Bull Will

Skin effect & proximity effect

Advanced training course B

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R&D Engineering

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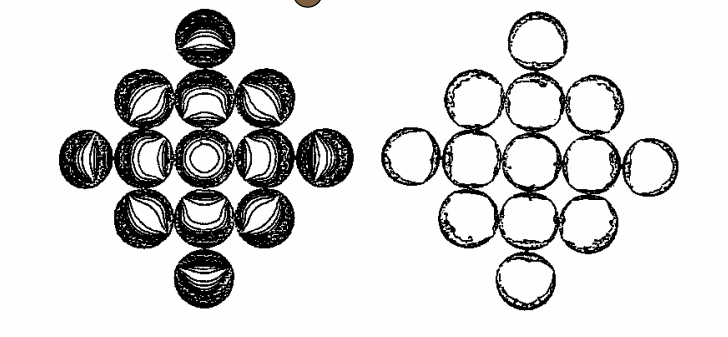
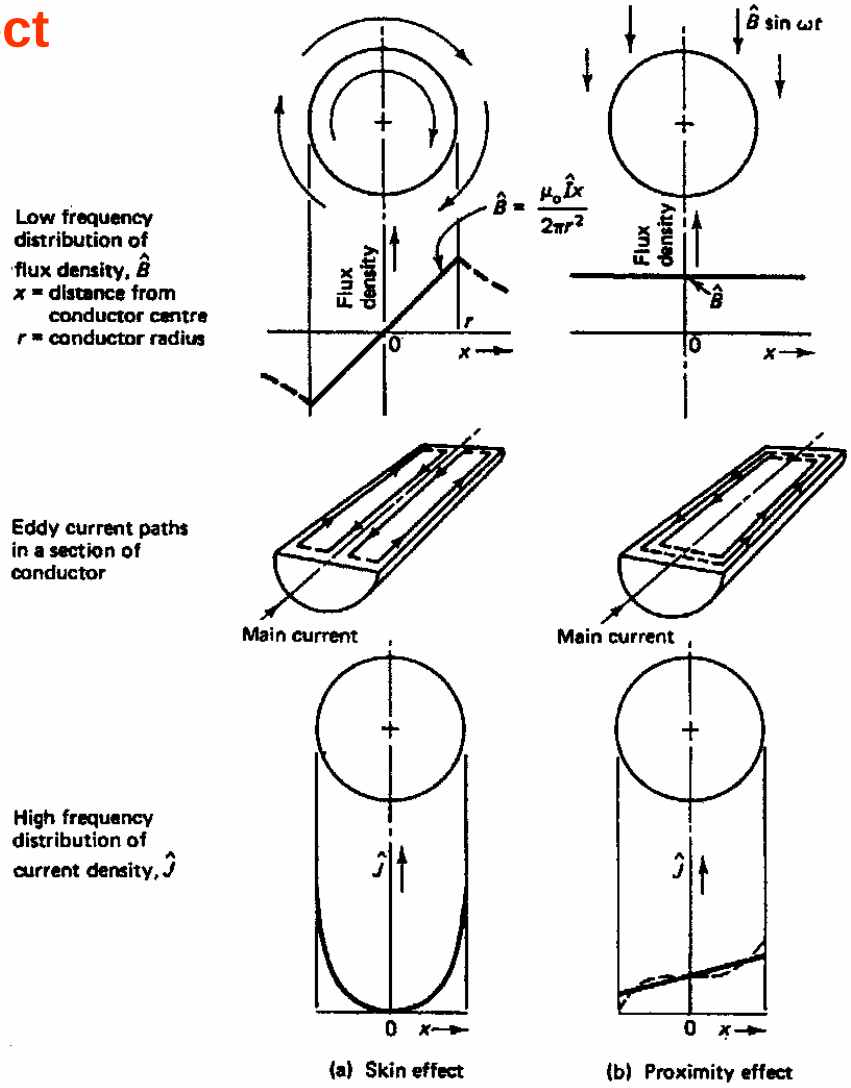
Skin effect and proximity effect



@100KHz @1MHz

1A/conductor wire

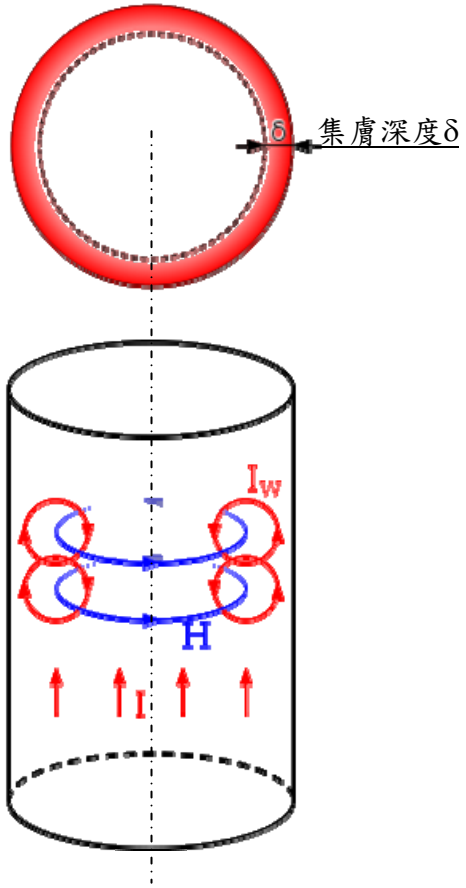
The influence of eddy current caused by **skin**/**proximity** effect on the Litz wire.



• Skin effect – qualitative description

集膚效應（又稱**趨膚效應**）是指**導線內有交流電或者交變電磁場**時，導線內部的電流分布不均勻的一種現象。隨著與導線表面的距離逐漸增加，導體內的電流密度呈指數遞減，即導體內的電流會集中在導體的表面。從與電流方向垂直的橫切面來看，導體的中心部分幾乎沒有電流流過，只在導體邊緣的部分會有電流。簡單而言就是電流集中在導體的「皮膚」部分，所以稱為集膚效應。產生這種效應的原因主要是變化的電磁場在導體內部產生了渦旋電場進而引發**渦電流**，在導體內側與原來的電流部份相抵消。

資料引用"維基百科"



導體內變動的電流I會產生變動的感應磁場H。而變動的磁場H又會在導體內產生感應電動勢，進而引發渦電流Iw。從Iw的方向來看，可以理解導體內側原來的電流被大部份抵消，而在外緣的部份則產生加成效果！

• Skin effect – quantitative description

在一個理想導體中，隨著與導體表面的距離逐漸增加，導體內的**電流密度**J呈指數遞減:

$$J = J_s \cdot e^{-\frac{(R-x)}{\delta}}$$

其中，J_s 是導體表面的電流密度，$R-x$ 表示電流與導體表面的距離，δ 是一個和導體的電阻率以及交流電的頻率有關的係數，稱為**集膚深度**。

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}}$$

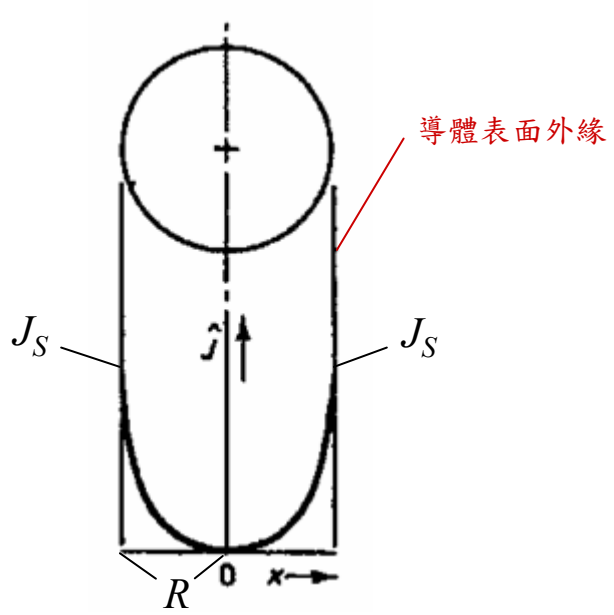
其中：

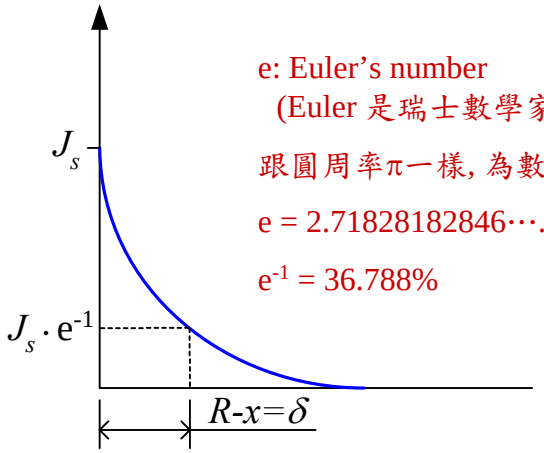
ρ = 導體的電阻率

ω = 交流電的角頻率 = $2\pi \times$ 頻率

μ = 導體的絕對磁導率= $\mu_o \cdot \mu_r$，其中 μ_o 是真空磁導率，μ_r 是導體的相對磁導率

資料引用"維基百科"





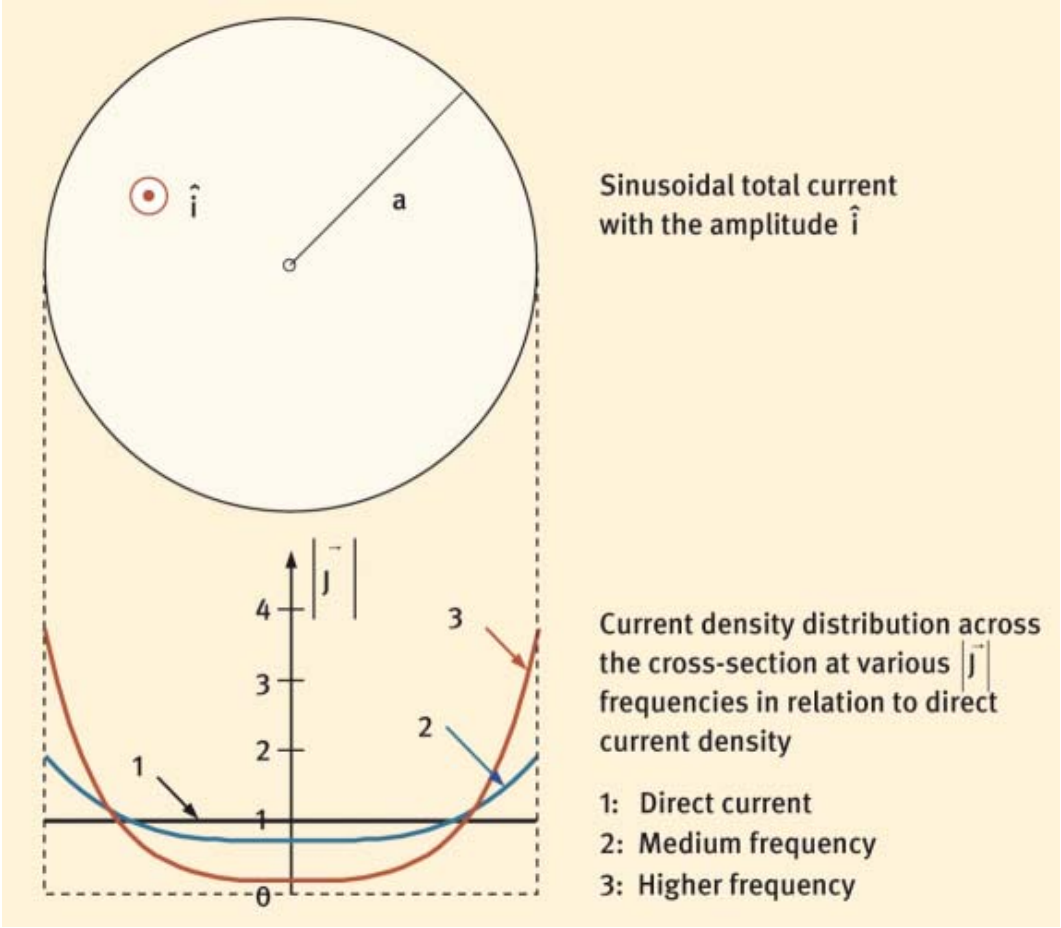
e: Euler's number
(Euler 是瑞士數學家)

跟圓周率π一樣, 為數學常數

e = 2.71828182846….

e^{-1} = 36.788%

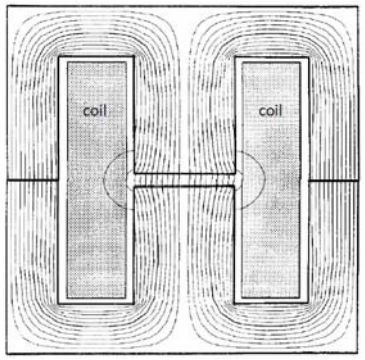
- **Skin effect on a single wire at different frequencies**

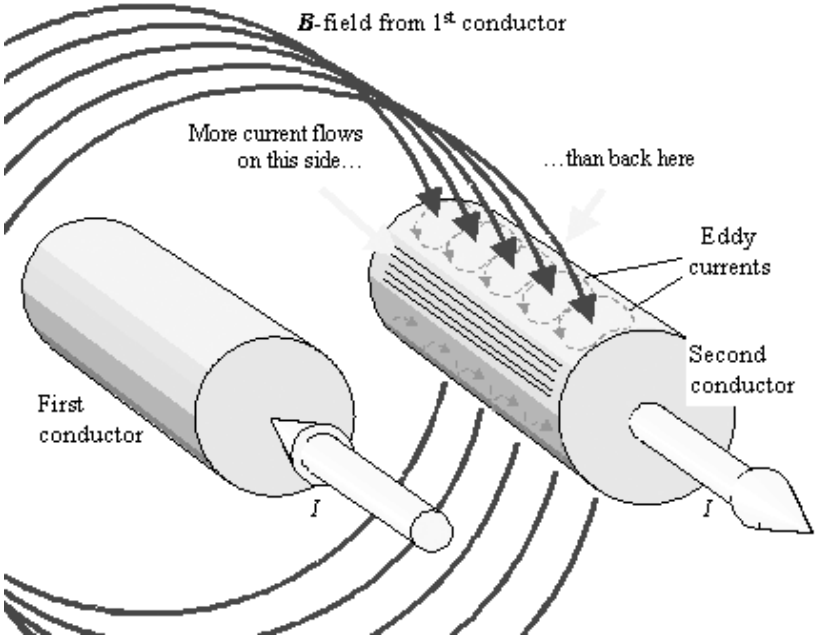


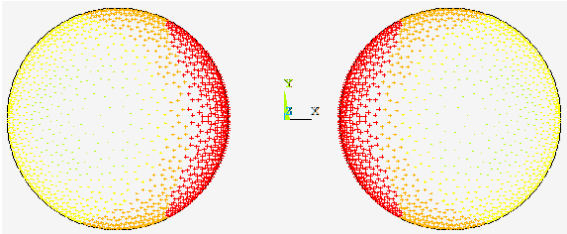
• Proximity effect – qualitative description

鄰近效應是指導線處於**外在變化的磁場**環境中，且該磁場在與線軸垂直的方向上具有分量，則會在導線內引發出**渦電流**。在多圈數或多繞組的繞線結構中，相鄰載流導線所產生外在環繞變化的磁場對該導線會引發出較大渦電流，其影響也最為顯著，會造成電流擠向一側。故以鄰近效應稱呼之。

其他如漏磁場與鐵芯氣隙邊緣磁場外鼓對導線之影響，都可歸類為鄰近效應現象。



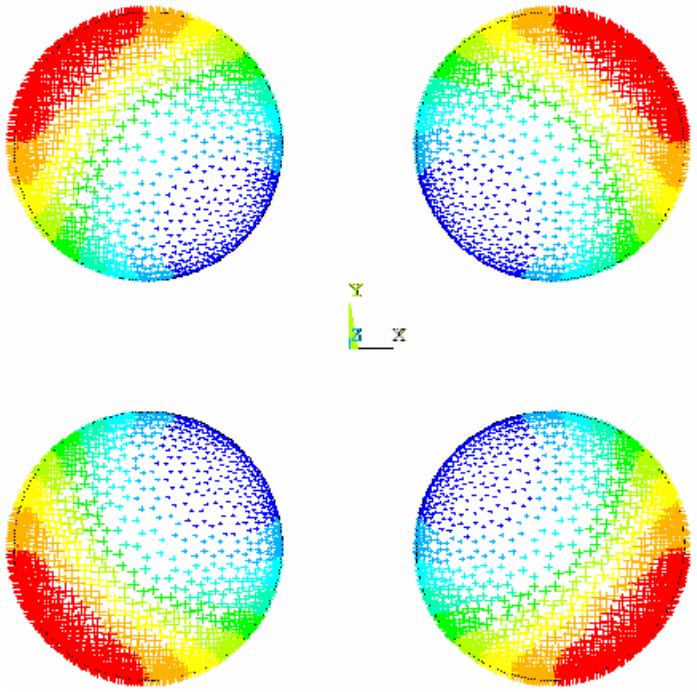




電流密度分布擠向內側

(兩導線上之電流不同向)

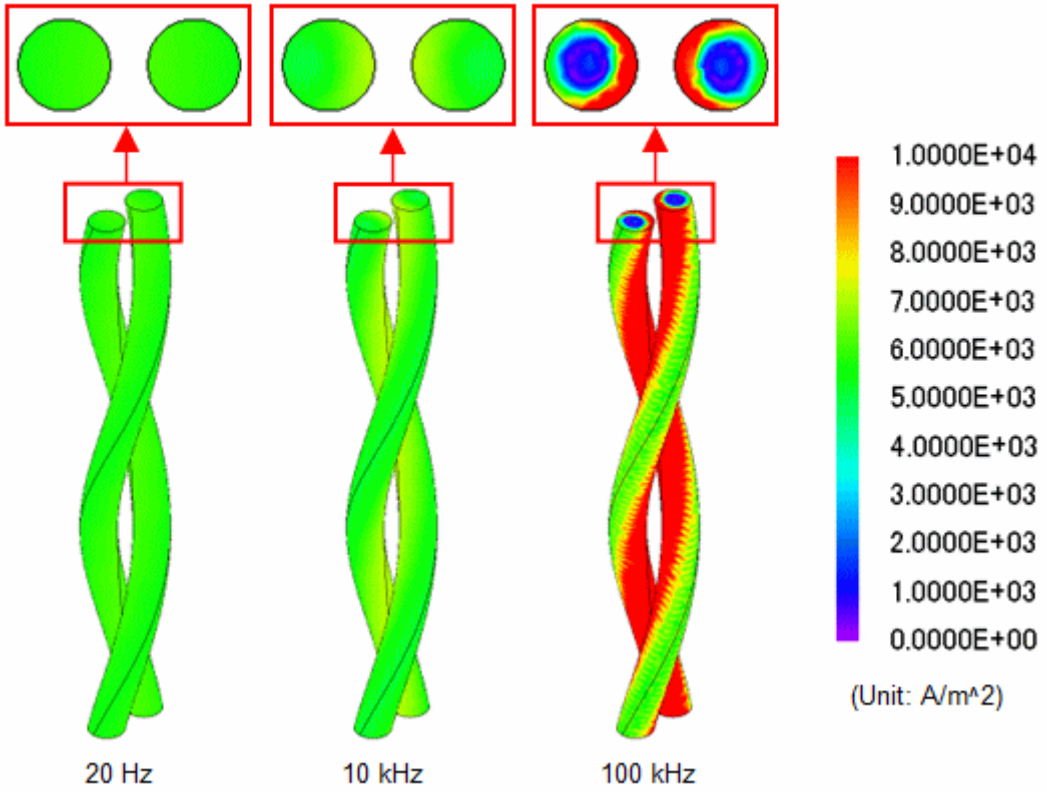
- **Proximity effect on the wire of 4 parallel strands with unidirectional current**



4 股線電流同向，則電流分布擠向外側

(紅色密度最高, 藍色密度最低)

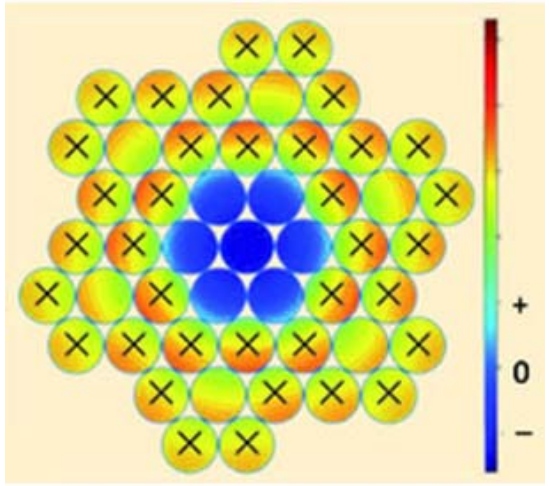
- **Skin and Proximity dual effect on the wire of 2 twisted strands with indirect current**

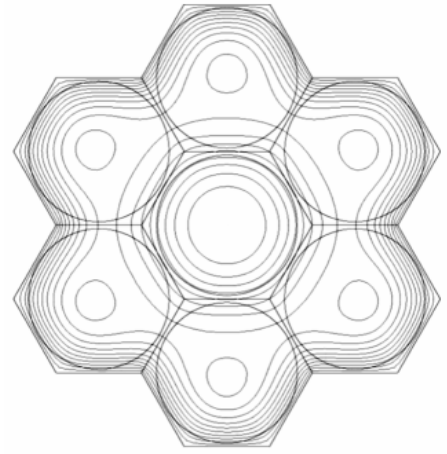


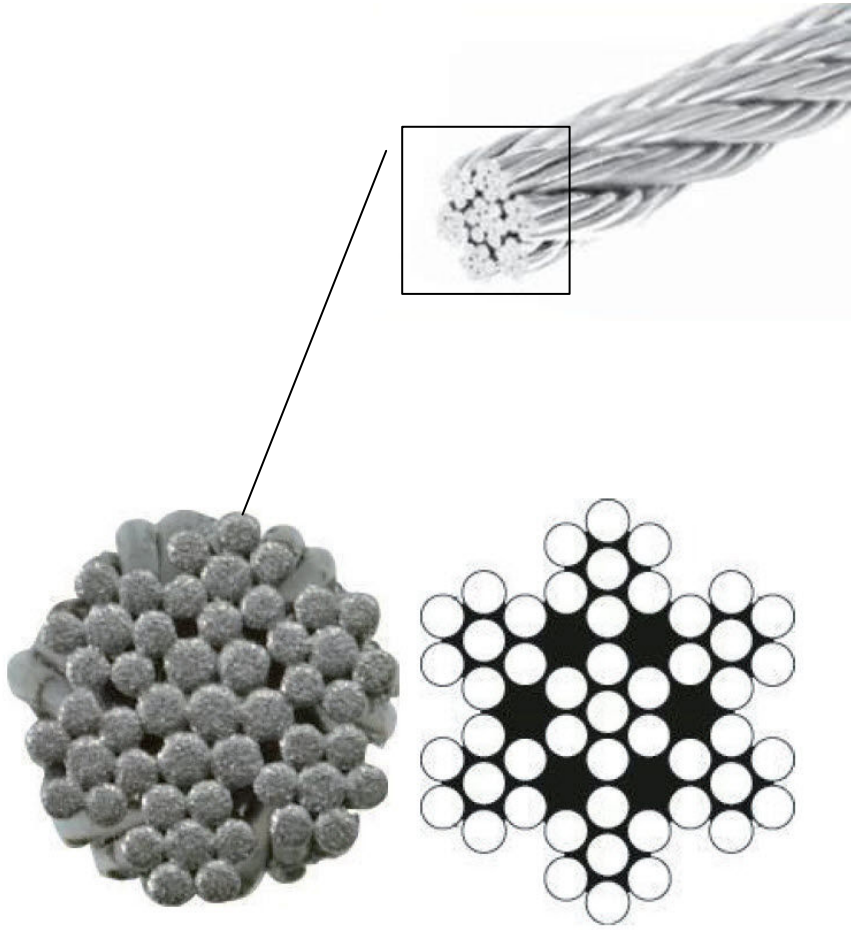
Current density distribution in the copper wire

兩股絞線電流不同向

- **Skin and Proximity dual effect on the wire of ∅0.2x49p twisted strands with unidirectional AC current at 100KHz**







- **AC resistance R_{ac} due to skin effect and proximity effect (two wires)**

$$R_{ac} = R_{dc}\left(1 + y_s + y_p\right)$$ By reference to IEC 60287

, and

$$y_s = \frac{x_s^4}{192 + x_s^4} \qquad y_p = \frac{x_p^4}{192 + 0.8x_p^4} \times \left(\frac{d_c}{S}\right)^2 \times 2.9$$

in which

$$x_s = x_p = 8\pi f \times 10^{-7} \times \left(\frac{k}{R_{dc}}\right)$$

where

R_{dc}: DC resistance in Ω

y_s: Skin effect factor; y_p: proximity effect factor

d_c: Diameter of conductor in mm

S: Spacing between two conductor centers in mm

k: 1 for circular, stranded conductor construction

f: Frequency in Hz

Thank you for listening!