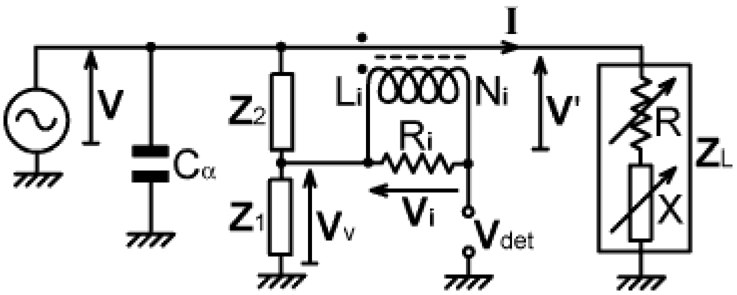
Analysis of Douma's generator PF-correction scheme[1]

By David Knight

A drawback associated with having a reactive voltage-sampling network at the transmitter side of an impedance monitoring bridge is that it leaves the generator with a reactive load when the bridge is balanced. In **US Patent No. 2734169**, Douma offers a solution to this problem, which involves producing a correction voltage to be added to the sum of the bridge current and voltage analogs. The situation that Douma considered is illustrated below (note that current-transformer secondary stray capacitance and propagation delay are neglected in the derivation that follows):



In this case there is a capacitance C_α permanently connected across the generator, causing a phase-shift that cannot be taken into account when $\mathbf{Z}_L$ is adjusted to balance the bridge. We can however envisage a situation in which the system is somehow adjusted to make the generator see a pure resistance R_0; in which case, presuming that the voltage-sampling impedance $\mathbf{Z}_1 + \mathbf{Z}_2$ is sufficiently large to be neglected (or is actually responsible for the capacitance C_α), and that the current transformer insertion impedance is sufficiently small to be neglected, R_0 will be the parallel combination of $\mathbf{Z}_L$ and the impedance of the capacitance C_α, i.e.:

$$R_0 = \mathbf{Z}_L \,//\, \mathbf{j}X_{C\alpha}$$

which can be written:

$$1/R_0 = (1/\mathbf{Z}_L) + (1/\mathbf{j}X_{C\alpha})$$

and so the load admittance will be:

$$1/\mathbf{Z}_L = (1/R_0) - (1/\mathbf{j}X_{C\alpha})$$

The output of the bridge will be:

$$\mathbf{V}_{det} = \frac{\mathbf{V}\,\mathbf{Z}_1}{\mathbf{Z}_1 + \mathbf{Z}_2} - \frac{\mathbf{I}\,(R_i \,//\, \mathbf{j}X_{Li})}{N_i}$$

Where

1 Version 1.00, 17th Feb. 2014.
Derived from an html article first published in 2007.
Please check the author's website to make sure you have the most recent version of this document: http://www.g3ynh.info/zdocs/bridges .

$\mathbf{I} = \mathbf{V'} / \mathbf{Z_L} = \mathbf{V'} \, [\, (1/R_0) - (1/\mathbf{j}X_{C\alpha}) \,]$

hence:

$$\mathbf{V_{det}} = \frac{\mathbf{V} \, \mathbf{Z_1}}{\mathbf{Z_1} + \mathbf{Z_2}} - \frac{\mathbf{V'} \, (R_i \, // \, \mathbf{j}X_{Li})}{N_i \, R_0} + \frac{\mathbf{V'} \, (R_i \, // \, \mathbf{j}X_{Li})}{\mathbf{j}X_{C\alpha} \, N_i}$$

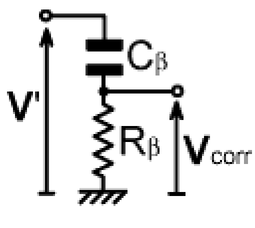
The first two terms of this expression are the normal balance condition for the bridge, and have parameters that can be chosen so that the terms add to zero when $\mathbf{Z_L} = R_0$. The third term is the error in the balance condition due to the fact that $\mathbf{Z_L} \neq R_0$ when the load seen by the generator is equal to R_0. This shows that we can alter the balance condition of the bridge in such a way that the adjustment of $\mathbf{Z_L}$ will compensate for the presence C_α by adding a correction voltage $\mathbf{V_{corr}}$ to $\mathbf{V_{det}}$ such that $\mathbf{V_{det}} + \mathbf{V_{corr}} = 0$. The required correction voltage is the negative of the last term in the expression above, i.e.:

$\mathbf{V_{corr}} = -\mathbf{V'} \, (R_i \, // \, \mathbf{j}X_{Li}) \, / \, (\, \mathbf{j}X_{C\alpha} \, N_i \,)$

It will take quite an elaborate network to obtain exactly this voltage, but Douma made the sensible observation that the capacitance C_α will generally be small, since the main use of the correction is to cancel the effect of using a capacitive voltage-sampling network at the generator side of the bridge. Hence C_α will only cause a serious shift in load phase angle at high frequencies, and the correction voltage at low frequencies will be negligible. It is therefore legitimate to assume that significant correction will only occur when $X_{Li} >> R_i$, and hence $R_i \, // \, \mathbf{j}X_{Li} \approx R_i$, and so the simplified correction voltage becomes:

$\mathbf{V_{corr}} = -\mathbf{V'} \, R_i \, / \, (\, \mathbf{j}X_{C\alpha} \, N_i \,)$

Now consider the voltage divider circuit on the right. Its output is:



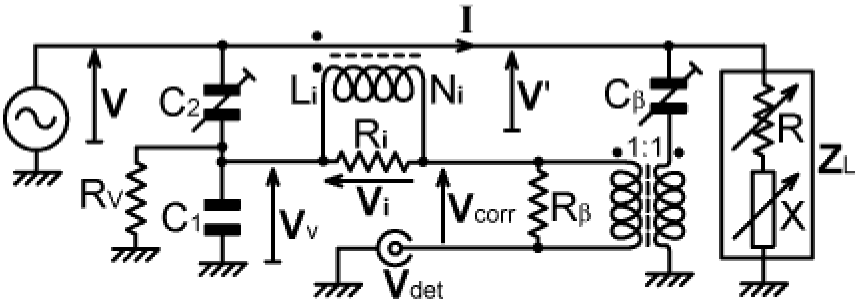
$\mathbf{V_{corr}} = \mathbf{V'} \, R_\beta \, / \, (R_\beta + \mathbf{j}X_{C\beta})$

but if $X_{C\beta} >> R_\beta$, this expression becomes to a good approximation:

$\mathbf{V_{corr}} = \mathbf{V'} \, R_\beta \, / \, (\mathbf{j}X_{C\beta})$

If we now choose C_β to be the same as C_α, then setting $R_\beta = R_i / N_i$ gives the required correction voltage, except that the sign should be negative (phase reversal is required).

That the approximation $X_{C\beta} >> R_\beta$ can be made to hold good can be seen by considering that R_i is typically about 50 Ω and N_i is usually in a range from 10 to 40 turns. Therefore R_β will never be greater than about 5 Ω, whereas the input-side capacitive voltage-sampling network for which C_α is a model will typically have a reactance of around -400 Ω at the highest frequency of operation, and this will only increase in magnitude at lower frequencies. The only remaining problem is that the correction voltage derived by the RC network is of the wrong polarity, and needs to be floating with respect to ground so that it can be added into $\mathbf{V_{det}}$. This calls for the use of a 1:1 isolation transformer, which is shown in Douma's final circuit below:



Note that the resistor R_β is connected to the secondary side of the transformer. This is done so that the transformer magnetising current (i.e., the current that flows because the inductance of the transformer is not infinite) is small in comparison to the current that flows due to the presence of the resistor. The resistor in this position will also damp any transformer resonances. This ensures that the phase of the current flowing out of the secondary is very close to 180° relative to the phase of the current in the primary, thereby establishing the required 90° difference between $\mathbf{V_{corr}}$ and **V'** to the best possible approximation.

If we assume that $R_V >> X_{C1}$ at high frequencies, the capacitance at the generator side of the bridge will be, to a good approximation, $C_1 C_2 / (C_1 + C_2)$. If we set $R_\beta = R_i / N_i$, and adjust $\mathbf{Z_L}$ (using an auxiliary bridge) so that the generator sees R_0, adjusting C_β will bring the bridge to balance at high frequencies when $C_\beta = C_1 C_2 / (C_1 + C_2)$.

The importance of Douma's correction method for generator-side reactance lies in the fact that it introduces the idea of obtaining bridge-balance by performing summations other than the generic $\mathbf{V_v} - \mathbf{V_i} = 0$. This is the key to making bridges that monitor only a single scalar attribute of a load impedance, such as its resistance or conductance. Douma's method also instructive in its use of a quadrature network, and of a transformer as a voltage sampling network. It does however represent several missed opportunities. Douma used a transformer as a voltage sampling device, but did not invent any of the transformer voltage-sample bridge topologies later patented by Sontheimer and Fredrick [**US Pat. No. 3426298**, 1969] Douma was fully conversant with the problem of generator power-factor error and displayed great ingenuity in overcoming it; but it did not occur to him that the solution might be simply to move the voltage sampling network to the other side of the current transformer (making it part of the load), or to include a small compensating inductance in series with the generator[2].

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2 '**A self-evaluating precision reference bridge**.' D W Knight, www.g3ynh.info/zdocs/bridges/ See section 7.