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Calculation Method for Normal Inducedlongitudinal Voltage on Pilot Cable

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Abstract
In this paper a full study and detailed calculations of the induced voltage in pilot cables are carried out.
First an introduction showing the importance of the induced voltage and its effect in pilot cables.
The first calculation method Flat Formation.
The second calculation method Trefoil Formation.
Then the results obtained for both methods and compared.
Finally a conclusion is conduct.
KeyWords: Induced Voltage, Normal Induced Longitudinal Voltage (NILV), Pilot cable

I. Introduction

Normal Induced Longitudinal Voltage (NILV) is generated onPilot Cable installed along with high tension Power Cable.

Expectable sources of the inducing current which causes NILV are as follows:

Three Phase Loading Current flowing in Power CableIn case that the distance between Power Cable and Pilot Cable installed are less than 2 or 3 meters, NILV on Pilot Cable is induced even If the three phase loading currents should be balanced.

Earth Return Sheathing CurrentSheath current, which is induced by phase current, flows through the sheath of Power Cable.

A part of this current flows through earth due to the phase to earth unbalance,although the sheath current has a screening effect against the induction due to the phase current. The current flowing through earth, which is called earth returning sheathcurrent, generally act as a screening current against the Induction due to the phase current .

However, it also plays the main role of the inducing current for communication line in case that this runs more than several meters away from Power Cable.

Normal Zero Phase CurrentSolidly grounded system is adopted in extra-high tension power line. Therefore, several percentage amount of zero-phase-current is generated, even in a normal condition, due to the unbalance in three phase loading current. This current flows through the ground ofsubstation and then is divided into two flows, one is the current which flows through the sheath of Power Cable and the other is the current which flows through earth. Only the latter (earth returning current) can act as inducing current, while it is very small in amount so as to benegligible.

After all, only Three Phase Loading Current isconsiderable in case that Pilot Cable runs less than several meters away from Power Line.

II. Calculation method for NILV

Induced Voltage generated by Phase Loading Current

$$V1 = j\,\omega[(Ma1 + z^2.Mb1 + z.Mc1).l1 + (z^2.Ma2 + z.Mb2 + Mc2).l2 + (z.Ma3 + Mb3 + z^2.Mc3).l3]\,.I_L.K_o \quad (Volt)(1)$$

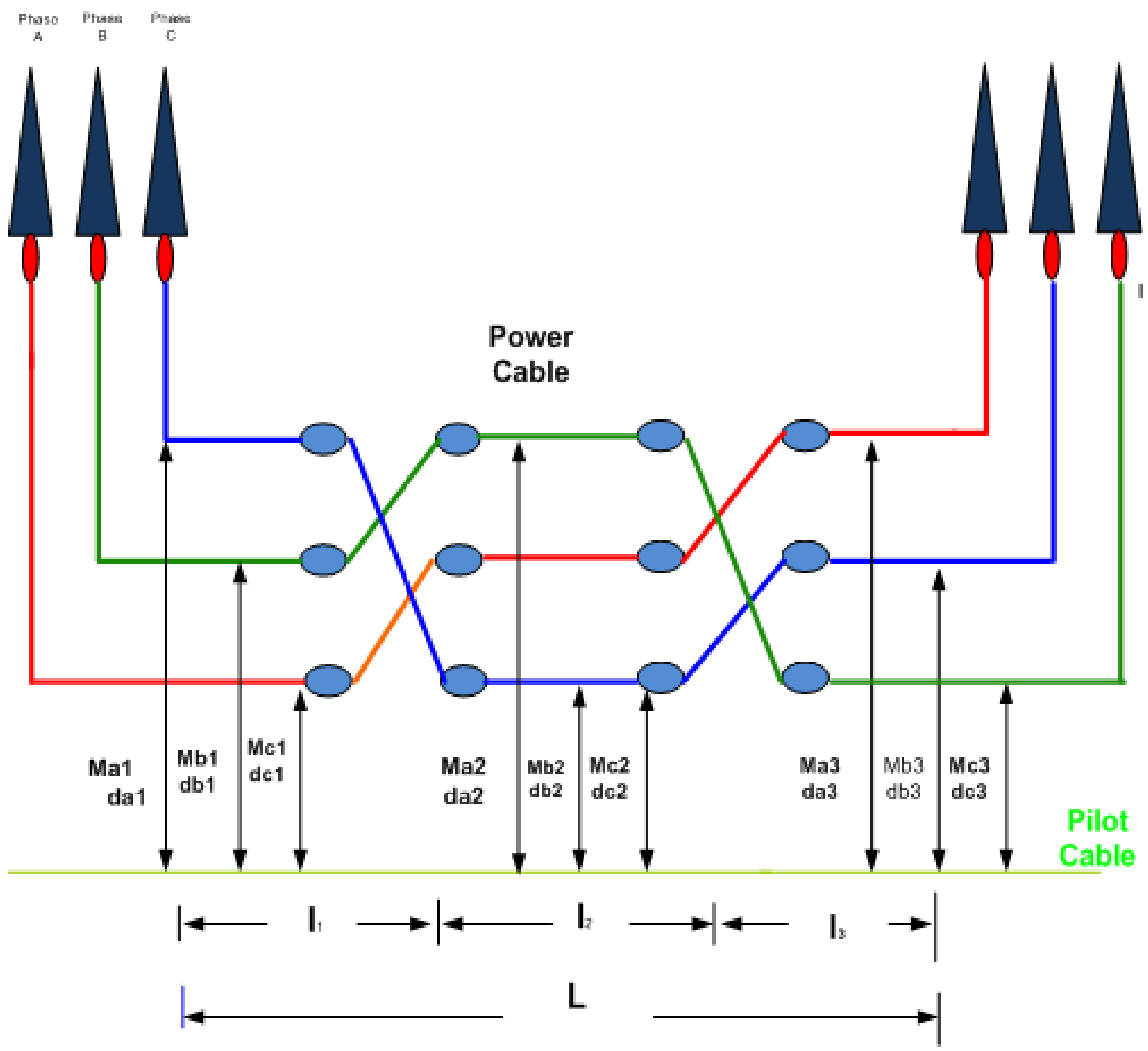


Figure.1 One Completed Transpositioned Span

Where V1 : NILV (Volt)

ω : 2πf (f : Commercial Frequency (Hz))

Mij : Mutual Impedance between each phase circuit of Power Cableand Pilot Cable (H/km)

ll_i : Equivalent Parallel Running Length of Power Cable
and Pilot Cable (km)
i.e.the length between the points of transposition

d_{ij} : Distance between each phase circuit of Power Cable
and Pilot Cable (cm)

I_L: Phase Current of Power Cable (A)

K_o : Total Screening Factor
Z : $e^{\frac{j2}{3\pi}}$

When the transposition of three phase current circuits is adopted the induced voltage on Pilot can be derived from equation (1).
And then using Carson-Pollazzek's formula, the following formula
is obtained in case ofkd<0.5 .
1st term of equation (1)

$$j\,\omega\,.(Ma1 + z^2.Mb1 + z.Mc1).l1$$

$$= j\,\omega\left[\left(4.6\ \log\frac{2}{k.da1} - 0.1544 - j\frac{\pi}{2}\right) + z^2\left(4.6\ \log\frac{2}{k.db1} - 0.1544 - j\frac{\pi}{2}\right) + z\left(4.6\ \log\frac{2}{k.dc1} - 0.1544 - j\frac{\pi}{2}\right)\right].l1 \times 10^{-4}$$

$$= j\,\omega(4.6)\left[\log\frac{2}{k.da1} + z^2\log\frac{2}{k.db1} + z\ \log\frac{2}{k.dc1}\right].l1\ \times 10^{-4}$$

Then $1 + z + z^2 = 0$

$$= j\,\omega(4.6)\left[\log\frac{2}{k.da1} - \frac{1}{2}\log\frac{2}{k.db1} - j\frac{\sqrt{3}}{2}\log\frac{2}{k.db1} - \frac{1}{2}\log\frac{2}{k.dc1} + j\ \frac{\sqrt{3}}{2}\log\frac{2}{k.dc1}\right].l1\ \times 10^{-4}$$

$$= 2.3\ \omega\left[\sqrt{3}\ .\log\frac{dc1}{db1} - j.\log\frac{da1^2}{db1\ .\ dc1}\right] l1\ \times 10^{-4}$$

Note; $k=\sqrt{4\pi\sigma\omega} = 2\pi\sqrt{2d\sigma}$

σ ; Earth Conductivity (CGS emu)
generally $\sigma = 10^{-12} : 10^{-14}$
d : distance between power line and communication line (cm)
Assume $\sigma = 10^{-12}$, f = 50 , d = 36
And then

$$K_d = 0.0026 < 0.5$$

2nd term and 3rd term of equation(1)
In the same manner as 1st term.

$$j\omega\ (z^2\ .\ Ma2 + z.Mb2 + Mc2).l2$$

$$= 2.3\omega\left[\sqrt{3}\log\frac{db2}{da2} - j.\log\frac{dc2^2}{da2\ \ db2}\right].l_2 \times 10^{-4}$$

$$j\omega(\ z.Ma3 + Mb3 + z^2.Mc3\ ).l3$$

$$= 2.3\omega\left[\sqrt{3}.\log\frac{da3}{dc3} - j.\log\frac{db3}{da3\ \ dc3}\right].l3\ \times 10^{-4}$$

Finally the following equation is obtained

$$V1 = 2.3\ \omega.I_L.k_o \times 10^{-4}\left[\left(\sqrt{3}\log\frac{dc1}{db1} - j.\log\frac{da1^2}{db1\ .dc1}\right).l_1 + \left(\sqrt{3}.\log\frac{db2}{da2} - j.\log\frac{dc2^2}{da2\ \ db2}\right).l_2 + \left(\sqrt{3}.\log\frac{da3}{dc3} - \right.\right.$$

j.logdb32da3 dc3).l3(2)

III. Typical Example Of calculation Of NILV

The route profile and installation condition as in example 132KV power cable as shown in Fig.2 and Fig.3 respectively.
The normal induced longitudinal voltage at each completed transpositioned span is calculated by equation 2.

3. 1 Flat Formation

Substitute the following values for Equation2,
ω= 2πf = 314.2 (f = 50)
I_L = 670 (A) (max. current carrying capacity for flat formation)
da1 = da2 = da3 = 36 (cm) = 3D (D = 12 cm)
db1 = db2 = db3= 24 (cm) = 2D
dcl = dc2 = dc3 = 12 (cm) = D
Ko = 0.9 (Taking the shielding effect caused by Wire Armourof Pilot Cable into account)

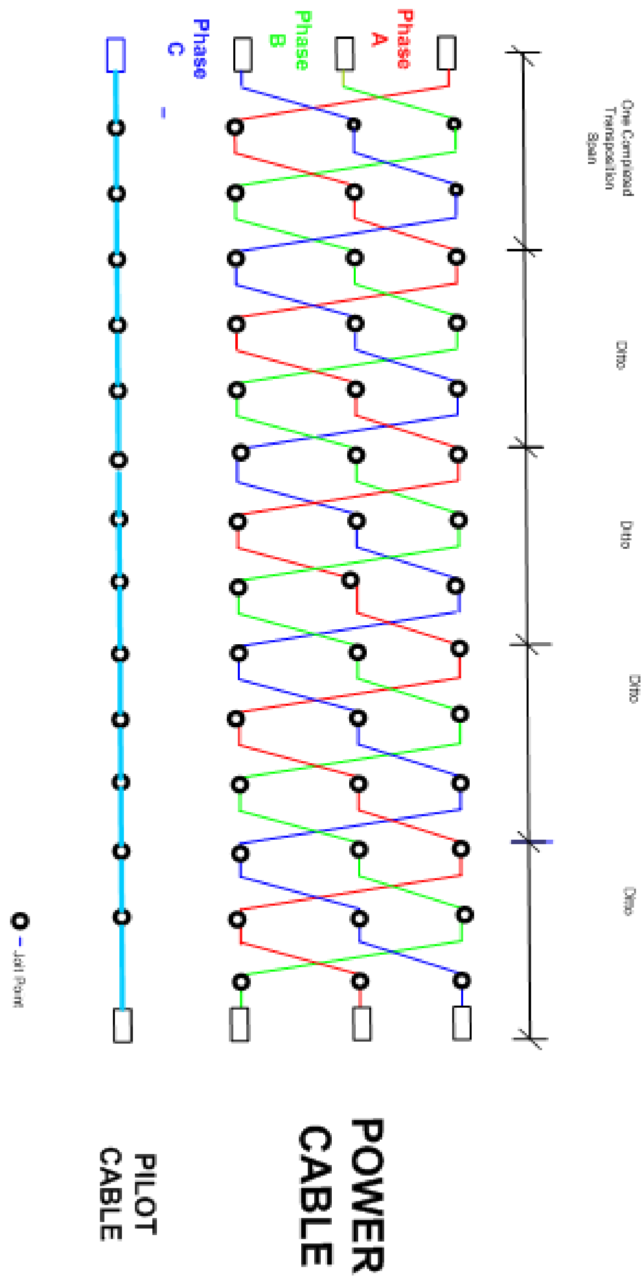
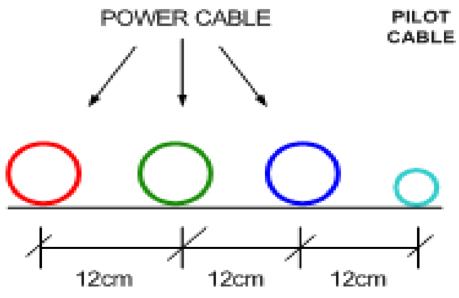
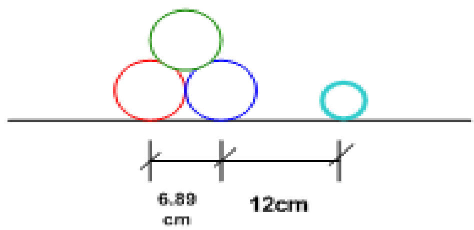


Figure. 2 Route Profile Of H.V Cable



a: flat formation



b: trefoil formation

Figure .3 Installation Condition Of
a: flat
b: trefoil

And then,

$$V1 = 43.57\left[(\sqrt{3}.\log\frac{D}{2D} - j.\log\frac{(3D)^2}{(2D).D}).l_1 + (\sqrt{3}\log\frac{2D}{3D} - j.\log\frac{D^2}{(3D)(2D)}).l_2 + (\sqrt{3}\log\frac{3D}{D} - j.\log\frac{(2D)^2}{(3D).D}).l_3\right]$$

$$= 43.57\,[(-0.5214 - j0.6532).l_1 + (-0.3050 + j0.7781).l_2 + (0.8264 - j0.1249).l_3]$$

Assume I_1 to be the shortest span in one completed transpositioned span.

(i.e. $l_1 \leq l_2$,$l_1 \leq l_3$)

$$V1 = 43.57\, l_1\,.[(-0.5214 - j\,0.6532\,) + (-0.3050\ + j\,0.7781).m + (0.8264 - j0.1249).n]$$

$$= \frac{43.57\,L}{1+m+n}[(-0.5214 - j0.6532) + (-0.3050 + jo.7781).m + (0.8264 - j\,0.1249).n](\text{volt})$$

Where;$l_1 + l_2 + l_3 = L$(one completed transpositioned length)

$$\frac{l_2}{l_1} = m\ \ (\geq 1)\ \ ,\ \ \frac{l_3}{l_1} = n\ \ (\geq 1)$$

$$\therefore 1 + m + n = \frac{L}{l_1}$$

$$l_1 = \frac{L}{1+m+n}$$

And so, the normal induced longitudinal voltage per unit length is obtained as follows.

$$V = \frac{V_1}{L} = \frac{43.57}{1+m+n}[(-0.5214 - j\,0.6532\,) + (-0.3050 + j0.7781).m\ + (\,0.8264 - j0.1249).n](\text{ Volt / Km })$$

$$|V|\ = \frac{43.57}{1+m+n}\sqrt{(-0.5214 - 0.3050\,m + 0.8264\,n)^2 + (\,-0.6532 + 0.7781m - 0.1249n)^2}\,(3)$$

3.2 Trefoil Formation

Substitute the following values for equation 2,

ω= 2πf = 314.2

I_L = 620 (A) (current carrying capacity for trefoil formation)

da1 = da2 = da3 = 18.89 (cm)

db1 = db2 = db3 = 16.56 (cm)
dcl = dc2 = dc3 = 12 (cm)
Ko = 0.9 (Taking the shielding effect caused by Wire Armour of Pilot Cable into account)

And then

$$V1 = 40.32\left[(\sqrt{3}.\log\frac{12.0}{16.56} - j.\log\frac{(18.89)^2}{16.56\times 12.0}).l_1 + (\sqrt{3}\log\frac{16.56}{18.89} - j.\log\frac{12.0^2}{(18.89)(16.56)}).l_2 + (\sqrt{3}\log\frac{18.89}{12.0} - j.\log\frac{(16.56)^2}{18.89\times 12.0}).l_3\right]$$

$$= 40.32\,[(-0.2423 - j0.2542)l_1 + (-0.099 + j0.3369)l_2 + (\,0.3413 - j0.0827)l_3](\text{volt})$$

Assume I_1 to be the shortest span in one completed transpositioned span.
(i.e. $l_1 \le l_2$,$l_1 \le l_3$)

$$V1 = 40.32\,l_1\,.\,[(-0.2423 - j\,0.2542\,) + (-0.099\ + j\,0.3369).m + (0.3413 - j0.0827).n]$$

$$= \frac{40.32\,L}{1+m+n}[(-0.2423 - j0.2542) + (-0.099 + j0.3369).m + (0.3413 - j\,0.0827).n](\text{volt})$$

And so, the normal induced longitudinal voltage per unit length is obtained as follows.

$$V = \frac{V_1}{L} = \frac{40.32}{1+m+n}[(-0.2423 - j\,0.2542\,) + (-0.099 + j0.3369).m\ + (\,0.3413 - j0.0827).n] \quad (\text{Volt/km})$$

$$|V| = \frac{40.32}{1+m+n}\sqrt{(-0.2423 - 0.099\,m + 0.3413\,n)^2 + (\,-0.2542 + 0.3369m - 0.0827n)^2} \quad (4)$$

IV. . Results

4.1 Results of Flat Formation

In case of l1 = l2 = l3 (i.e. m=n=1) .

V = 0

In case of l1≠l2 ≠l3

Allowable relation range for m and n are shown in Fig.4.This figure has been already listed in our Exampleas Fig.1.

Fig.5. shows .the calculated results of NILV when .thevaluem and n changes within the allowablerange shown in Fig.4.

Taking it into account that NILV per unit length under the worst condition is 8.7 volt/km (m= 1.94 & n=1 or m=1 & n=1.94) and that the whole length of this is cable 11 Km , the total NILV of this route is supposed approx. 96 volt at most .

Note; Even if l2 or l3 is assumed to be the shortest span, the same result is to be obtained.

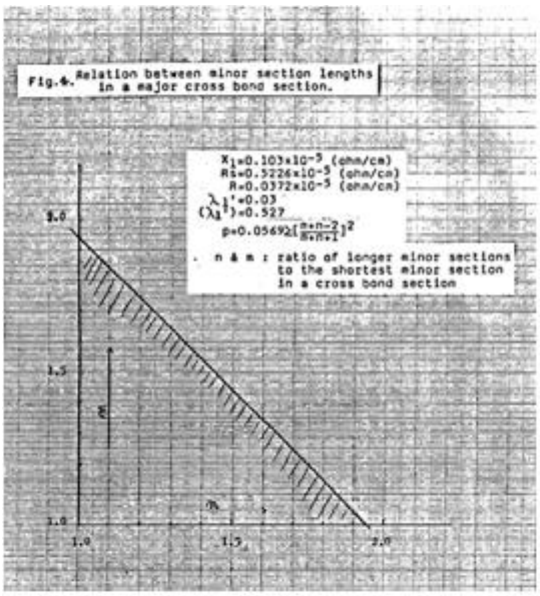


Fig.4. Relation between minor section lengths in a major cross bond section.

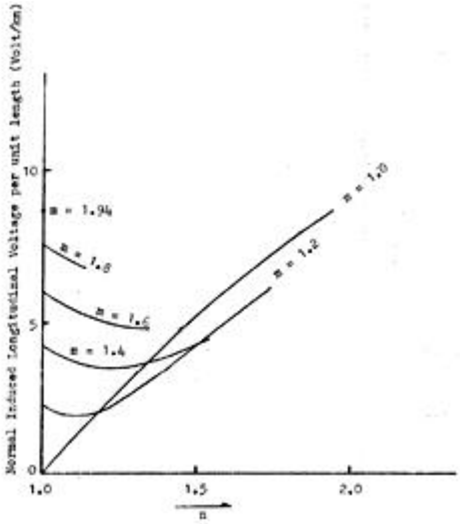


Fig.5 Calculation results of NILV at Flat Formation

4.2 Results of Trefoil Formation

In case of l1= l2 = l3 (i.e. m=n=1) .

V = 0

In case of l1≠l2 ≠l3

Allowable relation range for m and n are shown, in Fig.6.

Fig.7. shows the calculated results of NILV when the value m and n changes within the allowable range in Fig.6.

Taking it into account that NILV per unit length under the worst condition is 6.5 Volt/km (m = 3.52 & n=1 or m= 1 & n= 3.52)

and that the whole length of this cable is 11 Km , the total NILV of this route is supposed approx. 72 Volt at most

Note; Even if l2 or l3 is assumed to be the shortest span, the same result is to be Obtained.

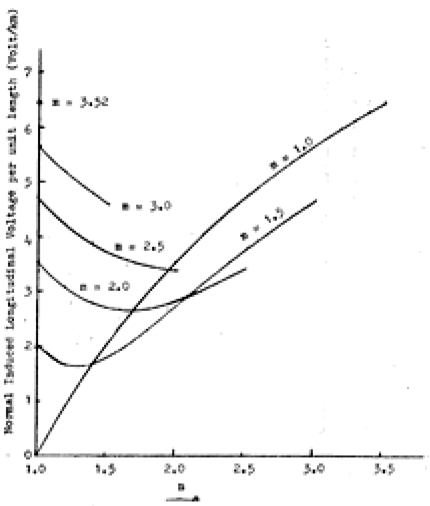
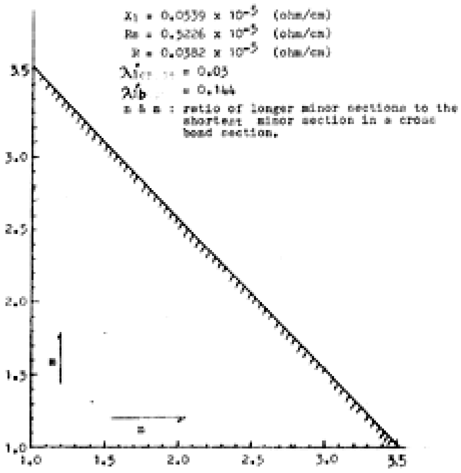


Fig.7 Calculation Results of NILV at Trefoil Formation

Fig. 6 Relation between minor sections in a major cross bond section. In case of trefoil formation



V. Conclusion

1. We conclude that to decrease the induced voltage across the pilot cable a cross-bonding method along with Trefoil method mentioned in the study in the installation of underground cables must be used.
2. Moreover, the induced voltage will not totally disappear and we need to protect the cable protection relays from it.
3. In practice to reduce the induced voltage and to isolate the fault a surge voltage limiters and transformer isolator are connected in the terminal block between pilot cable and protection relays.

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