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EFFECT OF A BUSHING ON MEASURING INSULATION POWER FACTOR OF A TRANSFORMER

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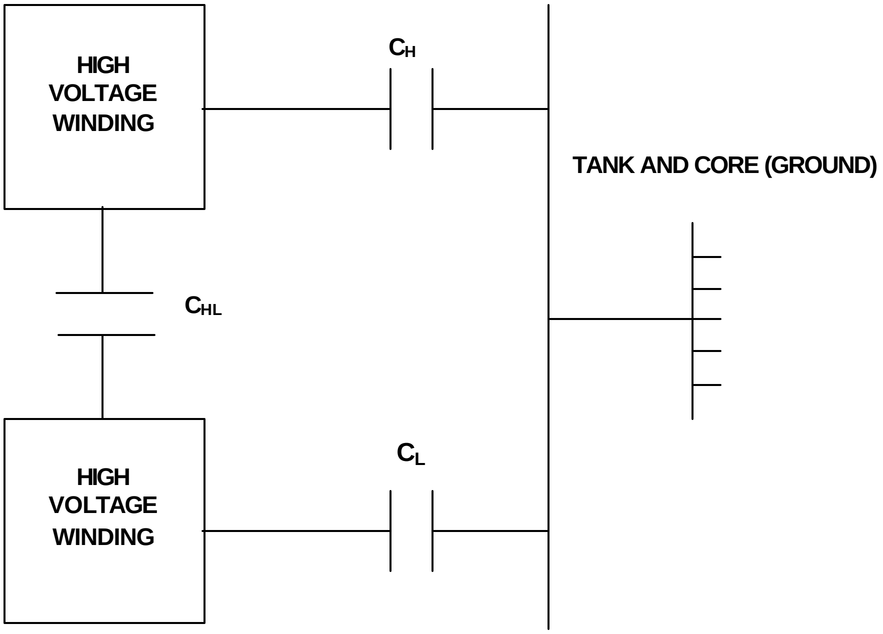
This paper explains why the effect of bushings on the measurement of power factor of transformer insulation is usually negligibly small. This paper also presents a simple method of eliminating the bushing effect entirely from the measured power factor of transformer insulation and bushing together although it is not necessary to do so in most cases.

Theory

Suppose we want to measure the capacitance of a high voltage winding of a transformer with Doble equipment. We will use test 2 of the Figure 4-27 described in the " Doble Type M2H 10-kV Portable Insulation Test set" (Figure 1). C_H includes the capacitance of a HV winding plus that of a HV bushing. As the capacitances of these components are connected in parallel, the total capacitance is the sum of all the capacitances, i.e.,

Figure 1. Ground Capacitance of a Two-winding Transformer



$$C_H = C_W + C_B$$

Where C_H is the total HV capacitance
C_W is the winding capacitance and
C_B is the bushing capacitance.

We can easily calculate the power factor of two insulation systems (bushing and winding) connected in parallel from the phase angles of the individual components by using the following equation

$$\tan(90^\circ - \theta_H) = \frac{C_w * \tan(90^\circ-\theta_W) + C_B * \tan(90^\circ-\theta_B)}{C_w + C_B}$$

Where θ_H is the phase angle of the winding and bushing together, i.e., $\cos(\theta_H)$ is the combined power factor
θ_W is the winding phase angle, i.e., $\cos(\theta_W)$ is the winding power factor and
θ_B is the bushing phase angle, i.e., $\cos(\theta_B)$ is the bushing power factor.

We know that $\tan(90^\circ - \theta_H)$ is almost equal to $\cos(\theta_H)$ for power factors less than 20%. For instance, when $\cos(\theta_H) = 0.20$ (20% power factor), $\theta_H=78.46^\circ$ and $\tan(90^\circ-78.46^\circ) = 0.20$. That is, $\tan(90^\circ - \theta_H) \approx \cos(\theta_H)$ when $\cos(\theta_H) < 0.20$.

Because the power factors of bushings and windings are much smaller than 20%, we can rewrite the above equation to the following equation by setting $\tan(90^\circ - \theta_H) = \cos(\theta_H)$ for all the θ's.

$$\cos(\theta_H) = \frac{C_w * \cos(\theta_W) + C_B * \cos(\theta_B)}{C_w + C_B} = \frac{C_w * \cos(\theta_W) + C_B * \cos(\theta_B)}{C_H}$$

As $\cos(\theta)$ is the power factor of a corresponding component, we can rewrite the above equation to equation (1).

$$P_H = \frac{P_W * C_W + P_B * C_B}{C_H} \qquad (1)$$

Where P_H is the power factor of the HV winding plus bushing, i.e., $\cos(\theta_H)$
P_W is the power factor of the HV winding alone, i.e., $\cos(\theta_W)$ and
P_B is the power factor of the HV bushing, i.e., $\cos(\theta_B)$

This equation shows that the power factor of a HV winding and a HV bushing together is the weighted average of the power factors of these two components by their capacitances. Because a bushing capacitance is normally much smaller than a winding capacitance, we can conclude that the effect of a bushing capacitance will be small.

For instance, the capacitance of a 115 kV 1200 amp bushing is about 250 ~ 450pF (Table 1) and the winding capacitance of a 240 MVA 550kV transformer would be about 9000 pF (Figure 2). Assume the C1 power factor of the bushing is 1% (Note this is above the maximum permissible POC or PRC power factor value). We will also assume that the C1 power factor of the HV winding is 0.3 %. Then the total power factor is

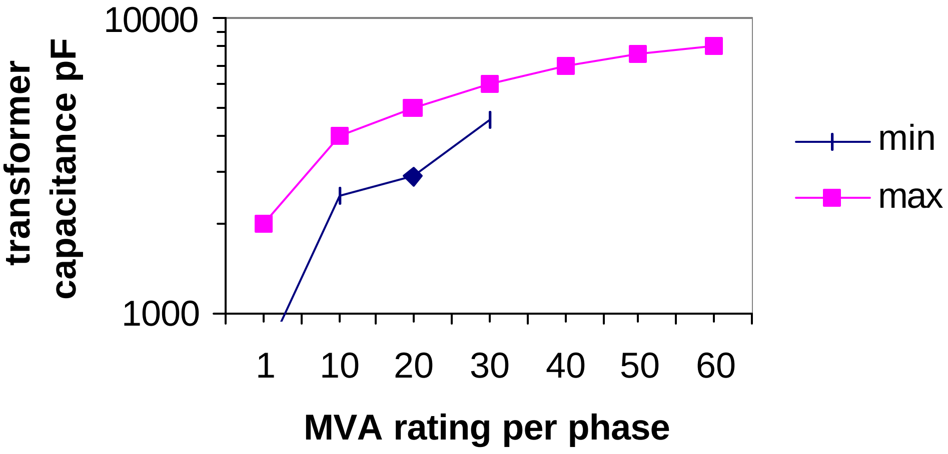
$$(1*400 + 0.3*9000) / (9000+400) = 0.329\%$$

As the difference of 0.029% (0.329-0.3) is less than the accuracy of our measuring device, we could ignore this difference.

Table 1. Capacitance to ground of outdoor bushings.
(These are not from Lapp data but from public domain information)

Kilovolts	Current (amperes)	Capacitance pF
23	400	200-450
	600	280
	1200	190-450
	2000	280-650
	3000	370-560
	4000	500-620
34.5	400	200-390
	600	150-220
	1200	170-390
	2000	240-360
	3000	350-620
46	400	200-390
	600	180-280
	1200	170-330
	2000	200-330
	400	180-270
69	600	250
	1200	160-290
	2000	210-320
115	800	250-450
	1200	250-420
	1600	250-430
138	800	250-450
	1200	250-420
	1600	250-460
161	800	260-440
	1200	260-440
	1600	260-440
196	800	350-550
	1200	350-550
	1600	350-550
345: BIL 1050	800-2000	550
1175	800-2000	500
1300	800-2000	450
500: BIL 1425	800-2000	500
1550	800-2000	500
1675	800-2000	520

Figure 2. Ground Capacitance of HV Windings of Transformers
Redrawn from an IEEE working group report



Therefore, we can see that the bushing power factor will not generally influence measurements of the transformer winding power factor. If we want to eliminate the bushing effects, we can use equation (2) which we obtain by solving equation (1) for P_W.

$$P_W = \frac{P_H * C_H - P_B * C_B}{C_H - C_B} \qquad (2)$$

We will use the same data to calculate P_W . Our measurements will show that the capacitance of the HV winding and the bushing together is 9400 pF and the power factor of these two together is .329%. Our measurements will also show that the capacitance and the power factor of the bushing are 400pF and 1%. Then the real power factor of the winding alone will be

$$(0.329 * 9400 - 1 * 400) /(9400-400) = 0.3\%$$

and the real capacitance of the winding is 9400 pF-400pF = 9000pF.
All the formulae developed above are valid for HV and LV windings of a multi-winding transformer. However, you will note that C_H of a three-winding transformer includes capacitances of the three windings and three bushings.

Example

Many things can affect the insulation power factor measurements especially in the field. When we measure the power factor, we should cross-check the measured values by using formulae (1) and (2) to see if there is any conflict among the data. If there is any significant difference (we have to consider the tolerance of measurements), we must check the test equipment set-up and repeat the test.

We will present here one set of data received from a customer.

C_H = 2800 pF
P_H = 1.64%
C_B = 350 pF
P_B = 1.1 %
C_W = 9400 pF
P_w = 0.27%

We expect that $C_B + C_W = C_H$ but the former ($C_B + C_W$) is 9750 pF and the latter (C_H) is 2800 pF. This is a contradiction and indicates that measurements were incorrect.

We also expect equation (1) holds. We do not know which value (between 2800 and 9750 pF) we have to use for C_H in this formula. Since 9750 pF is more reasonable, we use this value and get 0.32% form the right hand side of equation (1). This is quite different from 1.64% (P_H) the value we obtain from the left-hand side. This is another contradiction.

This indicates there were measurement errors. The customer confirmed their measurements were incorrect after reviewing their data and equipment set-up.

Conclusions

1. The measurement of the insulation power factor of a transformer is not affected by a POC type bushings (with maximum C1 power factor of 0.5%) or a PRC type bushing (with a maximum C1 power factor of 0.85%).

2. We can eliminate the effects of the bushing entirely by using the formula presented in this paper

3. Poor measurement conditions can cause unusual measurements in the field.

4. If the bushing power factor is much smaller than that of a transformer winding, the P_H reading is lower than P_W as explained above. Even in this case, you can use the above formulae we developed to determine P_W.