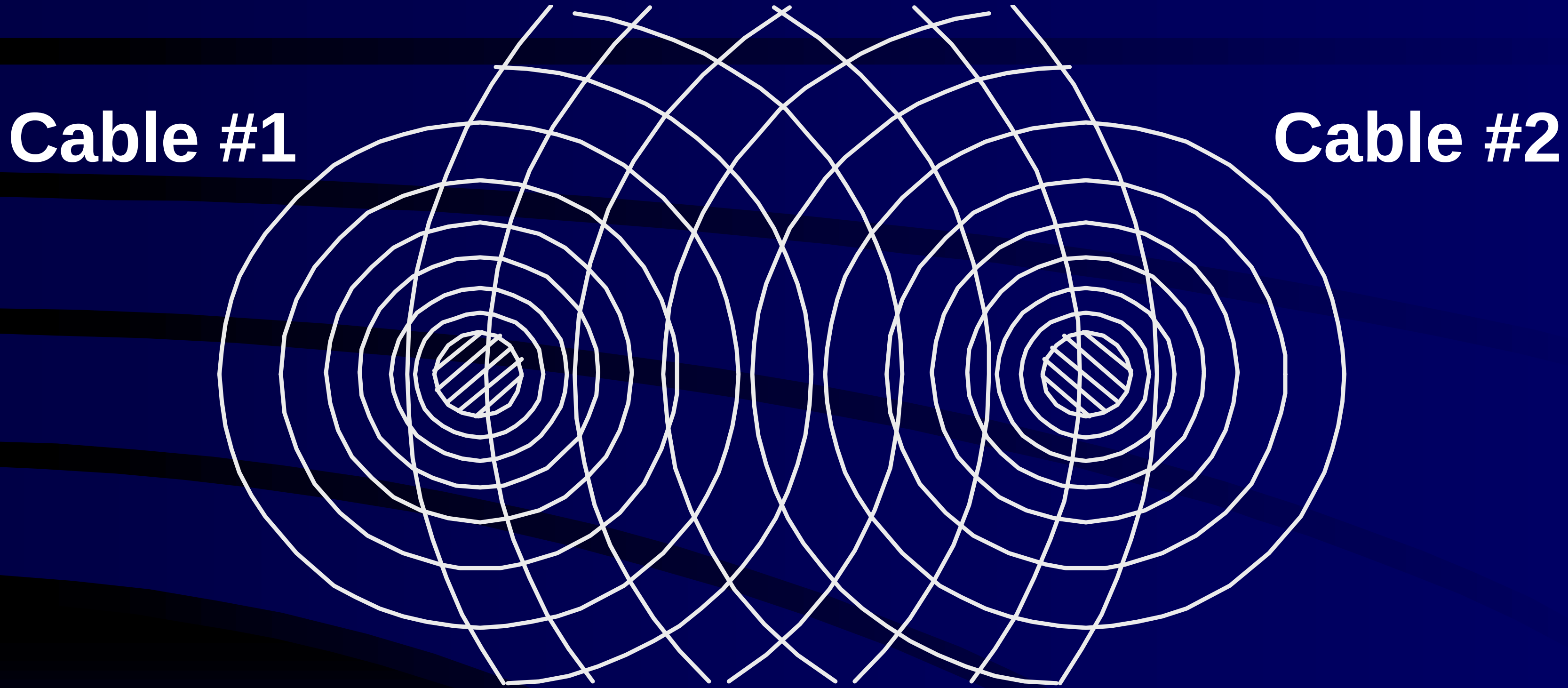
Where:

T_c is conductor temperature, °C

R_{dc} is dc conductor resistance at T_c, μΩ/φτ

K_s varies with conductor construction and coating, if any

Two Cables Carrying Current Will Have Magnetic Fields Interacting with Each Other



- Magnetic field (flux) from each cable links the adjacent cable.
- This causes a force to exist between the cables.
- If the currents are time varying, a voltage is induced into the adjacent cable.

PROXIMITY EFFECT

Conductors spaced close to one another and carrying alternating current will have the current distribution in each conductor altered by mutual reactance. This results in increased resistance known as proximity effect.

The increase is commonly designated as Y_{cp} in the formula $R_{ac} = R_{dc} \cdot (1 + Y_{cs} + Y_{cp})$

In most cases if conductor spacing exceeds 10 times the conductor diameter proximity effect will be less than 1% and can be neglected

PROXIMITY EFFECT AT 60 Hz

$$Y_{cp} = f(X_p)\cdot\left(\frac{D_c}{S}\right)^2\cdot\left[\frac{1.18}{f(X_p)+0.27}+0.312\cdot\left(\frac{D_c}{S}\right)^2\right]$$

$$f(X_p) = \frac{11}{\left[\frac{R_{dc}@T_c}{K_p}+\frac{4\cdot K_p}{R_{dc}@T_c}-2.56\cdot\left(\frac{K_p}{R_{dc}@T_c}\right)^2\right]^2}$$

Where:

T_c is conductor temperature, °C

R_{dc} is dc conductor resistance at T_c, μΩ/φτ

K_p varies with conductor construction and coating, if any

COMMONLY USED K_s , K_p VALUES

Conductor Type	Conductor Coating	K_s	K_p
Concentric Round	None, Tin, Lead Alloy	1.0	1.0
Conc. Compressed	None, Tin, Lead Alloy	1.0	1.0
Compact Round	None	1.0	0.6

MAGNETIC CONDUIT EFFECT

Cables installed in pipe or conduit made of magnetic materials will have a further increase in ac resistance.

The increase is approximated by multiplying Y_{cs} and Y_{cp} by 1.7 resulting in the formula

$$R_{ac} = R_{dc} \cdot [1 + (Y_{cs} + Y_{cp}) \cdot 1.7]$$

This multiplying factor is applied whether the cables are in the cradled or triangular configuration.

CONDUCTOR DIAMETERS

This makes it desirable to revisit the subject of conductor diameters which was neglected in Part I.

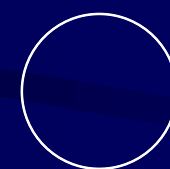
In Part I we compared the advantages of solid vs stranded conductors.

For electric utility underground cables, Class B stranded conductors are the overwhelming favorite.

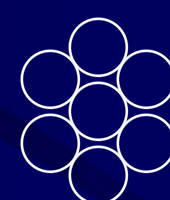
Conductor Designs for Insulated Cables

- Stranding increases:
  - flexibility
  - diameter for the same metal area
  - resistance for the same metal area

Solid Conductor

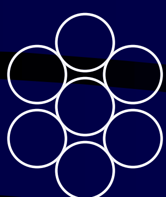


Stranded Conductor



Conductor Designs for Insulated Cables

Class B stranding is based on the recognition that for circles of equal diameter, 6 will almost exactly fill the space around 1, 12 fill the space around 6, 18 around 12, …(add 6 to the number in the outer ring each time to fill the next ring).

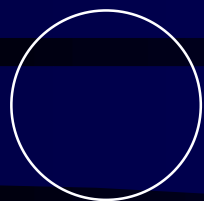


1 + 6 = 7 strand

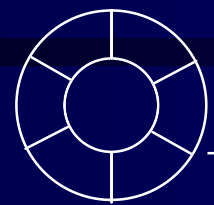
Next layer: 7 + 12 = 19 strand	(6 + 6 = 12)
Next layer: 19 + 18 = 37 strand	(12 + 6 = 18)
Next layer: 37 + 24 = 61 strand	(18 + 6 = 24)
Next layer: 61 + 30 = 91 strand	(24 + 6 = 30)

Continue sequence….

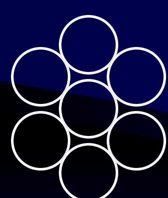
CONDUCTOR DIAMETERS



SOLID



COMPACT



CONCENTRIC ROUND STRANDED

Concentric may be compressed up to, but not exceeding a 3% diameter reduction

- Compact has about a 3.5 % larger diameter than solid.
- Concentric Round has about a 14 % larger diameter than solid

CONDUCTOR DIAMETERS

For the conductor sizes commonly used in underground distribution, the conductor diameter differences may not have a significant impact on skin and proximity effect.

The difference in diameter between concentric round and concentric round compressed is not normally sufficient to have an impact on connectors, splices & terminations.

The diameter differences between compact and concentric round/compressed can have a definite impact on connectors, splices and terminations. You must check!

COMPACT CONDUCTOR ADVANTAGES

They increase flexibility with minimal increase in diameter as compared with a solid conductor.

They offer material savings when covered/insulated.

The reduced diameter may allow for the use of smaller ducts/conduits (the most obvious first step in designing reduced diameter cables).

EFFECTIVE AC RESISTANCE

In Part I we gave the effective ac resistance for voltage drop calculations as:

$$R_{ac} = R_{dc} \cdot (1 + Y_{cs} + Y_{cp}) + ?R$$

Where ?*R* was the “apparent” increase in conductor resistance due to losses induced in the cable shield, sheath, armor, metallic conduit, …….by the current carrying conductor.

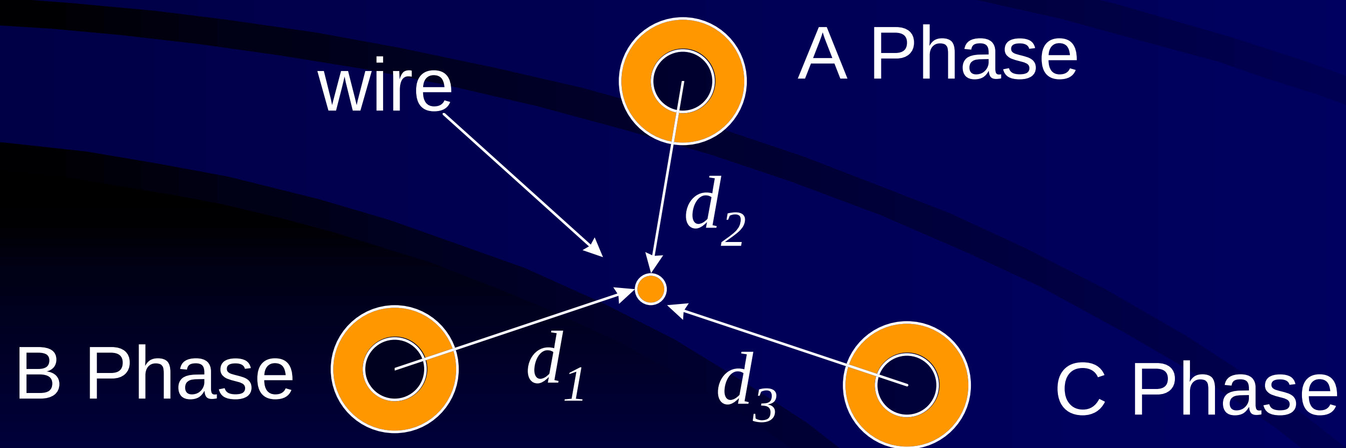
Let’s examine the common case of shield losses.

A WIRE IN THE PRESENCE OF 3 CONDUCTORS CARRYING ALTERNATING CURRENT WILL HAVE 3 VOLTAGES INDUCED IN THE WIRE.

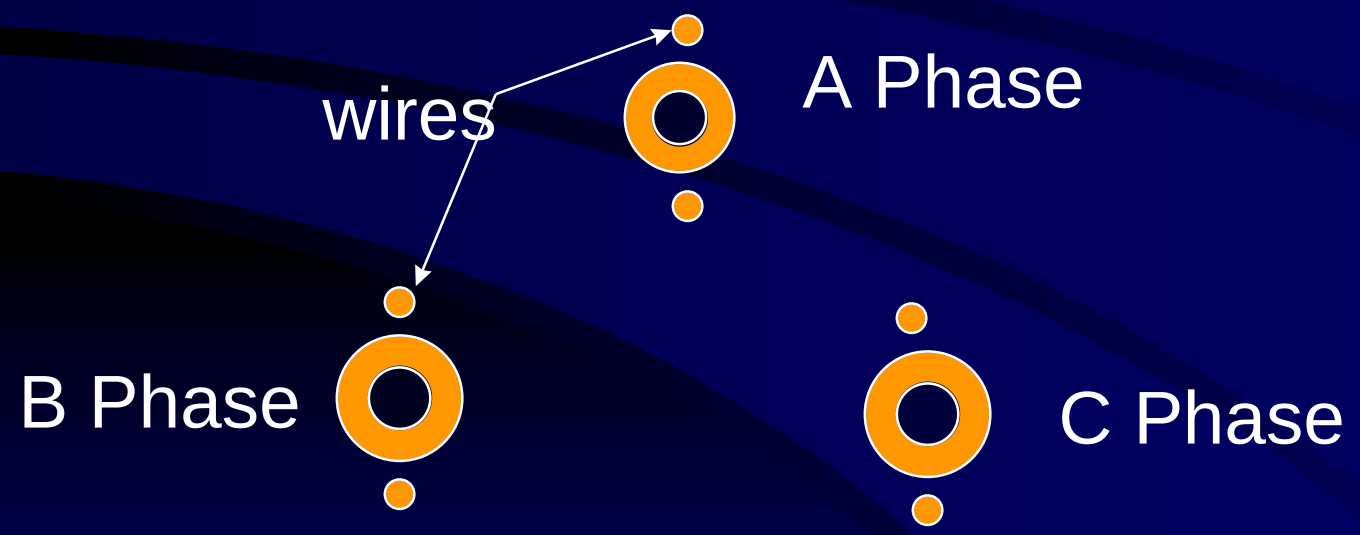
THE VOLTAGE INDUCED PER UNIT LENGTH BY EACH CONDUCTOR IS LARGER IF THE INDUCING CURRENT IS GREATER AND IF IT IS CLOSER TO THE WIRE.

IF THE CURRENTS IN EACH OF THE CONDUCTORS ARE OUT OF PHASE WITH EACH OTHER, THE TOTAL VOLTAGE INDUCED IN THE WIRE IS THE VECTOR SUM OF THE VOLTAGES INDUCED IN THE WIRE.

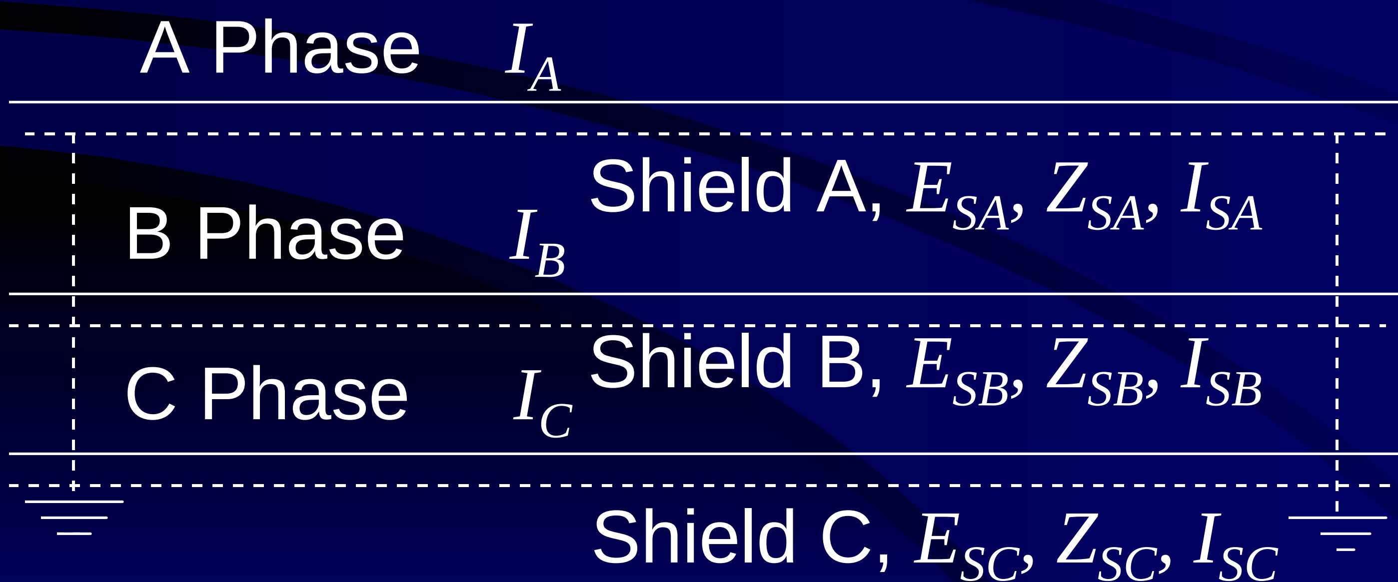
If the three conductors are a balanced 3-phase 60 Hz circuit with $d_1 = d_2 = d_3$ the voltages induced will be equal in magnitude but 120º out of phase. The vector sum of the voltage induced in the wire is zero.



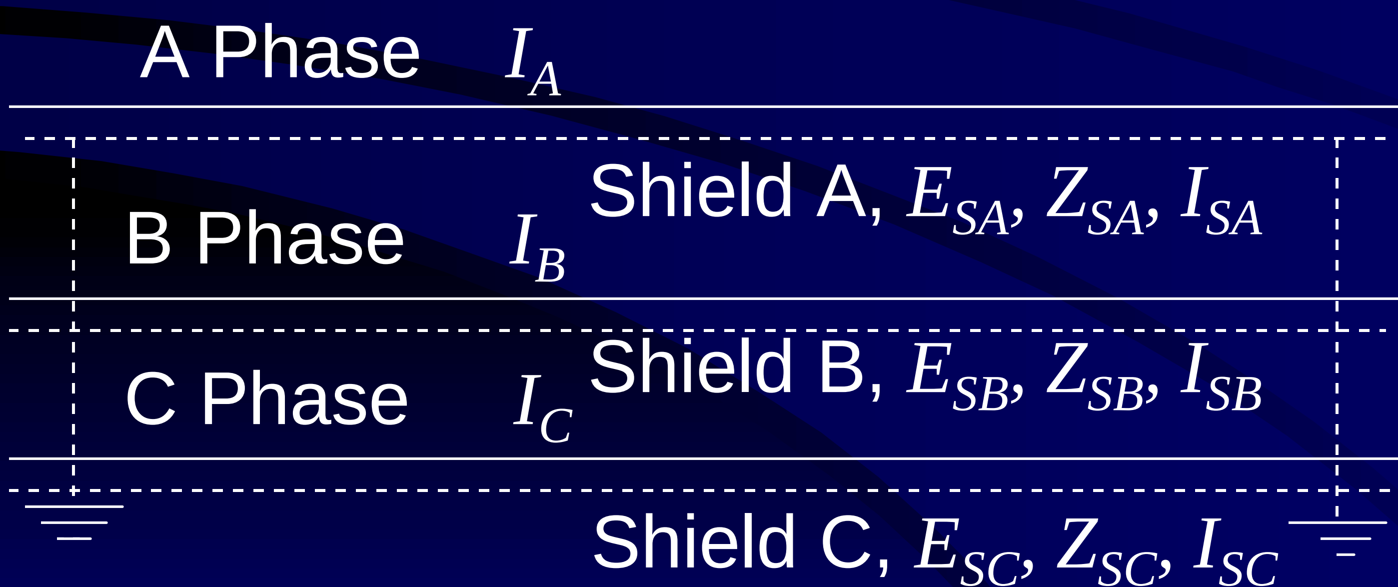
Shield wires are always closest to the phase they surround, so in a balanced 3-phase circuit the voltage induced by adjacent phases will not be as great as the voltage induced by the phase they surround. This results in a net voltage induced in the shield wires (vector sum).



In a 3-phase ac circuit, phase currents I_A, I_B, I_C induce voltages E_{SA}, E_{SB}, E_{SC} into shields A, B, and C. If, as is typical in distribution circuits, shields A, B, and C are inter-connected and complete a circuit, currents will flow in shields A, B, and C through impedances Z_{SA}, Z_{SB}, and Z_{SC} resulting in shield currents I_{SA}, $I_{SB,}$, and I_{SC}



Shield currents I_{SA}, I_{SB}, and I_{SC} will result in I^2R losses as they flow through the shield resistances of shields A, B, and C. This results in heat that has a negative effect on ampacity and an apparent increase in conductor resistance having a negative effect on voltage drop.



CABLE SHIELD IMPEDANCE

In order to determine the magnitude of the current flowing in the shield it is necessary to determine the magnitude of the voltage induced in the shield per unit length and the shield impedance per unit length. Since the impedance is $R_s + jX_s$ we need to determine both shield resistance and reactance.

We will begin with a review of how to determine shield resistance.

LAY LENGTH

For concentrically applied wires, tapes, or straps, LAY LENGTH is the distance advanced along the underlying core for one complete revolution of the wire, tape, or strap around the underlying core.

LAY LENGTH is often specified as a multiple of the diameter over or under the wires, tapes, or straps.

MEAN SHIELD/SHEATH DIAMETER

- The mean shield/sheath diameter is the average of the diameter under the shield/sheath and the diameter over the shield/sheath.
- The common symbol for mean shield/sheath diameter is D_{sm}.

EFFECTIVE LENGTH OF SHIELD/SHEATH L_{eff}

- For concentric wires or straps, not in contact, or tapes with no overlap, over a circular core, the effective length per unit lay length is given by:

$$L_{eff} = \sqrt{(\pi \cdot D_{sm})^2 + (Lay\ Length)^2}$$

EFFECTIVE LENGTH OF LAPPED TAPE SHIELD

- The effective length of lapped tape shields is a variable because of the metal-to-metal conduction at the tape laps.
  - When new, conduction at the laps (best case) makes the tape shield approach a tube and the effective length is equal to the unit cable length.
  - With age, corrosion at the laps (worst case) eliminates conduction at the laps and the effective length is that of tape(s) with no overlap.

EFFECTIVE LENGTH OF TUBULAR AND LONGITUDENALLY CORRUGATED SHIELDS/SHEATHS

The effective length of a smooth tubular shield/sheath is equal to the cable length.

For longitudinally corrugated sheaths, contact the cable manufacturer or, as an approximation, add 15% to the unit cable length.

METALLIC SHIELD/SHEATH ***RESISTANCE*** R_s

Given the effective cross-section area of the shield/sheath A_{eff}, at any given temperature T, the shield/sheath resistance is

$$R_{sT} = \frac{\rho_{volT} \cdot \left(L_{eff}\right)}{A_{eff}}$$

Where:

?$_{volT}$ is the volume resistivity of the shield metal at temperature T

A_{eff} is determined from the formulas in Part I

ELECTRICAL PROPERTIES OF CONDUCTOR MATERIALS

Metal	Conductivity Annealed Cu is 100%	Volume Resistivity @20ºC Ω·m (10^{-8})	Temp. Coeff. of Resist./ºC
Silver	106	1.626	0.0041
Cu, Annealed	100	1.724	0.0039
Cu, HD	97	1.777	0.0038
Cu, Tinned	95-99	1.741-1.814	---
1350 Al, HD	61.2	2.817	0.00404
1350 Al, 0	61.8	2.790	0.00408

ELECTRICAL PROPERTIES OF CONDUCTOR MATERIALS (cont'd)

Metal	Conductivity Annealed Cu is 100%	Volume Resistivity @20ºC Ω·m (10^{-8})	Temp. Coeff. of Resist./ºC
6201 T81 Al	52.5	3.284	0.00347
Sodium	40	4.3	---
Nickel	25	6.84	0.006
Mild Steel	12	13.8	0.0045
Lead	7.73	22.3	0.0039

INDUCED SHIELD VOLTAGE

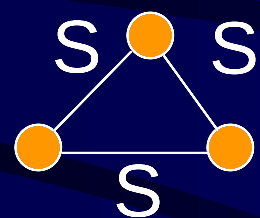
We will not rigorously derive the induced shield voltage but rather examine a specific case and reference "The Underground Systems Reference Book", EEI, 1957, page 10-41.

For the simple case of an isolated, balanced, 3-phase, 3-single conductor, shielded cable, ac circuit in equilateral triangular spacing, the induced shield/sheath voltage per phase ampere is:

$$E_{SA} = E_{SB} = E_{SC} = (I_A \text{ or } I_B \text{ or } I_C)\cdot X_M$$

INDUCED SHIELD VOLTAGE

This simplicity is not common as symmetry, and equal spacing is not common in practical cases. (see ref. for the more typical cases). However, the simple case will illustrate the points to be made.



$$X_M = 2\pi f \cdot \left[0.1404 \cdot \log_{10}\left(\frac{S}{r_{sm}}\right)\right] \cdot 10^{-3} \text{ O to neut./1000 ft}$$

And r_{sm} is mean shield radius - Note: $D_{sm}/2 = r_{sm}$

SHIELD IMPEDANCE - CURRENT - LOSS

Shield Impedance $Z_S = \sqrt{R_S^2 + X_m^2}$ O/1000 ft at 60 Hz

Shield Current $I_S = \frac{E_S}{Z_S} = \frac{I_{phase} \cdot X_m}{\sqrt{R_S^2 + X_m^2}}$ am p

Shield Loss $= I_s^2 R_s = \frac{I_p^2 X_m^2 \cdot R_s}{R_s^2 + X_m^2}$ watt

Ratio Shield to Conductor Loss $= \frac{I_s^2 R_s}{I_p^2 R_c}$

Or $\frac{R_s}{R_c} \cdot \frac{X_m^2}{R_s^2 + X_m^2}$ This ratio deserves some study!

SHIELD TO CONDUCTOR LOSS RATIO– A URD/UD CABLE LOOK

We know that X_m increases with phase spacing. A “ball park” range from 1/0 AWG Al, strd, 345 mil, full neutral, 35 kV triplex to 1000 kcmil Al, strd, 175 mil, 1/3rd neutral, 7.5” triangular spacing we have:

X_m = 0.02 to 0.05 O to neutral/1000 ft.

Shield resistance is straight forward and a ball park range for the above is R_s = 0.18 to 0.06 O/1000 ft.

Let’s use these ranges to review the effects on shield loss ratio.

SHIELD LOSS RATIOS-EXAMPLES

$$\frac{R_s}{R_c}$$

For full neutral $R_s/R_c = 1$

For 1/3rd neutral $R_s/R_c = 3$

times

$$\frac{X_m^2}{R_s^2 + X_m^2}$$

$R_s = 0.06$, $X_m = 0.05$ ratio is 0.410

$= 0.18$, $= 0.02$ ratio is 0.012

$= 0.18$, $= 0.05$ ratio is 0.072

Now

1 x 0.012= 0.012 Much ado about nothing!

3 x 0.410= 1.230 Wow! More loss (heat) generated by the shield than the conductor.

1 x 0.072= 0.072 Still not all that bad.

IMPACT ON APPARENT RESISTANCE

Recall $$\Delta R = \frac{R_s \cdot X_m^2}{R_s^2 + X_m^2} = 0.41 \cdot R_s$$

And, since $R_s = 3 \cdot R_c$, then $0.41 \cdot (3 \cdot R_c) = 1.23 \cdot Rc$

Or, the increase in apparent resistance due to shield loss actually exceeds the conductor resistance.

The impact on voltage drop is certainly not positive!

IMPACT ON APPARENT REACTANCE

$$\Delta X_L = -\frac{X_m^3}{R_s^2 + X_m^2}$$

Or, there is a decrease in the apparent reactance to positive or negative sequence currents.

As with apparent resistance, this is for the simple case of cables in an equilateral triangular configuration.

WHAT DOES ALL THIS SHIELD LOSS RATIO STUDY TELL US

When cable shield resistance is low enough to approach the magnitude of the mutual reactance, shield loss can be high.

Shield losses cost $, reduce ampacity, and increase voltage drop, so they should be minimized. One method is to avoid selecting a shield with lower resistance than necessary.

Another method is to keep heavily shielded cables in close spacing.

WHAT DOES ALL THIS SHIELD LOSS RATIO STUDY TELL US

Neutral requirements are a factor in shield selection. Better feeder balance may allow for lighter shields. Caution! Harmonics may be a complicating issue. Part 3?

Short circuit requirements are a factor in shield selection. Selecting shields to maximize short circuit capability while minimizing shield loss is possible. Part 3?

The use of metallic conduit (especially magnetic materials) further complicates matters. Part 3?

WHAT DOES ALL THIS SHIELD LOSS RATIO STUDY TELL US

For the more common cases of cables in non-symmetrical configurations shield losses will result in different impedances for each cable.

This can have a major impact on load sharing with cables operated in parallel. Part 3?

The use of metallic non-magnetic conduit, sheaths and armor will cause further effects similar those caused by shield losses. Part 3?

QUESTION RATE SCHEDULE

ANSWERS------------------------ $ 1.00

ANSWERS THAT
REQUIRE THOUGHT---------- $ 2.00

CORRECT ANSWERS-------- $ 4.00

DUMB LOOKS ARE STILL FREE