Module 2 : Current and Voltage Transformers

Lecture 9 : VT Tutorial

Objectives

In this lecture we will solve tutorial problems to:

- Design a CCVT.
- Find out the value of tuning inductance.
- Find out ratio error and phase angle error.
- Performance analysis of VT.

Example 1 :

Design a CCVT for a 132kV transmission line using the following data. Resistive Burden (3ϕ) = 150VA, frequency deviation to be subjected to $\Delta f = 3Hz$, phase angle error β = 40 minutes. Consider four choices of V_2 as 33 kV, 11 kV, 6.6 kV and 3.3 kV. Transmission line voltage V = 132 kV. The standardized VT secondary voltage is 110 volts (L - L).

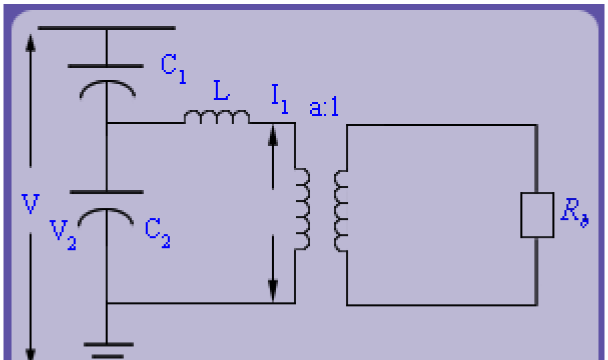

Fig 9.1 Schematic Diagram of CCVT

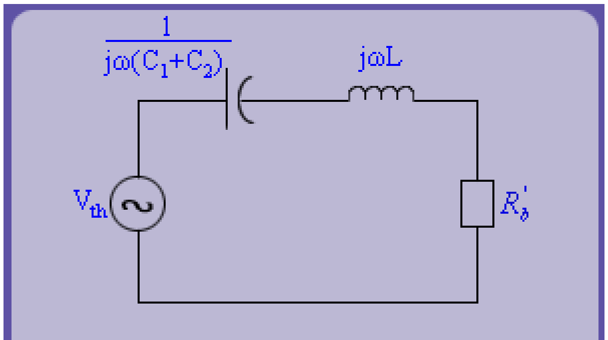

Fig 9.2 Equivalent Circuit of Fig 9.1

Answer:

Let V_2 (L - N) be the voltage to be produced by the capacitive potential divider with capacitance values C_1 and C_2. Let L be the value of tuning inductor. Our first task is to come up with a value of L. Here the specification for phase angle error β is 40 minutes. Variation in frequency can be upto $\Delta f = 3Hz$ approximately. Phase angle error for change in ω from ω_0 by $\Delta\omega$ in the above equivalent circuit can be calculated as follows:

$$\Delta V_L - \Delta V_C = jI \frac{d}{d\omega}(\omega L - \frac{1}{\omega C_{eq}})\Delta\omega$$

$$= I(L + \frac{1}{\omega_0^2 C_{eq}})\Delta\omega$$

At tuning frequency,

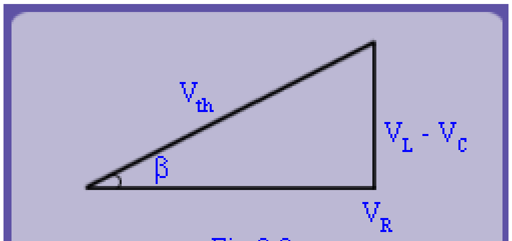

Fig 9.3

$$\omega_0^2 = \frac{1}{LC_{eq}}$$

Substituting $\omega_0^2 = 1/LC$

$(\Delta V_L - \Delta V_C) = I(L+L)\Delta\omega$

Example 1: (contd..)

From figure 9.3, $\tan\beta = \frac{|V_L - V_C|}{|V_R|} = \frac{2LI\Delta\omega}{a^2 R_b I} = \frac{2L\Delta\omega}{a^2 R_b}$. For small enough β, $\tan\beta$ = β and hence from its % phase angle error $\beta \approx \frac{2L\Delta\omega}{a^2 R_b}$ x 100 --- (1)

Using this equation the value L for different values of V_2 is found out.

(1) Let V_2 be 33kV (L - N) Then;

$$\frac{3V_2^2}{R_b'} = 150$$

$$R_b' = a^2 R_b = 217.8 \times 10^5\,\Omega$$

$$\Delta\omega = 2\pi \times \Delta f = 2\pi \times 3$$

$$\beta = 40\min = \frac{\pi \times 40}{180 \times 60} = 0.01164\ rad$$

From eqn (1)

$$L = \frac{\beta \times R_b'}{2 \times \Delta\omega} = \frac{0.01164 \times 217.8 \times 10^5}{2 \times 2\pi \times 3} = 6722.2H$$

$$C_1 + C_2 = \frac{1}{\omega^2 L} = 1.51 \times 10^{-9} F = 1.51 \times 10^{-3} \mu F$$

Example 1 : (contd..)

(2) $V_2 = 11kV(L-N)$

$$R_b' = \frac{3 \times (11 \times 10^3)^2}{150} = 242 \times 10^4\,\Omega$$

$$L = \frac{\beta \times R_b'}{2 \times \Delta\omega} = \frac{0.01164 \times 242 \times 10^4}{2 \times 2\pi \times 3}$$

$= 747.2H$

$$C_1 + C_2 = \frac{1}{\omega^2 L} = \frac{1}{(3/4)^2 \times 747.2}$$

$= 1.36 \times 10^{-2} \mu F$

(3) $V_2 = 6.6kV$

$$R_b' = \frac{3 \times (6.6 \times 10^3)^2}{150}$$

$= 87.12 \times 10^4\,\Omega$

$$L = \frac{\beta \times R_b'}{2 \times \Delta\omega} = \frac{0.01164 \times 87.12 \times 10^4}{2 \times 2\pi \times 3}$$

$= 269H,$

$C_1+C_2=3.77\times10^{-2}\ \mu F$

(4) $V_2=3.3kV$

$$R_b^{'} = \frac{3\times(3.3\times10^3)^2}{150}$$

$=21.78\times10^4\ \Omega$

$$L=\frac{\beta\times R_b^{'}}{2\times\Delta\omega}=\frac{0.01164\times21.78\times10^4}{2\times2\pi\times3}$$

$=67.25H$

$C_1+C_2=0.151\mu F$

Example 1 : (contd..)

The values of L, C_1+C_2 for different values of V_2 are tabulated below.

V_2	L in H	$C_1+C_2\ \ \mu F$
33 kV	6722.2	0.00151
11 kV	747.2	0.0136
6.6 kV	269	0.0377
3.3 kV	67.25	0.151

From the above table it is clear that smaller the value of V_2 , the smaller is the value of L and higher the value of C_1 and C_2 for tuning condition. If we select too low value of V_2 and L then capacitance values will be beyond available limits, and if we select higher value of V_2 and L, then CCVT's inductor will become bulky. So a compromise solution is necessary and let us select V_2 = 6.6 kV

For V_2 = 6.6 kV

L = 269 H

$C_1+C_2=0.0377\mu F$

Now, $\frac{V}{V_2}=\frac{C_1+C_2}{C_1}$

$$\frac{132\times10^3}{\sqrt{3}\times6.6\times10^3}=\frac{0.0377\times10^{-6}}{C_1}$$

$$C_1=\frac{0.0377\times\sqrt{3}\times6.6\times10^3\times10^{-6}\ \mu F}{132\times10^3}$$

$=0.0033\mu F$

$C_2=0.0344\mu F$

In this design, we have explained the basic concept for CCVT design and we assumed the transformer to be ideal. However in real life design, the value of magnetizing impedance of transformer, resistance of reactor etc have to be taken into account, as the ratio error α and the phase angle error β will also get affected by these values. The next example brings out these issues.

Example 2:

The equivalent circuit of a CCVT is shown in fig 9.4. The values of C_1 and C_2 are 0.0018 μF and 0.0186 μF respectively. Tuning

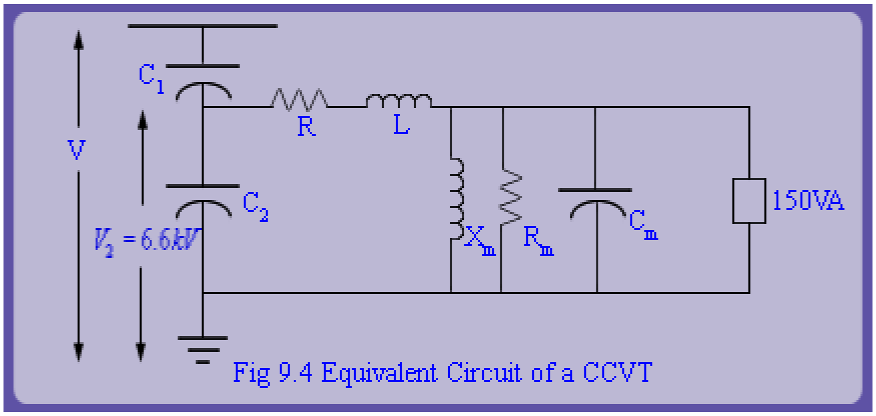

Fig 9.4 Equivalent Circuit of a CCVT

inductor has an inductance of 497H and resistance of 4620 Ω. X_m of the VT referred to 6.6 kV side is 1MΩ, core loss = 20 watts per phase, VA burden = 150VA per phase. Value of C_m for compensating the current drawn by X_m is equal to $3.183\times10^{-9}F$.

(a) Verify the appropriateness of choice of L and C_m.

(b) Find out the nominal value of V/V_2

(c) If the frequency drops from 50Hz to 47Hz, what would be the values of ratio error and phase angle error?

Answer (a):

If $C_1=0.0018\mu F$ and $C_2=0.0186\mu F$ then the value L of tuning inductor is given by

$$L=\frac{1}{\omega^2(C_1+C_2)}$$

where $\omega=2\pi f$ and f = nominal frequency. Thus,

$$L=\frac{1}{(2\pi\times50)^2(0.0018+0.0186)\times10^{-6}}$$

= 496.7 H which is equal to the given value of L.

Now, $X_m=1\times10^6\,\Omega$ C_m has to be in parallel resonance with X_m. Therefore,

$$X_m=\frac{1}{\omega C_m}$$

$$C_m=\frac{1}{\omega X_m}=\frac{1}{(2\pi\times50)\times1\times10^6}$$

$$=3.183\times10^{-9}F$$

The value is also same as the selected value of C_m. Hence, the selection of both L and C_m is appropriate.

Answer (b):

$$\frac{V}{V_2}=\frac{C_1+C_2}{C_1}=\frac{0.0018+0.0186}{0.0018} = 11.33$$

V = 11.33 x 6.6 $=\frac{132}{\sqrt{3}}kV$

Thus, this VT is connected to a 132 kV bus.

Example 2: (contd..)

Answer (c):

Core loss = 20 W

$$\frac{V_2^2}{R_m}=20W$$

$$R_m=\frac{V_2^2}{20}=\frac{(6600)^2}{20}$$

$$=2.18\times10^6\Omega$$

VA burden = 150VA (resistive)

$$\frac{V_2^2}{R_b} = 150$$

$$R_b = \frac{V_2^2}{150} = \frac{(6600)^2}{150}$$

$$= 2.904 \times 10^5 \Omega$$

The equivalent circuit can be represented as shown below.

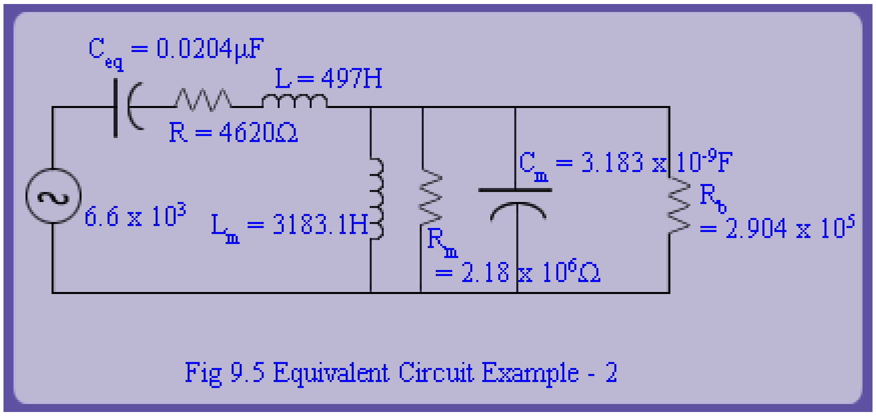

Fig 9.5 Equivalent Circuit Example - 2

$X_m = 10^6 \Omega$ at f = 50 Hz

$$2\pi f L_m = 10^6$$

$$L_m = \frac{10^6}{2\pi} = 3183.1H$$

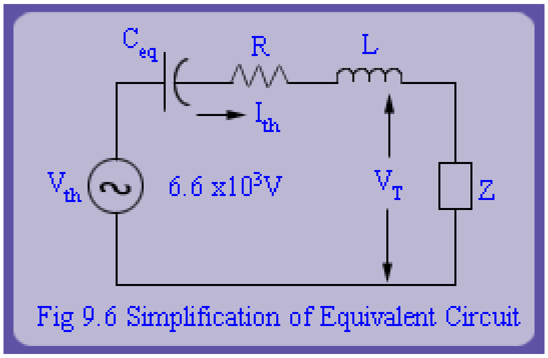

Fig 9.6 Simplification of Equivalent Circuit

Example 2 : (contd..)

The frequency of interest is 47Hz. Hence values of X_m and other impedance can be calculated at 47Hz. Figure 9.5 can be simplified as figure 9.6.

Where $\frac{1}{Z} = \frac{1}{R_m} - \frac{j}{X_m} + j\omega C_m + \frac{1}{R_b}$

$$= \frac{1}{2.18 \times 10^6} - \frac{j}{2\pi \times 47 \times 3183.1} + j\,2\pi \times 47 \times 3.183 \times 10^{-9} + \frac{1}{2.904 \times 10^5}$$

$$= 0.459 \times 10^{-6} - j1.064 \times 10^{-6} + j0.94 \times 10^{-6} + 3.44 \times 10^{-6}$$

$$= (3.902 - j0.124) \times 10^{-6} = 3.904 \times 10^{-6} \underline{|-1.82^\circ}$$

$$Z = \frac{1}{3.904 \times 10^{-6} \underline{|-1.82}} = 256147.5 \underline{|1.82^\circ}\Omega$$

$$= 256018.32 + j8135.15\Omega$$

$$I_{th} = \frac{V_{th}}{R + j\omega L - \frac{j}{\omega C} + Z}$$

$$= \left[\frac{6600\underline{|0}}{4620 + j2\pi \times 47 \times 497 - \frac{j}{2\pi \times 47 \times 0.0204 \times 10^{-6}} + 256018.32 + j8135.15} \right]$$

$$= \frac{6600\angle 0}{[4620 + j146768.9 - j165994 + 256018.32 + j8135.15]}$$

$$= \frac{6600\angle 0}{260638.32 - j11089.84}$$

$$= \frac{6600\angle 0}{260874.14\angle -2.44^\circ} A$$

$$V_T = I_{th} \times Z$$

$$= \frac{6600\angle 0}{260874.14\angle -2.44^\circ} \times 256147.5\angle 1.82^\circ$$

$$= 6480.42\angle 4.26^\circ$$

Amplitude or ratio error of a CCVT is equal to $\frac{V_{th} - V_T}{V_{th}} \times 100$ where V_{th} is the Thevenin equivalent voltage source is nothing but open circuit emf. V_T is the terminal voltage on load. Hence % ratio error

$$= \frac{(6600 - 6480.42)}{6600} \times 100$$

=1.81%

Phase angle error $= 4.26^\circ$.

Clearly, the phase angle error is on the higher side.

Review Questions

1. Assume that the primary voltage of a CCVT is 400 kV and the voltage to be produced by the capacitive potential divider is

   3.3 kV. If C_2 is taken as 0.02 μF, determine the value of tuning inductance at frequency of 50Hz.

2. In figure 9.4 if V = 230 kV, V_2 = 6.6 kV (L-N) C_1 = 0.001 μF and X_m = 1.2 MΩ, then find out the values of tuning

   inductance and capacitance to be connected across CCVT's secondary for compensating X_m. Standardized secondary voltage of a VT is 110V (L-L).

3. Design a CCVT for a 400 kV transmission line using the following data. Secondary resistive burden (3ϕ) = 300VA.

   Core loss (3ϕ) = 50W. $\Delta f = \pm 3Hz$. Consider 3 choices of V_2 = 3.3 kV, 6.6 kV, 11 kV. Take phase angle error β = 40 min. and standard VT secondary voltage =110 V (L-L).

Recap

In this lecture by solving the tutorial problems we have learnt the following:

- How to decide V_2.
- How to choose L.

- How to decide C_1 and C_2.

- How to evaluateperformance of VT.