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Impedance of Four-Conductor Cable

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Naval Sea Systems Command

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14. ABSTRACT

This report documents analytic methods for calculating the resistance, differential mode inductance and capacitance, and common mode inductance and capacitance of four-conductor Medium Voltage Direct Current (MVDC) power cable intended for shipboard applications. These cables have individual conductor shields and overall cable shields. This report also provides estimates for the dimensions, weight, and ampacity of the cable.

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1. Introduction

Future shipboard direct current (d.c.) distribution systems will likely use four-conductor cables to minimize magnetic signatures. As shown in figure 1, opposite conductors are of the same polarity

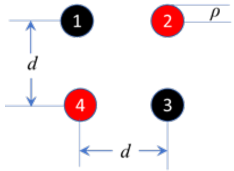

Figure 1. Four conductor cable conductor configuration

While MIL-HDBK-299 provides guidance for calculating the impedance of three conductor cable, it does not provide the same guidance for four conductor cable. Furthermore, MIL-HDBK-299 does not provide guidance for calculating common mode impedance. This document will provide guidance for calculating the resistance, inductance, and capacitance of four conductor cable in both common mode and differential mode. This document also provides estimates of the characteristics of Medium Voltage Direct Current (MVDC) cable including weight and ampacity.

Insulation thickness and allowable operating temperature limits will likely be different from MVDC cables as compared to Medium Voltage Alternating Current (MVAC) cables. These differences are currently not well understood, hence the assumed values for insulation thickness should be viewed as an approximation subject to more thorough analysis and research on the impact of partial discharge and space charge on MVDC cable. Additional research is also needed to determine the maximum expected transient voltages (and how often they occur) due to normal operation, faults, and lightning.

Resistance

The resistance of a conductor per unit length is primarily a function of the cross-sectional area, temperature, and frequency. To a lesser degree, the type of stranding also has an impact. Table 1 provides the d.c. resistance and weight of Navy standard conductors up to 300 cmil. The data from this table are derived from MIL-HDBK-299 and ASTM B8.

The d.c. resistance (R_{DC}) of a single wire is given by:

$$R_{DC} = \frac{\rho_{Cu} L}{A}$$

Where

ρ_{Cu} = Conductor resistivity at a given temperature, measured in ohms-cmil / ft.

L = Length of conductor in feet

A = Conductor cross-sectional area in circular mil (cmil)

$$A = 4\rho^2$$

Where

ρ = Conductor radius (half conductor diameter) in mils (Thousandths of an inch)

The conductor resistivity (ρ_{Cu}) for a given Temperature T (˚C) is given by

$$\rho_{Cu} = 10.371\big(1 + 0.00393(T - 20)\big)$$

This equation can also be used to adjust the resistance of a cable at 20 ˚C to another temperature

$$R(T) = R_{20C}\big(1 + 0.00393(T - 20)\big)$$

Or more generally, the resistance R_{To} for temperature T_o (˚C) can be adjusted to another temperature

$$R(T) = R_{To}\big(1 + 0.00393(T - T_o)\big)$$

Stranding will result in an approximately 2% increase in resistance per MIL-HDBK-299 and ASTM B8.

Table 1: DC resistance of Navy Standard Conductor sizes

Designation	Ares of Cross-Section (cmil)	AWG	Conductor Diameter (mil) of solid conductor	Conductor Diameter (mil) Concentric Strand	Number of Strands	Class	R_DC (ohms/1000ft) 20 C	R_DC (ohms/1000ft) 45 C	R_DC (ohms/1000ft) 65 C	Weight (lbs/1000ft)
SG-3	2580	16	50.79	57.60	7	B	4.101	4.503	4.827	7.974
SG-4	4110	14	64.11	72.60	7	B	2.573	2.825	3.028	12.680
SG-9	10380	10	101.88	115.50	7	B	1.019	1.119	1.199	32.060
SG-14	13090	9	114.41	129.60	7	B	0.808	0.887	0.951	40.420
SG-23	20820	7	144.29	163.50	7	B	0.508	0.558	0.598	64.280
SG-50	52620	3	229.39	263.00	19	C	0.201	0.221	0.237	162.500
SG-75	83690	1	289.29	333.20	37	C	0.126	0.138	0.148	258.400
SG-100	105600	0	324.96	374.40	61	D	0.100	0.110	0.118	325.800
SG-150	167800	000	409.63	471.60	61	D	0.063	0.069	0.074	518.100
SG-200	211600	0000	460.00	530.10	61	D	0.050	0.055	0.059	653.100
SG-300	300000		547.72	631.40	91	D	0.036	0.040	0.042	926.300
Source	MIL-HDBK-299	ASTM B8	calculated from area of cross section	calculated based on ASTM B8	MIL-HDBK-299	ASTM B8	MIL-HDBK-299	MIL-HDBK-299	MIL-HDBK-299	ASTM B8

For a.c. currents, the skin effect will result in more current flowing on the surfaces of the wire instead of in the center. The skin effect results in the a.c. resistance being higher than the d.c. resistance. While the exact formula is well documented (see Riba 2015 for example), it is based on Kelvin functions and their derivatives in a manner that is difficult to compute with accuracy.

Consequently, this exact formula is usually not used in practice. Riba 2015 provides several alternatives, including one presented in IEC 60287-1-1.

MIL-HDBK-299 uses a method based on the skin effect ratio (SER) which is the a.c. resistance at a given frequency divided by the d.c. resistance (neglecting proximity effects). The SER is calculated in two steps. First a factor *F* is calculated and is proportional to the inverse of the skin depth. The formula for *F* as listed in MIL-HDBK-299 is:

$$F = 0.027677\sqrt{\frac{f}{R_{dc}}}$$

The equation as listed by Neher and McGrath (1957) is insignificantly different (after unit conversions):

$$F = 0.027670\sqrt{\frac{f}{R_{dc}}}$$

Where;

f = frequency in Hz.

R_{dc} = ohms per 1000 ft

The SER for $F \leq 0.3$ is 1.0

For $0.3 < F \leq 4.99$, the SER is obtained from the table in Appendix A.

For $F > 4.99$, an alternate method must be used.

For high frequencies ($F > 4.99$) the a.c. resistance can be approximated by assuming all of the current flows uniformly on the surface of the conductor to a depth equal to the skin depth.

The skin depth is given by:

$$\delta = \frac{1}{\sqrt{\pi f \mu_r \mu_o \sigma}}$$

Were

f = frequency in Hz.

μ_r = Relative permeability (1.0 for copper)

μ_o = Permeability of free space = $4\pi 10^{-7}$ in N/A^2

σ = conductivity (S/m) reciprocal of resistivity ρ_{cu} (ohms – meter)

δ = skin depth (m)

Now

$$R_{dc} = \frac{\rho_{cu}}{\pi r^2} \text{ (Ohms per meter)}$$

Where

r = radius of conductor in meters

conductivity is thus given by:

$$\sigma = \frac{1}{R_{dc}\pi r^2}$$

$$\delta = \frac{1}{\sqrt{\pi f \mu_r \mu_o \sigma}} = \sqrt{\frac{R_{dc}\pi r^2}{\pi f 4\pi 10^{-7}}} = r\sqrt{\frac{R_{dc}}{f 4\pi 10^{-7}}}\,(meters)$$

If R_{dc} is provided in ohms per 1000 ft, and r in mils (ρ), the equation becomes

$$\delta = \rho\sqrt{\frac{R_{dc}}{304.8 f 4\pi 10^{-7}}} = 51.10\rho\sqrt{\frac{R_{dc}}{f}}\ mils$$

The a.c. resistance is thus given by (assuming the skin depth is a small fraction of the radius)

$$R_{ac} = R_{dc}\frac{\rho^2}{2\delta\rho - \delta^2} = R_{dc}\frac{\rho}{\delta}\left(\frac{\rho}{2\rho - \delta}\right)$$

$$R_{ac} = R_{dc}\frac{\rho}{2\delta}\left(\frac{1}{1 - \frac{\delta}{2\rho}}\right)$$

This is approximated by:

$$R_{ac} \approx R_{dc}\frac{\rho}{2\delta}\left(1 + \frac{\delta}{2\rho}\right) = R_{dc}\left(\frac{\rho}{2\delta} + \frac{1}{4}\right)$$

$$\frac{\rho}{2\delta} = \frac{1}{2\left(51.10\sqrt{\frac{R_{dc}}{f}}\right)}$$

$$R_{ac} \approx \left(.009785\sqrt{\frac{f}{R_{dc}}} + \frac{1}{4}\right)R_{dc}$$

$$R_{ac} \approx (0.3536F + .25)R_{dc}$$

Note that for $F = 4.99$, this equation calculates a SER of 2.0145 while Appendix A shows a SER of 2.0392. At this point, the two methods are in agreement within less than 1.3%.

Table 2 provides the a.c. resistance of Navy standard conductors at various frequencies and a temperature of 65 ˚C. The calculations used Appendix A for F < 4.9 and the above equation for F > 4.9. Note that for larger values of F, the results do not match MIL-HDBK-299 at 60 Hz and 400 Hz.

Table 2: AC resistance of Navy Standard Conductor sizes at 65˚C

Designation	AWG	R_DC (ohms/ 1000ft) 65 C	F at 60 Hz	F at 400 Hz	F at 1,000 Hz	F at 10,000 Hz	F at 100,000 Hz	SER at 60 Hz	SER at 400 Hz	SER at 1,000 Hz	SER at 10,000 Hz	SER at 100,000 Hz	R_AC (ohms/ 1000ft) 60 Hz	R_AC (ohms/ 1000ft) 400 Hz	R_AC (ohms/ 1000ft) 1,000 Hz	R_AC (ohms/ 1000ft) 10,000 Hz	R_AC (ohms/ 1000ft) 100,000 Hz
SG-3	16	4.827	0.10	0.25	0.40	1.26	3.98	1.00	1.00	1.00	1.01	1.67	4.827	4.827	4.827	4.888	8.063
SG-4	14	3.028	0.12	0.32	0.50	1.59	5.03	1.00	1.00	1.00	1.03	2.03	3.028	3.028	3.029	3.126	6.141
SG-9	10	1.199	0.20	0.51	0.80	2.53	7.99	1.00	1.00	1.00	1.18	3.08	1.199	1.199	1.201	1.415	3.688
SG-14	9	0.951	0.22	0.57	0.90	2.84	8.97	1.00	1.00	1.00	1.27	3.42	0.951	0.951	0.954	1.203	3.255
SG-23	7	0.598	0.28	0.72	1.13	3.58	11.32	1.00	1.00	1.01	1.52	4.25	0.598	0.599	0.603	0.908	2.542
SG-50	3	0.237	0.44	1.14	1.80	5.68	17.97	1.00	1.01	1.05	2.26	6.61	0.237	0.239	0.249	0.536	1.565
SG-75	1	0.148	0.56	1.44	2.27	7.19	22.74	1.00	1.02	1.12	2.79	8.29	0.148	0.151	0.166	0.413	1.227
SG-100	0	0.118	0.62	1.61	2.55	8.06	25.47	1.00	1.03	1.19	3.10	9.26	0.118	0.122	0.140	0.366	1.092
SG-150	000	0.074	0.79	2.03	3.22	10.17	32.17	1.00	1.08	1.39	3.85	11.62	0.074	0.080	0.103	0.285	0.860
SG-200	0000	0.059	0.88	2.28	3.60	11.39	36.02	1.00	1.12	1.53	4.28	12.99	0.059	0.066	0.090	0.252	0.766
SG-300		0.042	1.05	2.70	4.27	13.50	42.70	1.01	1.23	1.77	5.02	15.35	0.042	0.052	0.075	0.211	0.645

2. Inductance

2.1. Differential Mode Inductance

As shown by Doerry and Amy (2018), the differential mode inductance per unit length of cable for each set of paralleled conductors of a single polarity (phase) with the configuration depicted in figure 1 is given by.

$$L_{phase\_quad} = \frac{\mu_0}{4\pi}\left[\ln\frac{d}{r\sqrt{2}}\right] (\mu H\ per\ meter)$$

$$r = \rho e^{-\frac{\mu r}{4}}\ \text{(geometric mean)}$$

$$\mu_0 = 1.257\ \mu H\ per\ meter$$

$$\frac{\mu_0}{4\pi} \approx 0.1\ \mu H\ per\ meter$$

For $\mu_r = 1$ (assume permeability of insulators is the same as free space) the geometric mean radius is approximated by:

$$r \approx 0.78\rho$$

This formulation ignores the impact of using stranded wire.

Cable specifications however, rarely provide the distance between conductors (*d*). Instead the Diameter (*D*) is provided and the thickness (*s*) of the sheathing (shield, jacket, and binder) can be estimated.

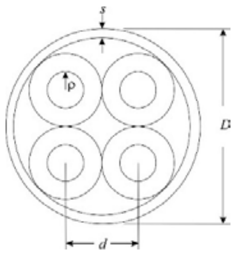

Figure 2: Cable Dimensions

If only the cable diameter and sheathing thickness are known, the conductor separation can be estimated as …

$$d = \frac{D - 2s}{1 + \sqrt{2}}$$

In some cases, the insulation, shield, and sheathing thickness of each conductor is provided. In these cases, the conductor separation *d* is twice the sum of the conductor radius, conductor insulation thickness, conductor shield thickness, and conductor sheathing thickness.

Derivation of differential mode inductance using equations from Grover (2009)

The self-inductance (µH per meter) of a round wire of radius ρ cm and length *l* cm is given by

$$L_{11} = .2\left[ln\left(\frac{2l}{\rho}\right) - \frac{3}{4}\right] \qquad \text{(Grover 7)}$$

The mutual inductance (µH per meter) with respect to the other conductor of same polarity is

$$M_{13} = .2\left[ln\left(\frac{l}{d\sqrt{2}} + \sqrt{1 + \frac{l^2}{2d^2}}\right) - \sqrt{1 + \frac{2d^2}{l^2}} + \frac{d\sqrt{2}}{l}\right] \qquad \text{(Grover 1)}$$

The mutual inductance (µH per meter) with respect to the other conductors of the opposite polarity is

$$M_{12} = M_{14} = -.2\left[ln\left(\frac{l}{d} + \sqrt{1 + \frac{l^2}{d^2}}\right) - \sqrt{1 + \frac{d^2}{l^2}} + \frac{d}{l}\right] \qquad \text{(Grover 1)}$$

The inductance of each phase (one way) is the sum of these or

$$L_1 = .2\left[\left[ln\left(\frac{2l}{\rho}\right) - \frac{3}{4}\right] + \left[ln\left(\frac{l}{d\sqrt{2}} + \sqrt{1 + \frac{l^2}{2d^2}}\right) - \sqrt{1 + \frac{2d^2}{l^2}} + \frac{d\sqrt{2}}{l}\right] - 2\left[ln\left(\frac{l}{d} + \sqrt{1 + \frac{l^2}{d^2}}\right) - \sqrt{1 + \frac{d^2}{l^2}} + \frac{d}{l}\right]\right]$$

$$L_1 = .2\left[ln\left(\frac{2l}{\rho}\right) - \frac{3}{4} + ln\left(\frac{l}{d\sqrt{2}} + \sqrt{1 + \frac{l^2}{2d^2}}\right) - \sqrt{1 + \frac{2d^2}{l^2}} + \frac{d\sqrt{2}}{l} - 2ln\left(\frac{l}{d} + \sqrt{1 + \frac{l^2}{d^2}}\right) + 2\sqrt{1 + \frac{d^2}{l^2}} - 2\frac{d}{l}\right]$$

$$L_1 = .2\left[ln\left(\frac{\left(\frac{2l}{\rho}\right)\left(\frac{l}{d\sqrt{2}} + \sqrt{1 + \frac{l^2}{2d^2}}\right)}{\left(\frac{l}{d} + \sqrt{1 + \frac{l^2}{d^2}}\right)^2}\right) - \frac{3}{4} - \sqrt{1 + \frac{2d^2}{l^2}} + \frac{d\sqrt{2}}{l} + 2\sqrt{1 + \frac{d^2}{l^2}} - 2\frac{d}{l}\right]$$

Assuming *l* >> *d*

$$L_1 \approx .2\left[ln\left(\frac{\left(\frac{2l}{\rho}\right)\left(\frac{l}{d\sqrt{2}}+\sqrt{\frac{l^2}{2d^2}}\right)}{\left(\frac{l}{d}+\sqrt{\frac{l^2}{d^2}}\right)^2}\right)-\frac{3}{4}-\left(1+\frac{d^2}{l^2}\right)+\frac{d\sqrt{2}}{l}+2\left(1+\frac{d^2}{2l^2}\right)-2\frac{d}{l}\right]$$

$$L_1 \approx .2\left[ln\left(\frac{\left(\frac{2l}{\rho}\right)\left(\frac{l}{d\sqrt{2}}+\frac{l}{d\sqrt{2}}\right)}{\left(\frac{l}{d}+\frac{l}{d}\right)^2}\right)+\frac{1}{4}\right]$$

$$L_1 \approx .2\left[ln\left(\frac{\left(\frac{2l}{\rho}\right)\left(\frac{2l}{d\sqrt{2}}\right)}{\left(\frac{2l}{d}\right)^2}\right)+\frac{1}{4}\right]$$

$$L_1 \approx .2\left[ln\left(\frac{\left(\frac{2l}{\sqrt{2}\rho}\right)}{\left(\frac{2l}{d}\right)}\right)+\frac{1}{4}\right]$$

$L_1 \approx .2\left[ln\left(\frac{d}{\sqrt{2}\rho}\right)+\frac{1}{4}\right]$ (this is actually an easier equation to use)

$$L_1 \approx .2\left[ln\left(\frac{d}{\sqrt{2}\rho}\right)+ln\left(e^{\frac{1}{4}}\right)\right]$$

$$L_1 \approx .2\left[ln\left(\frac{de^{\frac{1}{4}}}{\sqrt{2}\rho}\right)\right]$$

$L_1 \approx .2\left[ln\left(\frac{d}{\sqrt{2}r}\right)\right]$ where $r = \rho e^{-\frac{1}{4}} \approx 0.78\rho$

For conductors 1 and 3 in parallel, the inductance is half …

$$L_{one\ way} \approx .1\left[ln\left(\frac{d}{\sqrt{2}r}\right)\right]$$

The round-trip inductance is twice the one way

$$L_{roundtrip} \approx .2\left[ln\left(\frac{d}{\sqrt{2}r}\right)\right] = .2\left[ln\left(\frac{d}{\sqrt{2}\rho}\right)+\frac{1}{4}\right] \text{ µH per meter}$$

2.2. Common mode inductance

The common mode inductance of a four-conductor cable where the four conductors are all in parallel and all the return current returns via a path that is far from the conductors is given by the following equations. (Note this formulation includes the mutual inductance between the four conductors)

$$L_1 = .2\left[\left[ln\left(\frac{2l}{\rho}\right)-\frac{3}{4}\right]+\left[ln\left(\frac{l}{d\sqrt{2}}+\sqrt{1+\frac{l^2}{2d^2}}\right)-\sqrt{1+\frac{2d^2}{l^2}}+\frac{d\sqrt{2}}{l}\right]+2\left[ln\left(\frac{l}{d}+\sqrt{1+\frac{l^2}{d^2}}\right)-\sqrt{1+\frac{d^2}{l^2}}+\frac{d}{l}\right]\right]$$

$$L_1 = .2\left[ln\left(\frac{2l}{\rho}\right)+ln\left(\frac{l}{d\sqrt{2}}+\sqrt{1+\frac{l^2}{2d^2}}\right)+2ln\left(\frac{l}{d}+\sqrt{1+\frac{l^2}{d^2}}\right)-\sqrt{1+\frac{2d^2}{l^2}}+\frac{d\sqrt{2}}{l}-2\sqrt{1+\frac{d^2}{l^2}}+2\frac{d}{l}-\frac{3}{4}\right]$$

$$L_1 = .2\left[ln\left(\left(\frac{2l}{\rho}\right)\left(\frac{l}{d\sqrt{2}}+\sqrt{1+\frac{l^2}{2d^2}}\right)\left(\frac{l}{d}+\sqrt{1+\frac{l^2}{d^2}}\right)^2\right)-\sqrt{1+\frac{2d^2}{l^2}}-2\sqrt{1+\frac{d^2}{l^2}}+\frac{d}{l}\left(2+\sqrt{2}\right)-\frac{3}{4}\right]$$

Assuming *l* >> *d*

$$L_1 \approx .2\left[ln\left(\left(\frac{2l}{\rho}\right)\left(\frac{l}{d\sqrt{2}}+\sqrt{1+\frac{l^2}{2d^2}}\right)\left(\frac{l}{d}+\sqrt{1+\frac{l^2}{d^2}}\right)^2\right)-1-2-2\frac{d^2}{l^2}+\frac{d}{l}\left(2+\sqrt{2}\right)-\frac{3}{4}\right]$$

$$L_1 \approx .2\left[ln\left(\left(\frac{2l}{\rho}\right)\left(\frac{l}{d\sqrt{2}}+\sqrt{1+\frac{l^2}{2d^2}}\right)\left(\frac{l}{d}+\sqrt{1+\frac{l^2}{d^2}}\right)^2\right)-3.75+\frac{d}{l}\left(2+\sqrt{2}\right)\right]$$

$$L_1 \approx .2\left[ln\left(\left(\frac{2l}{\rho}\right)\left(\frac{2l}{d\sqrt{2}}\right)\left(2\frac{l}{d}\right)^2\right)-3.75\right]$$

$$L_1 \approx .2\left[ln\left(\frac{16l^4}{\sqrt{2}\rho d^3}\right)-3.75\right]$$

The common mode self-inductance of all four conductors, being in parallel, is ¼ that of one conductor.

$$L_{cms} \approx .2\left[0.25ln\left(\frac{16l^4}{\sqrt{2}\rho d^3}\right)-\frac{3.75}{4}\right]$$

$$L_{cms} \approx .2\left[ln\left(\frac{2l}{\left(\sqrt{2}\rho d^3\right)^{.25}}\right)-\frac{3.75}{4}\right] \quad \text{(µH per meter)}$$

This can be shown to be equivalent to the equation Grover (2009) provides for the self-inductance of the four conductors in parallel:

$$L_{cms} = .2\left[ln\left(\frac{2l}{R}\right)-1\right] \text{ µH per meter} \qquad \text{(Grover 14)}$$

$$R = \left(4ra^3\right)^{.25} \qquad \text{(Grover 15)}$$

$$r = \rho e^{-\frac{1}{4}}$$

$$a = \frac{\sqrt{2}}{2}d$$

ρ = radius of the conductor (m)

d = distance between adjacent conductors (m)

l = length of the conductor (m)

Note that the common mode self-inductance of the four cables without shield is a nonlinear function of the length

The round-trip common mode inductance (µH per meter) of a four-conductor cable where the four conductors are all in parallel and all the return current returns via a shield is given by Grover (Equation 26)

$$L_{shield} = 0.2\left[ln\left(\frac{\rho_1}{\alpha}\right) + \frac{2\frac{\rho_2^2}{\rho_1^2}}{1-\frac{\rho_2^2}{\rho_1^2}} ln\left(\frac{\rho_1}{\rho_2}\right) + \frac{1}{n} ln\left(\frac{\alpha}{n\rho}\right) + ln(\zeta) + \frac{1}{4n} - 1\right]$$

Where

$\rho_1 = outer\ radius\ of\ shield$

$\rho_2 = inner\ radius\ of\ shield$

$\alpha = radius\ of centers\ of\ the\ conductors = \frac{d}{\sqrt{2}}$

$\rho = radius\ \ of\ the\ conductors$

$n = number\ of\ conductors$ *(in this case n = 4)*

ln(ζ) = *From Grover Table 4 on page 23*

$$ln(\zeta) \approx 0.333\left(1 - \frac{\rho_2}{\rho_1}\right)$$

The outer radius of the shield can be approximated as half the diameter minus the jacket thickness.

$\rho_1 = \rho_2 + t_1$

$\frac{\rho_2}{\rho_1} = \frac{\rho_1 - t_1}{\rho_1} = 1 - \frac{t_1}{\rho_1}$

$\frac{\rho_1}{\rho_2} = \frac{\rho_1}{\rho_1 - t_1} = 1 + \frac{t_1}{\rho_1 - t_1}$

$$ln(\zeta) \approx 0.333\left(\frac{t_1}{\rho_1}\right)$$

$$\left(\frac{\rho_2}{\rho_1}\right)^2 = 1 - 2\frac{t_1}{\rho_1} + \left(\frac{t_1}{\rho_1}\right)^2$$

$$\frac{2\frac{\rho_2^2}{\rho_1^2}}{1-\frac{\rho_2^2}{\rho_1^2}} = 2\frac{\left(1 - 2\frac{t_1}{\rho_1} + \left(\frac{t_1}{\rho_1}\right)^2\right)}{\left(2\frac{t_1}{\rho_1} - \left(\frac{t_1}{\rho_1}\right)^2\right)} = 2\left(\frac{1}{2\frac{t_1}{\rho_1} - \left(\frac{t_1}{\rho_1}\right)^2} - 1\right) = \frac{1}{\frac{t_1}{\rho_1} - \frac{1}{2}\left(\frac{t_1}{\rho_1}\right)^2} - 2 = \frac{1}{\frac{t_1}{\rho_1}\left(1 - \frac{1}{2}\frac{t_1}{\rho_1}\right)} - 2$$

Resulting in the following equation for L_{shield}:

$$L_{shield} = 0.2\left[ln\left(\frac{\sqrt{2}\rho_1}{d}\right) + \left(\frac{1}{\frac{t_1}{\rho_1}\left(1 - \frac{1}{2}\frac{t_1}{\rho_1}\right)} - 2\right) ln\left(\frac{\rho_1}{\rho_1 - t_1}\right) + \frac{1}{4} ln\left(\frac{d}{4\sqrt{2}\rho}\right) + 0.333\left(\frac{t_1}{\rho_1}\right) - \frac{15}{16}\right]$$

2.3 Skin Effect

The previous calculations do not take the skin effect into account. The self-inductance terms should be adjusted to account for the current concentrating at the surface of the conductors.

Recall, at low frequencies, the self-inductance of a conductor is given by

$$L_{11} = 0.2\left[ln\left(\frac{2l}{\rho}\right) - \frac{3}{4}\right] \text{ (µH per meter)} \qquad \text{(Grover 7)}$$

At high frequencies, with the current assumed to be uniform within the skin depth δ, the self-inductance of a conductor can be calculated using the same equation used for the self-inductance of the shield:

$$L_{11} \approx 0.2\left[ln\left(\frac{2l}{\rho}\right) + 0.333\left(\frac{\delta}{\rho}\right) - 1\right] \text{ (µH per meter)}$$

Hence the maximum reduction in inductance is .25 µH per meter.

For simplicity, it may be easiest to assume the low frequency self inductance for $\frac{\delta}{\rho} > 0.75$ and the high frequency self inductance for $\frac{\delta}{\rho} \leq 0.75$. (The two expressions result in the same self inductance at $\frac{\delta}{\rho} = 0.75$)

Thus at $\frac{\delta}{\rho} \leq 0.75$, the inductance calculation for each conductor is estimated to be reduced by $0.25 - 0.333\left(\frac{\delta}{\rho}\right)$ µH per meter as compared to the low frequency calculation.

Since there are two conductors in parallel, the differential mode cable inductance at high frequency is equal to the differential mode cable inductance at low frequency reduced by half the reduction for a single conductor. With all four conductors in parallel, the common mode cable inductance is reduced by one fourth the reduction for a single conductor.

An interesting point is that for four conductor cable with large conductors, the differential mode inductance is less than .125 µH per meter which would imply a negative inductance – clearly impossible. Hence the use of Finite Element Analysis is recommended to calculate the inductances at high frequencies. In any case, it is important to understand that as the frequency increases, the inductance will decrease.

For MVDC Cable, absent actual cable data, the following values are assumed:

Insulation Thickness: (Based on Anixter 2013)

6 kV	115 mils
12 kV	175 mils
18 kV	260 mils

Shield thickness for individual conductors: 10 mils (Based on Anixter 2013)

Tape around all conductors: 5 mils

Copper Braid Shield for overall cable assumed to be two layers of 32 AWG wire: 16 mils

Tape around shield: 5 mils

Jacket thickness (Based on MIL-DTL-24643/86): 90 mils.

With these parameters, the differential mode and common mode inductance at low frequencies can be estimated as shown in tables 3, 4 and 5.

Table 3: Differential Mode and Common Mode Estimated Inductance of 6 kV cable

Designation	Ares of Cross-Section (cmil)	AWG	Conductor Diameter (mil) of solid conductor	Conductor Diameter (mil) Concentric Strand	Number of Strands	Class	Conductor Insulation (mil)	Conductor Shield (mil)	Cable Tape (mil)	Cable Shield t1 (mil)	Cable Tape and Jacket (mil)	Conductor Separation d (mil)	Geometric Mean Radius r (mil)	Differential Mode Inductance for each set of conductors (uH per meter)	**Differential Mode Inductance for each set of conductors (uH per 1000 ft)**	Outer Radius of the cable shield rho_1 (mils)	Common Mode Inductance (uH per meter)	**Common Mode Inductance (uH per 1000 ft)**
SG-3	2580	16	50.79	57.60	7	B	115	10	5	16	95	307.6	22.4	0.227	**69.2**	392.3	0.157	**47.8**
SG-4	4110	14	64.11	72.60	7	B	115	10	5	16	95	322.6	28.3	0.209	**63.6**	410.4	0.147	**44.9**
SG-9	10380	10	101.88	115.50	7	B	115	10	5	16	95	365.5	45.0	0.175	**53.3**	462.2	0.130	**39.5**
SG-14	13090	9	114.41	129.60	7	B	115	10	5	16	95	379.6	50.5	0.167	**50.9**	479.2	0.126	**38.3**
SG-23	20820	7	144.29	163.50	7	B	115	10	5	16	95	413.5	63.7	0.152	**46.5**	520.1	0.118	**36.0**
SG-50	52620	3	229.39	263.00	19	C	115	10	5	16	95	513	102.4	0.126	**38.5**	640.2	0.104	**31.8**
SG-75	83690	1	289.29	333.20	37	C	115	10	5	16	95	583.2	129.7	0.116	**35.2**	725.0	0.098	**30.0**
SG-100	105600	0	324.96	374.40	61	D	115	10	5	16	95	624.4	145.8	0.111	**33.8**	774.7	0.096	**29.2**
SG-150	167800	000	409.63	471.60	61	D	115	10	5	16	95	721.6	183.6	0.102	**31.1**	892.0	0.091	**27.8**
SG-200	211600	0000	460.00	530.10	61	D	115	10	5	16	95	780.1	206.4	0.098	**30.0**	962.7	0.089	**27.1**
SG-300	300000		547.72	631.40	91	D	115	10	5	16	95	881.4	245.9	0.093	**28.4**	1084.9	0.086	**26.2**

Table 4: Differential Mode and Common Mode Estimated Inductance of 12 kV cable

Designation	Ares of Cross-Section (cmil)	AWG	Conductor Diameter (mil) of solid conductor	Conductor Diameter (mil) Concentric Strand	Number of Strands	Class	Conductor Insulation (mil)	Conductor Shield (mil)	Cable Tape (mil)	Cable Shield t1 (mil)	Cable Tape and Jacket (mil)	Conductor Separation d (mil)	Geometric Mean Radius r (mil)	Differential Mode Inductance for each set of conductors (uH per meter)	**Differential Mode Inductance for each set of conductors (uH per 1000 ft)**	Outer Radius of the cable shield rho_1 (mils)	Common Mode Inductance (uH per meter)	**Common Mode Inductance (uH per 1000 ft)**
SG-3	2580	16	50.79	57.60	7	B	175	10	5	16	95	427.6	22.4	0.260	**79.3**	537.2	0.172	**52.3**
SG-4	4110	14	64.11	72.60	7	B	175	10	5	16	95	442.6	28.3	0.240	**73.3**	555.3	0.162	**49.3**
SG-9	10380	10	101.88	115.50	7	B	175	10	5	16	95	485.5	45.0	0.203	**62.0**	607.1	0.143	**43.5**
SG-14	13090	9	114.41	129.60	7	B	175	10	5	16	95	499.6	50.5	0.195	**59.3**	624.1	0.138	**42.2**
SG-23	20820	7	144.29	163.50	7	B	175	10	5	16	95	533.5	63.7	0.178	**54.2**	665.0	0.130	**39.6**
SG-50	52620	3	229.39	263.00	19	C	175	10	5	16	95	633	102.4	0.147	**45.0**	785.1	0.114	**34.8**
SG-75	83690	1	289.29	333.20	37	C	175	10	5	16	95	703.2	129.7	0.134	**40.9**	869.8	0.107	**32.7**
SG-100	105600	0	324.96	374.40	61	D	175	10	5	16	95	744.4	145.8	0.128	**39.1**	919.6	0.104	**31.7**
SG-150	167800	000	409.63	471.60	61	D	175	10	5	16	95	841.6	183.6	0.118	**35.8**	1036.9	0.098	**30.0**
SG-200	211600	0000	460.00	530.10	61	D	175	10	5	16	95	900.1	206.4	0.113	**34.3**	1107.5	0.096	**29.2**
SG-300	300000		547.72	631.40	91	D	175	10	5	16	95	1001.4	245.9	0.106	**32.2**	1229.8	0.092	**28.1**

Table 5: Differential Mode and Common Mode Estimated Inductance of 18 kV cable

Designation	Ares of Cross-Section (cmil)	AWG	Conductor Diameter (mil) of solid conductor	Conductor Diameter (mil) Concentric Strand	Number of Strands	Class	Conductor Insulation (mil)	Conductor Shield (mil)	Cable Tape (mil)	Cable Shield t1 (mil)	Cable Tape and Jacket (mil)	Conductor Separation d (mil)	Geometric Mean Radius r (mil)	Differential Mode Inductance for each set of conductors (uH per meter)	**Differential Mode Inductance for each set of conductors (uH per 1000 ft)**	Outer Radius of the cable shield rho_1 (mils)	Common Mode Inductance (uH per meter)	**Common Mode Inductance (uH per 1000 ft)**
SG-3	2580	16	50.79	57.60	7	B	260	10	5	16	95	597.6	22.4	0.294	**89.5**	742.4	0.187	**57.1**
SG-4	4110	14	64.11	72.60	7	B	260	10	5	16	95	612.6	28.3	0.273	**83.2**	760.5	0.177	**53.9**
SG-9	10380	10	101.88	115.50	7	B	260	10	5	16	95	655.5	45.0	0.233	**71.1**	812.3	0.157	**47.8**
SG-14	13090	9	114.41	129.60	7	B	260	10	5	16	95	669.6	50.5	0.224	**68.2**	829.3	0.152	**46.4**
SG-23	20820	7	144.29	163.50	7	B	260	10	5	16	95	703.5	63.7	0.206	**62.7**	870.2	0.143	**43.5**
SG-50	52620	3	229.39	263.00	19	C	260	10	5	16	95	803	102.4	0.171	**52.2**	990.3	0.125	**38.2**
SG-75	83690	1	289.29	333.20	37	C	260	10	5	16	95	873.2	129.7	0.156	**47.5**	1075.0	0.118	**35.8**
SG-100	105600	0	324.96	374.40	61	D	260	10	5	16	95	914.4	145.8	0.149	**45.4**	1124.8	0.114	**34.7**
SG-150	167800	000	409.63	471.60	61	D	260	10	5	16	95	1011.6	183.6	0.136	**41.4**	1242.1	0.107	**32.7**
SG-200	211600	0000	460.00	530.10	61	D	260	10	5	16	95	1070.1	206.4	0.130	**39.6**	1312.7	0.104	**31.8**
SG-300	300000		547.72	631.40	91	D	260	10	5	16	95	1171.4	245.9	0.121	**37.0**	1435.0	0.100	**30.4**

3. Capacitance

3.1. Conductor to Conductor Shield Capacitance

At relatively low frequencies, where the shields are all grounded, the primary cable capacitance is that between the conductor and the conductor shield. The capacitance per unit length is given by:

$$C_{per\_unit\_length} = \frac{2\pi k\varepsilon_o}{ln\left(\frac{D_{shield}}{D_{conductor}}\right)} \text{ (Farads/meter)}$$

$$C_{per\_unit\_length} = \frac{(304.8\times10^6)2\pi k\varepsilon_o}{ln\left(\frac{D_{shield}}{D_{conductor}}\right)} \text{ (μF/(1000 ft))}$$

Where
k = dielectric constant
ε_o = vacuum permittivity (≈ 8.854×10^{-12} F·m^{-1})

Restating

$$C_{per\_unit\_length} = \frac{(.016956)k}{ln\left(\frac{D_{shield}}{D_{conductor}}\right)} \text{ (μF/(1000 ft))}$$

Nominal dielectric constants of some insulators are:

Ethylene Propylene Rubber (EPR)	2.24 (Can vary significantly)
Nylon	4.00
Polyethylene (Cross-Linked) (XLPE)	2.30
Polypropylene	2.24
Silicone Rubber	2.6
Polyvinyl Chloride	2.7

3.2. Differential Mode Capacitance

Under the assumption there is a high impedance between the power system and ground, and that all the shields are grounded, then the differential mode capacitance is equal to one half of twice the capacitance of the conductor to conductor shield capacitance. The one half factor accounts for the capacitances from line to line consisting of two capacitances in series. The factor of 2 accounts for two conductors being in parallel. See Table 6 for estimated differential mode capacitance of MVDC cables.

3.3. Common Mode Capacitance

Under the assumption there is a high impedance between the power system and ground, and that all the shields are grounded, then the common mode capacitance is equal to four times the capacitance of the conductor to conductor shield capacitance. The factor of 4 accounts for all four conductors being in parallel. See Table 6 for estimated common mode capacitance of MVDC cables.

Table 6: Differential Mode and Common Mode Estimated Capacitance

Designation	Conductor Diameter (in)	6 kV Conductor Shield Diameter (in)	12 kV Conductor Shield Diameter (in)	18 kV Conductor Shield Diameter (in)	6 kV Differential Mode Capacitance (uF / 1000ft)	12 kV Differential Mode Capacitance (uF / 1000ft)	18 kV Differential Mode Capacitance (uF / 1000ft)	6 kV Common Mode Capacitance (uF / 1000ft)	12 kV Common Mode Capacitance (uF / 1000ft)	18 kV Common Mode Capacitance (uF / 1000ft)
SG-3	0.058	0.288	0.408	0.578	0.024	0.020	0.017	0.097	0.080	0.068
SG-4	0.073	0.303	0.423	0.593	0.027	0.022	0.019	0.109	0.089	0.074
SG-9	0.116	0.346	0.466	0.636	0.036	0.028	0.023	0.142	0.112	0.091
SG-14	0.130	0.360	0.480	0.650	0.038	0.030	0.024	0.153	0.119	0.097
SG-23	0.164	0.394	0.514	0.684	0.044	0.034	0.027	0.178	0.136	0.109
SG-50	0.263	0.493	0.613	0.783	0.062	0.046	0.036	0.248	0.184	0.143
SG-75	0.333	0.563	0.683	0.853	0.074	0.054	0.041	0.297	0.217	0.166
SG-100	0.374	0.604	0.724	0.894	0.081	0.059	0.045	0.326	0.236	0.179
SG-150	0.472	0.702	0.822	0.992	0.098	0.070	0.052	0.393	0.281	0.210
SG-200	0.530	0.760	0.880	1.050	0.108	0.077	0.057	0.433	0.308	0.228
SG-300	0.631	0.861	0.981	1.151	0.126	0.088	0.065	0.502	0.354	0.260

4. Cable Dimensions and Mass Properties

Based on the dimensions assumed in section 2, the cable dimensions and mass properties for MVDC cable can be estimated. From Section 2:

$$d = \frac{D - 2s}{1 + \sqrt{2}}$$

Hence the overall diameter (D) of the cable can be estimated by

$$D = d\left(1 + \sqrt{2}\right) + 2s$$

The conductor separation (d) is twice the sum of the conductor radius, conductor insulation thickness, conductor shield thickness, and conductor sheathing thickness.

The weight of the cable is estimated by summing estimates for its elements:

$$\begin{aligned} W_{cable} = {} & W_{conductors} + W_{Conductor\_insulation} + W_{Conductor\_Shield} + W_{Cable\_Shield} \\ & + W_{Cable\_Sheathing} + W_{filler} \end{aligned}$$

The conductor weight per unit length ($W_{conductors}$)can be obtained from a table in ASTM B8 for the given conductor size and multiplying by 4 (for the 4 conductors)

Alternately, the weight (lbs) per 1000 ft of a material is given by:

$$W_{1000ft} = G\left(62.42718\ \frac{lbs}{ft^3}\right)\left(\frac{1}{144}\frac{ft^2}{in^2}\right)\left(\frac{1000}{1}\frac{ft}{1000ft}\right)(A\ in^2)$$

$$W_{1000ft} = 433.5(GA)$$

Where

G = specific gravity of the material

A = Cross sectional area (square inches)

Copper has a specific gravity of 8.89

Insulation as a specific gravity of about 1.3

An alternate method calculating the conductor weight is

$$W_{conductors} = (4)(8.89)(433.5)\left(\frac{\pi}{4}\right)(D_{conductor})^2$$

$$W_{conductors} = 12107(D_{conductor})^2$$

Where

$D_{conductor}$ = Diameter of a conductor (inches)

The weight of the four shields for the individual conductors is given by:

$$W_{Conductor\_Shield} = (4)(8.89)(433.5)(\pi)(D_{conductor} + 2t_{insulation} + t_{shield})(t_{shield})$$

Where the thicknesses are all in inches.

Similarly, the overall cable shield weight can be estimated

$$W_{Cable\_Shield} = (8.89)(433.5)(\pi)\left(D - 2t_{jacket} - 2t_{tape} - t_{cable\_shield}\right)\left(t_{cable\_shield}\right)$$

If we assume the specific gravity of the remainder of the cable is roughly the same (G = 1.3), then the insulation, filler, and jacket weights combined are based on the cross section of the overall cable less the cross section of the conductors and shields

$$W_{insulation} = W_{Conductor\_insulation} + W_{Cable\_Sheathing} + W_{filler}$$

$$W_{copper} = W_{conductors} + W_{Conductor\_Shield} + W_{Cable\_Shield}$$

$$W_{insulation} = (1.3)(433.5)\pi\left(\frac{D^2}{4}\right) - \left(W_{copper}\right)\left(\frac{1.3}{8.89}\right)$$

$$W_{cable} = W_{copper} + W_{insulation}$$

The results of these calculations are presented in Tables 7 and 8.

Table 7: Cable conductor and shield weight estimates

Designation	6 kV Cable Diameter (inches)	12kV Cable Diameter (inches)	18 kV Cable Diameter (inches)	Conductor Weight (lbs/1000 ft)	6 kV Conductor Shield Diameter (inches)	12 kV Conductor Shield Diameter (inches)	18kV Conductor Shield Diameter (inches)	Conductor Shield Thickness (inches)	6 kV Conductor Shield Weight (lbs/1000 ft)	12 kV Conductor shield Weight (lbs/1000 ft)	18 kV Conductor Shield Weight (lbs/1000 ft)	Cable Tape and Jacket (in)	Cable Shield Thickness (inches)	6 kV Cable Shield Weight (lbs/1000 ft)	12 kV Cable shield Weight (lbs/1000 ft)	18 kV Cable Shield Weight (lbs/1000 ft)
SG-3	0.97	1.26	1.67	32	0.288	0.408	0.578	0.010	144	202	285	0.095	0.016	149	205	285
SG-4	1.01	1.30	1.71	51	0.303	0.423	0.593	0.010	151	210	292	0.095	0.016	156	212	292
SG-9	1.11	1.40	1.81	128	0.346	0.466	0.636	0.010	172	230	313	0.095	0.016	176	232	312
SG-14	1.15	1.44	1.85	162	0.360	0.480	0.650	0.010	179	237	319	0.095	0.016	183	239	318
SG-23	1.23	1.52	1.93	257	0.394	0.514	0.684	0.010	195	254	336	0.095	0.016	198	255	334
SG-50	1.47	1.76	2.17	650	0.493	0.613	0.783	0.010	244	302	384	0.095	0.016	245	301	381
SG-75	1.64	1.93	2.34	1034	0.563	0.683	0.853	0.010	278	336	418	0.095	0.016	278	334	413
SG-100	1.74	2.03	2.44	1303	0.604	0.724	0.894	0.010	298	356	438	0.095	0.016	297	353	433
SG-150	1.97	2.26	2.67	2072	0.702	0.822	0.992	0.010	345	403	485	0.095	0.016	343	399	478
SG-200	2.12	2.41	2.82	2612	0.760	0.880	1.050	0.010	373	431	513	0.095	0.016	370	426	505
SG-300	2.36	2.65	3.06	3705	0.861	0.981	1.151	0.010	422	480	562	0.095	0.016	417	473	553

Table 8: Cable weight estimates

Designation	6 kV Copper Weight (lbs/1000 ft)	12 kV Copper Weight (lbs/1000 ft)	18 kV Copper Weight (lbs/1000 ft)	6 kV Insulation Weight (lbs/1000 ft)	12 kV Insulation Weight (lbs/1000 ft)	18 kV Insulation Weight (lbs/1000 ft)	6 kV cable weight (lbs/1000 ft)	12 kV cable weight (lbs/1000 ft)	18 kV cable weight (lbs/1000 ft)
SG-3	325	439	601	373	643	1154	698	1082	1755
SG-4	358	472	634	400	680	1203	758	1152	1837
SG-9	476	591	752	480	786	1347	956	1377	2100
SG-14	523	637	799	507	822	1396	1030	1460	2195
SG-23	651	765	927	575	911	1514	1226	1676	2441
SG-50	1139	1253	1415	791	1188	1879	1929	2441	3293
SG-75	1589	1703	1865	958	1399	2151	2547	3102	4016
SG-100	1898	2012	2174	1062	1528	2316	2959	3540	4490
SG-150	2760	2874	3036	1321	1848	2721	4081	4722	5757
SG-200	3355	3469	3631	1490	2053	2977	4845	5522	6609
SG-300	4544	4659	4821	1800	2426	3440	6345	7085	8260

5. Cable Ampacity

The cable ampacity is determined by the temperature at the conductor surface and at the outer layer of the cable jacket. The conductor surface temperature must be below the rated temperature of the insulation for the desired service life. The outer layer of the cable jacket must be cool enough to touch safely. Additionally, the assumed ambient temperature of the air in the space also limits the amount of heat that can be dissipated while also limiting the conductor and cable jacket temperature. The ampacity for a given cable design should be based on detailed analysis, such as finite element analysis. An estimate for the ampacity of a four conductor MVDC cable can be developed from a three conductor MVAC cable.

For the cable jacket temperature, MIL-STD-1472G establishes an exposure limit for plastic or wood of 85 °C for momentary contact and 69 °C for prolonged contact or handling.

MIL-DTL-917F states that interior shipboard equipment shall be designed to operate at an ambient temperature up to 50 °C. IEEE 45.8 lists a default ambient temperature of 45 °C.

MIL-DTL-917F indicates the maximum temperature for Cross-linked, modified polyethylene (XLPE) insulation is 125 °C for hook-up wire. Industry practice is to design for the maximum conductor temperature of 90 °C for operating temperature and 130 °C for overload temperature.

Another choice for insulation is Ethylene Propylene Rubber (EPR). Depending on formulation, it can withstand continuous temperatures up to 150 °C

MIL-HDBK-299 Table XIII indicates voltage drop calculations are based on a temperature of 65 °C. It is inferred that this corresponds to the conductor temperature.

Table 9 provides estimates for the ampacity of MVDC cables based on scaling the ampacity of 3 phase cable from Table 7 of IEEE Std 45.8-2016 by curve fitting the conductor circular mils to ampacity. This table is for marine installations with cables spaced less than one cable diameter between adjacent cables and assumes an ambient temperature of 45° C. A scaling factor of $\frac{\sqrt{3}}{2}$ was used to adjust the ampacity of each conductor to account for the additional conductor. This scaling factor ensures the heat produced per foot of cable is the same for the three and four conductor cables. This adjustment is likely conservative, since the diameter of the cable will increase and thereby increase the surface area and heat transfer, but this approximation is reasonable until more detailed analysis is performed. The cable ampacity of the four-conductor cable is twice the conductor ampacity since two conductors are connected in parallel. To avoid extrapolation, the ampacities of smaller conductors are not included.

Table 9: Cable Ampacity Estimate for 4 conductor cable

		Conductor Ampacity (amps) for 3 conductor Cable				Conductor Ampacity (amps) for 4 Conductor Cable				Cable Ampacity (amps) for 4 Conductor Cable			
Designation	AWG	6kV 90C	6kV 105C	12kV 90C	12kV 105C	6kV 90C	6kV 105C	12kV 90C	12kV 105C	6kV 90C	6kV 105C	12kV 90C	12kV 105C
SG-23	7	75	84			65	73			129	146		
SG-50	3	111	126	120	135	97	109	104	117	193	218	209	234
SG-75	1	145	164	152	171	126	142	131	148	252	285	263	295
SG-100	0	168	190	173	194	145	165	150	168	291	329	300	337
SG-150	000	226	256	229	257	196	222	198	222	392	444	397	444
SG-200	0000	262	298	265	296	227	258	229	256	454	516	458	512
SG-300		322	367	327	363	279	318	283	315	558	636	567	629

6. Concluding Thoughts

The intent of this document has been to gain an understanding of the potential properties of MVDC four-conductor cables. The calculations and tables are likely adequate for relatively low frequencies (up to 10 kHz or so). As was shown in the attempt to correct the inductance formulas for the skin effect, a better method is needed. Furthermore, at high frequencies, new methods are needed to better model cable characteristics.

The cable weighs and ampacity are highly dependent on the design of the insulation systems. Gaining a better understanding of Space Charge and Partial Discharge within MVDC cables as sell as determining the maximum expected transient voltages due to normal operation, faults, and lightning will enable optimization of the cable design to maximize cable ampacity while minimizing weight.

References

Anixter, “Technical Information Handbook, Wire and Cable,” Fifth Edition, 2013.

ASTM, “Standard Specification for Concentric-Lay-Stranded Copper Conductors, Hard, Medium-Hard, or Soft,” ASTM B8-11, Reapproved 2017.

Department of Defense, “Cable Comparison handbook, Data Pertaining to Electric Shipboard Cable,” MIL-HDBK-299, 15 October 1991.

Department of Defense, “Design Criteria Standard, Human Engineering,” MIL-STD-1472G of 11 January 2021.

Department of Defense, “Detail Specification Sheet, Cable, Electrical -20 ˚C to+105 ˚C, 1000 Volts, Type LS4OW,” MIL-DTL-24643/68A of 11 July 2011.

Doerry, Dr. Norbert, and Dr. John Amy Jr., " MVDC Distribution Systems," presented at ASNE AMTS 2018, Philadelphia PA, March 28-29, 2018

Grover, Frederick W., *Inductance Calculations*, Dover Publications, Inc., Mineola NY, 2009

International Electrotechnical Commission (IEC), “Electric cables – Calculation of the current rating – Part 1-1: Current rating equations (100 % load factor) and calculation of losses – General,” IEC 60287-1-1.

Neher, J. H., and M.H. McGrath, “The Calculation of the Temperature Rise and Load Capability of Cable Systems,” Transactions of the American Institute of Electrical Engineers, Part III: Power Apparatus and Systems, Vol 76, October 1957, pp. 752-764.

Riba, J. Analysis of formulas to calculate the AC resistance of different conductors' configurations. "Electric power systems research", 01 Octubre 2015, p. 93-100. http://hdl.handle.net/2117/77077

Appendix A: Table for Calculating Skin Effect Ratio

The following table is from Neher and McGrath (1957) with two values corrected (F = 2.48 and F = 4.43). Enough data is provided to enable linear interpolation between points. This table extends the information provided in MIL-HDBK-299 to an additional significant digit for F, but with one less significant digit for the SER.

The SER is 0 for $F < 0.3$. Use the skin depth method for $F > 4.99$

F	*Skin Effect*	*SER*
0.3	0	1
0.31	0	1
0.32	0.0001	1.0001
0.33	0.0001	1.0001
0.34	0.0001	1.0001
0.35	0.0001	1.0001
0.36	0.0001	1.0001
0.37	0.0001	1.0001
0.38	0.0001	1.0001
0.39	0.0001	1.0001
0.4	0.0001	1.0001
0.41	0.0001	1.0001
0.42	0.0002	1.0002
0.43	0.0002	1.0002
0.44	0.0002	1.0002
0.45	0.0002	1.0002
0.46	0.0002	1.0002
0.47	0.0003	1.0003
0.48	0.0003	1.0003
0.49	0.0003	1.0003
0.5	0.0003	1.0003
0.51	0.0004	1.0004
0.52	0.0004	1.0004
0.53	0.0004	1.0004
0.54	0.0005	1.0005
0.55	0.0005	1.0005
0.56	0.0005	1.0005
0.57	0.0006	1.0006
0.58	0.0006	1.0006
0.59	0.0006	1.0006
0.6	0.0007	1.0007
0.61	0.0007	1.0007
0.62	0.0008	1.0008
0.63	0.0008	1.0008
0.64	0.0009	1.0009
0.65	0.001	1.001
0.66	0.001	1.001
0.67	0.0011	1.0011
0.68	0.0011	1.0011
0.69	0.0012	1.0012
0.7	0.0012	1.0012
0.71	0.0013	1.0013
0.72	0.0014	1.0014
0.73	0.0015	1.0015
0.74	0.0016	1.0016
0.75	0.0017	1.0017
0.76	0.0018	1.0018
0.77	0.0019	1.0019
0.78	0.0019	1.0019
0.79	0.002	1.002
0.8	0.0021	1.0021
0.81	0.0022	1.0022

0.82	,	0.0024	,	1.0024
0.83	,	0.0025	,	1.0025
0.84	,	0.0026	,	1.0026
0.85	,	0.0028	,	1.0028
0.86	,	0.0029	,	1.0029
0.87	,	0.003	,	1.003
0.88	,	0.0031	,	1.0031
0.89	,	0.0033	,	1.0033
0.9	,	0.0034	,	1.0034
0.91	,	0.0036	,	1.0036
0.92	,	0.0038	,	1.0038
0.93	,	0.0039	,	1.0039
0.94	,	0.0041	,	1.0041
0.95	,	0.0043	,	1.0043
0.96	,	0.0045	,	1.0045
0.97	,	0.0047	,	1.0047
0.98	,	0.0048	,	1.0048
0.99	,	0.005	,	1.005
1	,	0.0052	,	1.0052
1.01	,	0.0054	,	1.0054
1.02	,	0.0056	,	1.0056
1.03	,	0.0058	,	1.0058
1.04	,	0.0061	,	1.0061
1.05	,	0.0063	,	1.0063
1.06	,	0.0065	,	1.0065
1.07	,	0.0068	,	1.0068
1.08	,	0.007	,	1.007
1.09	,	0.0073	,	1.0073
1.1	,	0.0076	,	1.0076
1.11	,	0.0079	,	1.0079
1.12	,	0.0081	,	1.0081
1.13	,	0.0084	,	1.0084
1.14	,	0.0087	,	1.0087
1.15	,	0.009	,	1.009
1.16	,	0.0094	,	1.0094
1.17	,	0.0097	,	1.0097
1.18	,	0.01	,	1.01
1.19	,	0.0103	,	1.0103
1.2	,	0.0107	,	1.0107
1.21	,	0.0111	,	1.0111
1.22	,	0.0114	,	1.0114
1.23	,	0.0118	,	1.0118
1.24	,	0.0122	,	1.0122
1.25	,	0.0126	,	1.0126
1.26	,	0.013	,	1.013
1.27	,	0.0134	,	1.0134
1.28	,	0.0138	,	1.0138
1.29	,	0.0142	,	1.0142
1.3	,	0.0147	,	1.0147
1.31	,	0.0152	,	1.0152
1.32	,	0.0156	,	1.0156
1.33	,	0.0161	,	1.0161
1.34	,	0.0166	,	1.0166
1.35	,	0.0171	,	1.0171
1.36	,	0.0176	,	1.0176
1.37	,	0.0181	,	1.0181
1.38	,	0.0186	,	1.0186
1.39	,	0.0192	,	1.0192
1.4	,	0.0197	,	1.0197
1.41	,	0.0202	,	1.0202
1.42	,	0.0208	,	1.0208
1.43	,	0.0214	,	1.0214
1.44	,	0.022	,	1.022
1.45	,	0.0226	,	1.0226
1.46	,	0.0232	,	1.0232
1.47	,	0.0239	,	1.0239
1.48	,	0.0245	,	1.0245
1.49	,	0.0252	,	1.0252
1.5	,	0.0258	,	1.0258
1.51	,	0.0265	,	1.0265

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1.53    ,    0.0279    ,    1.0279
1.54    ,    0.0286    ,    1.0286
1.55    ,    0.0293    ,    1.0293
1.56    ,    0.0301    ,    1.0301
1.57    ,    0.0308    ,    1.0308
1.58    ,    0.0316    ,    1.0316
1.59    ,    0.0324    ,    1.0324
1.6     ,    0.0332    ,    1.0332
1.61    ,    0.034     ,    1.034
1.62    ,    0.0349    ,    1.0349
1.63    ,    0.0357    ,    1.0357
1.64    ,    0.0366    ,    1.0366
1.65    ,    0.0375    ,    1.0375
1.66    ,    0.0383    ,    1.0383
1.67    ,    0.0392    ,    1.0392
1.68    ,    0.0402    ,    1.0402
1.69    ,    0.0411    ,    1.0411
1.7     ,    0.0421    ,    1.0421
1.71    ,    0.043     ,    1.043
1.72    ,    0.044     ,    1.044
1.73    ,    0.045     ,    1.045
1.74    ,    0.046     ,    1.046
1.75    ,    0.047     ,    1.047
1.76    ,    0.0481    ,    1.0481
1.77    ,    0.0491    ,    1.0491
1.78    ,    0.0502    ,    1.0502
1.79    ,    0.0513    ,    1.0513
1.8     ,    0.0524    ,    1.0524
1.81    ,    0.0535    ,    1.0535
1.82    ,    0.0547    ,    1.0547
1.83    ,    0.0558    ,    1.0558
1.84    ,    0.057     ,    1.057
1.85    ,    0.0582    ,    1.0582
1.86    ,    0.0594    ,    1.0594
1.87    ,    0.0606    ,    1.0606
1.88    ,    0.0619    ,    1.0619
1.89    ,    0.0631    ,    1.0631
1.9     ,    0.0644    ,    1.0644
1.91    ,    0.0657    ,    1.0657
1.92    ,    0.067     ,    1.067
1.93    ,    0.0683    ,    1.0683
1.94    ,    0.0697    ,    1.0697
1.95    ,    0.0711    ,    1.0711
1.96    ,    0.0724    ,    1.0724
1.97    ,    0.0738    ,    1.0738
1.98    ,    0.0753    ,    1.0753
1.99    ,    0.0767    ,    1.0767
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2.03    ,    0.0826    ,    1.0826
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2.17    ,    0.1058    ,    1.1058
2.18    ,    0.1076    ,    1.1076
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2.2     ,    0.1113    ,    1.1113
2.21    ,    0.1131    ,    1.1131
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2.23	,	0.1169	,	1.1169
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2.77	,	0.2474	,	1.2474
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2.79	,	0.2533	,	1.2533
2.8	,	0.2562	,	1.2562
2.81	,	0.2592	,	1.2592
2.82	,	0.2621	,	1.2621
2.83	,	0.2651	,	1.2651
2.84	,	0.2681	,	1.2681
2.85	,	0.2711	,	1.2711
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2.87	,	0.2772	,	1.2772
2.88	,	0.2803	,	1.2803
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2.9	,	0.2865	,	1.2865
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3.07	,	0.341	,	1.341
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3.09	,	0.3477	,	1.3477
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3.17	,	0.3747	,	1.3747
3.18	,	0.3782	,	1.3782
3.19	,	0.3816	,	1.3816
3.2	,	0.385	,	1.385
3.21	,	0.3885	,	1.3885
3.22	,	0.392	,	1.392
3.23	,	0.3955	,	1.3955
3.24	,	0.3989	,	1.3989
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3.31	,	0.4235	,	1.4235
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3.34	,	0.4342	,	1.4342
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3.36	,	0.4414	,	1.4414
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3.38	,	0.4485	,	1.4485
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3.4	,	0.4557	,	1.4557
3.41	,	0.4593	,	1.4593
3.42	,	0.4629	,	1.4629
3.43	,	0.4666	,	1.4666
3.44	,	0.4702	,	1.4702
3.45	,	0.4738	,	1.4738
3.46	,	0.4774	,	1.4774
3.47	,	0.4811	,	1.4811
3.48	,	0.4847	,	1.4847
3.49	,	0.4884	,	1.4884
3.5	,	0.492	,	1.492
3.51	,	0.4957	,	1.4957
3.52	,	0.4994	,	1.4994
3.53	,	0.503	,	1.503
3.54	,	0.5067	,	1.5067
3.55	,	0.5104	,	1.5104
3.56	,	0.514	,	1.514
3.57	,	0.5177	,	1.5177
3.58	,	0.5214	,	1.5214
3.59	,	0.5251	,	1.5251
3.6	,	0.5288	,	1.5288
3.61	,	0.5325	,	1.5325

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3.62    ,    0.5362   ,    1.5362
3.63    ,    0.5399   ,    1.5399
3.64    ,    0.5436   ,    1.5436
3.65    ,    0.5473   ,    1.5473
3.66    ,    0.551    ,    1.551
3.67    ,    0.5548   ,    1.5548
3.68    ,    0.5585   ,    1.5585
3.69    ,    0.5622   ,    1.5622
3.7     ,    0.5659   ,    1.5659
3.71    ,    0.5696   ,    1.5696
3.72    ,    0.5733   ,    1.5733
3.73    ,    0.5771   ,    1.5771
3.74    ,    0.5808   ,    1.5808
3.75    ,    0.5845   ,    1.5845
3.76    ,    0.5882   ,    1.5882
3.77    ,    0.592    ,    1.592
3.78    ,    0.5957   ,    1.5957
3.79    ,    0.5994   ,    1.5994
3.8     ,    0.6031   ,    1.6031
3.81    ,    0.6069   ,    1.6069
3.82    ,    0.6106   ,    1.6106
3.83    ,    0.6144   ,    1.6144
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3.86    ,    0.6256   ,    1.6256
3.87    ,    0.6293   ,    1.6293
3.88    ,    0.633    ,    1.633
3.89    ,    0.6368   ,    1.6368
3.9     ,    0.6405   ,    1.6405
3.91    ,    0.6442   ,    1.6442
3.92    ,    0.648    ,    1.648
3.93    ,    0.6517   ,    1.6517
3.94    ,    0.6555   ,    1.6555
3.95    ,    0.6592   ,    1.6592
3.96    ,    0.6629   ,    1.6629
3.97    ,    0.6667   ,    1.6667
3.98    ,    0.6704   ,    1.6704
3.99    ,    0.6741   ,    1.6741
4       ,    0.6779   ,    1.6779
4.01    ,    0.6816   ,    1.6816
4.02    ,    0.6853   ,    1.6853
4.03    ,    0.6891   ,    1.6891
4.04    ,    0.6928   ,    1.6928
4.05    ,    0.6965   ,    1.6965
4.06    ,    0.7003   ,    1.7003
4.07    ,    0.704    ,    1.704
4.08    ,    0.7077   ,    1.7077
4.09    ,    0.7114   ,    1.7114
4.1     ,    0.7152   ,    1.7152
4.11    ,    0.7189   ,    1.7189
4.12    ,    0.7226   ,    1.7226
4.13    ,    0.7263   ,    1.7263
4.14    ,    0.73     ,    1.73
4.15    ,    0.7338   ,    1.7338
4.16    ,    0.7375   ,    1.7375
4.17    ,    0.7412   ,    1.7412
4.18    ,    0.7449   ,    1.7449
4.19    ,    0.7486   ,    1.7486
4.2     ,    0.7523   ,    1.7523
4.21    ,    0.756    ,    1.756
4.22    ,    0.7597   ,    1.7597
4.23    ,    0.7634   ,    1.7634
4.24    ,    0.7671   ,    1.7671
4.25    ,    0.7708   ,    1.7708
4.26    ,    0.7745   ,    1.7745
4.27    ,    0.7782   ,    1.7782
4.28    ,    0.7819   ,    1.7819
4.29    ,    0.7856   ,    1.7856
4.3     ,    0.7893   ,    1.7893
4.31    ,    0.793    ,    1.793
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4.32	,	0.7967	,	1.7967
4.33	,	0.8004	,	1.8004
4.34	,	0.8041	,	1.8041
4.35	,	0.8078	,	1.8078
4.36	,	0.8114	,	1.8114
4.37	,	0.8151	,	1.8151
4.38	,	0.8188	,	1.8188
4.39	,	0.8225	,	1.8225
4.4	,	0.8261	,	1.8261
4.41	,	0.8298	,	1.8298
4.42	,	0.8335	,	1.8335
4.43	,	0.8371	,	1.8371
4.44	,	0.8408	,	1.8408
4.45	,	0.8445	,	1.8445
4.46	,	0.8481	,	1.8481
4.47	,	0.8518	,	1.8518
4.48	,	0.8555	,	1.8555
4.49	,	0.8591	,	1.8591
4.5	,	0.8628	,	1.8628
4.51	,	0.8664	,	1.8664
4.52	,	0.8701	,	1.8701
4.53	,	0.8737	,	1.8737
4.54	,	0.8773	,	1.8773
4.55	,	0.881	,	1.881
4.56	,	0.8846	,	1.8846
4.57	,	0.8882	,	1.8882
4.58	,	0.8919	,	1.8919
4.59	,	0.8955	,	1.8955
4.6	,	0.8991	,	1.8991
4.61	,	0.9028	,	1.9028
4.62	,	0.9064	,	1.9064
4.63	,	0.91	,	1.91
4.64	,	0.9137	,	1.9137
4.65	,	0.9173	,	1.9173
4.66	,	0.9209	,	1.9209
4.67	,	0.9245	,	1.9245
4.68	,	0.9281	,	1.9281
4.69	,	0.9317	,	1.9317
4.7	,	0.9353	,	1.9353
4.71	,	0.9389	,	1.9389
4.72	,	0.9425	,	1.9425
4.73	,	0.9461	,	1.9461
4.74	,	0.9497	,	1.9497
4.75	,	0.9533	,	1.9533
4.76	,	0.9569	,	1.9569
4.77	,	0.9605	,	1.9605
4.78	,	0.9641	,	1.9641
4.79	,	0.9677	,	1.9677
4.8	,	0.9713	,	1.9713
4.81	,	0.9749	,	1.9749
4.82	,	0.9785	,	1.9785
4.83	,	0.9821	,	1.9821
4.84	,	0.9857	,	1.9857
4.85	,	0.9892	,	1.9892
4.86	,	0.9928	,	1.9928
4.87	,	0.9964	,	1.9964
4.88	,	1	,	2
4.89	,	1.0035	,	2.0035
4.9	,	1.0071	,	2.0071
4.91	,	1.0107	,	2.0107
4.92	,	1.0142	,	2.0142
4.93	,	1.0178	,	2.0178
4.94	,	1.0214	,	2.0214
4.95	,	1.0249	,	2.0249
4.96	,	1.0285	,	2.0285
4.97	,	1.0321	,	2.0321
4.98	,	1.0356	,	2.0356
4.99	,	1.0392	,	2.0392