AN IMPROVED METHOD OF MEASURING C_1 POWER FACTOR OF RESISTANCE-GRADED BUSHINGS

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ABSTRACT

This paper discusses C_1 power factor of a condenser bushing with resistance graded (RG) porcelain and proposes a method to obtain the intrinsic power factor of the RG bushing.

KEY WORDS

Condenser bushing, resistance-graded, C_1 power factor, power factor measurement.

INTRODUCTION

It is well-known that bushings with RG porcelain have superior performance in heavy pollution areas because a small current flowing in the semi-conductive glaze eliminates "dry band" arcing and also makes the voltage distribution across the porcelain more uniform.

Because the resistance of the porcelain surface alters the current at the C_1 tap in an RG bushing, the power factor at the tap can differ from the intrinsic C_1 power factor of the bushing core significantly. Therefore, it has been a challenge to measure the intrinsic C_1 power factor of RG bushings accurately.

Typically C_1 power factors of paper-oil condenser (POC) bushings with regular porcelain are 0.25%. An abnormal increase of C_1 power factor (1.5~2 times the C_1 power factor on the nameplate value or over 1% depending on user's experience) has been interpreted as possible deterioration of the internal insulation of a bushing.

The C_1 power factor of a new RG bushing measured by the standard test method differs from the intrinsic C_1 power factor of the core. The value measured can be higher or lower than the power factor of the core. Sometimes it can be a negative power factor [1,2,3].

Therefore, Osborn introduced a test procedure called "Ungrounded Specimen Test (UST) technique and/or to minimize any effect of resistance coating by use of the test set guard circuit"[2]. However, this method is unsatisfactory. The "guards" proposed by Osborn influence the electrical field and alter the C_1 power factor. The location of "guards"[2] can alter the C_1 power factor of a 138 kV RG bushing from -4.4% to +1.9%.

Because it is difficult to obtain the intrinsic C_1 power factor of a bushing with RG porcelain by present test methods, some utilities avoid using RG bushings even if RG bushings are one of the most suitable choices for the environment.

In this paper, we present a theory of C_1 power factors of RG bushings and introduce a more accurate measuring method.

In this paper the intrinsic values of C_1 and C_1 power factor of the condenser core are referred to as C_{1I} and C_1 PF_I. The values of C_1 and C_1 power factor measured at the tap of an RG bushing are referred to as C_{1M} and C_1 PF_M thereafter.

RG BUSHING

A typical RG bushing is shown in figure 1. It is identical to the regular bushing except that its upper porcelain has semi-conductive glaze. Clips and contact rings are used to connect the semi-conductive glaze to the high voltage conductor and the grounded flange of the bushing.

The design value of the RG surface resistance R_{RG0} is in the range of 10MΩ~100MΩ depending on the size of the bushing. The resistance can vary ±50% from the design value. The current flowing through the semi-conductive glaze is 1~2 mA when the bushing is energized.

Typical surface resistance and capacitance of RG bushings are shown in table 1, where C_{C0} is the total coupling capacitance between the core and RG glaze.

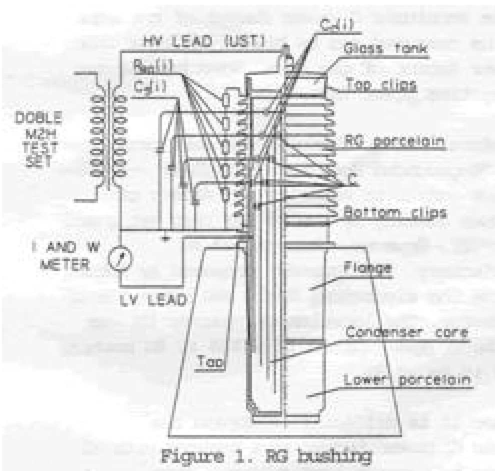


Figure 1. RG bushing

Table 1. Typical parameters of RG bushings

Bushing No.	BIL, kV	C_{1I}, pF	R_{RG0}, MΩ Norm.(min~max)	C_{C0}, pF Estimate
B-588722	150	524	10.4 (8.0~15.3)	53
B-567220	550	404	44.7 (46.4~85.0)	328
B-567320	650	368	72.9 (53.7~113.3)	334
B-567670	900	356	91.3 (60.4~182.6)	476

POWER FACTORS OF RG BUSHINGS

Since the surface resistance of RG porcelain is low, C_1 PF_M of an RG bushing measured by the GST (Grounded-Specimen Test Mode) method can be as high as 8% to 60%. Therefore, it is difficult to determine whether or not the internal insulation of an RG bushing is deteriorated using the normal GST method

The UST (Ungrounded-Specimen Test Mode) method allows us to measure the C_1 PF_I of the bushing with regular porcelain, but it cannot give C_1 PF_I of RG bushings correctly.

Figure 2 is the equivalent circuit of an RG bushing. C is the partial capacitance of the condenser core. For a condenser bushing designed using the principle of equal partial capacitance, $C = N * C_{1I}$, where N is the number of foils of the core.

In Fig. 2, R is used to simulate the power losses of C_1 PF_I. $R_{RG}(i)$ is the surface resistance of the RG porcelain between two adjacent nodes. $C_C(i)$ is the coupling capacitance between foil “i” and its adjacent RG surface. $C_S(i)$ is the stray capacitance between the adjacent RG surface and ground, where the air is dielectric medium. $R_C(i)$ is used to simulate the power losses of the power factor of the coupling capacitor $C_C(i)$.

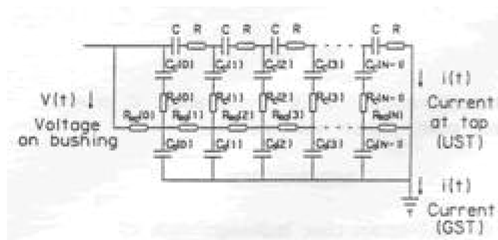


Figure 2. Equivalent circuit used to calculate C_1 power factor of an RG bushing

Because the values of $R_{RG}(i)$, $C_C(i)$ and $C_S(i)$ depend on the electrical field distribution of the bushing, it is very difficult to calculate and measure them.

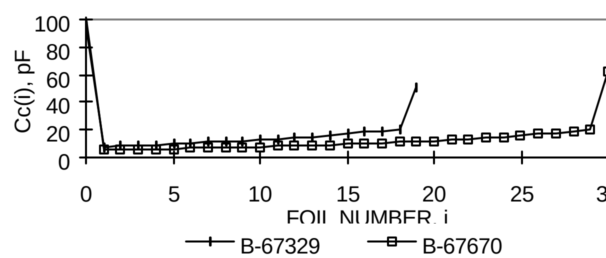


Figure 3. Coupling capacitance $C_C(i)$

We estimate $C_C(i)$ using a coaxial cylinder model. Some examples are shown in figure 3. $C_C(i)$ increases with index “i”, except $C_C(0)$ and $C_C(N)$. $C_C(0)$ is the capacitance between the conductor and the RG surface. $C_C(N)$ is the capacitance between the ground foil N and the RG surface. C_{C0} increases with bushing BIL level as shown in table 1.

$C_S(i)$ and C_{S0} show a similar trend as $C_C(i)$ and C_{C0}. C_{S0} is the sum of stray capacitance $C_S(i)$.

The circuit in Fig. 2 can be seen as a complex bridge circuit. The two daisy-chain circuits are bridged by N pieces of coupling capacitance $C_C(i)$. One daisy-chain consists of the partial capacitance of the core and the other mainly consists of the surface resistance of the RG porcelain. If the two daisy-chains have the same voltage distribution, there is no voltage across the coupling capacitance $C_C(i)$ and then no current flows through $C_C(i)$. Therefore, the surface resistance does not alter C_1 PF_M at all.

Since $R_{RG}(i)$ depends on the design of the core and porcelain, the voltage distributions in the two daisy-chain circuits are unlikely to be the same. Therefore the currents flow through coupling capacitance $C_C(i)$ and the surface resistance alters C_1 PF_M. Figure 4 shows an estimated voltage distribution across the coupling capacitors $C_C(i)$, where the voltage is measured from core to RG resistors $R_{RG}(i)$.

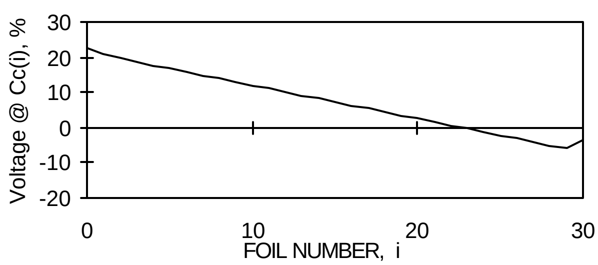


Figure 4. Voltage across the coupling capacitance $C_C(i)$ of a 900kV BIL RG bushing

We use a simple model in figure 5 to demonstrate how C_1 PF_M varies with the axial voltage distribution in an RG bushing when the UST method is used. Here the core is simplified with only two foils. The surface resistance of RG porcelain is $R_{RG0} = R_{RG1} + R_{RG2}$. R_{RG1}/R_{RG2} reflects the axial voltage distribution on the RG surface. The data from a 900kV BIL RG bushing are used for this example. C_S is assumed to be 100pF.

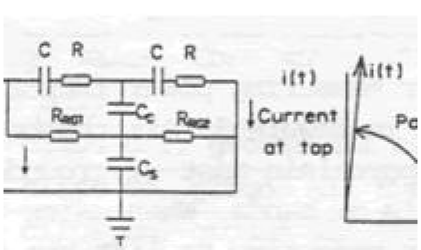


Figure 5. Circuit of an RG bushing with two foils

Our study shows that C_{1M} value will not change with C_1 PF_I, R_{RG0} and R_{RG1}/R_{RG2}, but C_1 PF_M does change with R_{RG1}/R_{RG2} and R_{RG0}, as shown in Fig. 6 and 7. C_1 PF_M can be greater or smaller than C_1 PF_I. It even can be a negative value. Negative C_1 PF_M means that the real part of the current measured at the tap is opposite to the polarity of the voltage on the bushing high voltage terminal. In an actual bushing, the relationship will be much more complex.

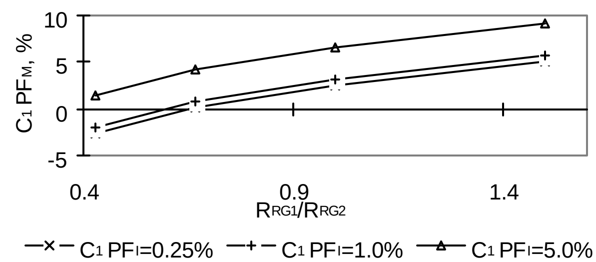


Figure 6. Relationship of C_1 PF_M to the distribution of surface resistance (R_{RG0}=91.3MΩ) of a 900kV BIL RG bushing

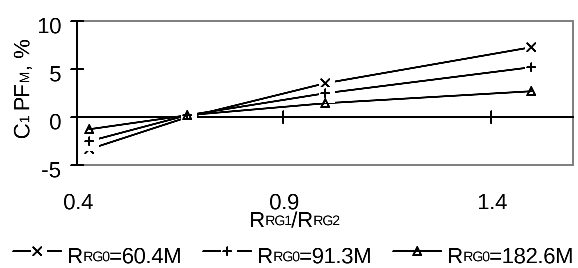


Figure 7. Relationship of C_1 PF_M to the balance of surface resistance (PF_I=0.25%) of a 900kV BIL RG bushing

Removing the clips on the RG bushing or using “guard” circuit can alter the current at the tap and vary the value of C_1 PF_M but this C_1 PF_M is not C_1 PF_I.

We studied the influence of stray capacitance C_S (the capacitance from core to ground) on C_{1M} and C_1 PF_M in the bushing with the regular porcelain. The results are shown in Table 2 and 3. The stray capacitance $C_S(i)$ is exaggerated by removing all the petticoats of the porcelain and moving the ground to the porcelain surface. In this case, $C_S(i)$ is the same as $C_C(i)$ in Fig. 2. We use C_{C0} in stead of C_{S0} to discuss the influence of the coupling capacitance on C_1 PF_M.

The C_1 value measured changes with the coupling capacitance C_{C0} but not with C_1 PF_I and C_C PF (power factor of C_C). C_{1M} measured by the UST method will be lower than C_{1I} when C_C is larger. By the UST method, C_{1M} is 1.7% smaller than C_{1I} with coupling capacitance of 0.2*C_{1I} and 14.9% smaller than C_{1I} with coupling capacitance of 1.0*C_{1I}. For regular bushings, C_{C0} is much smaller than C_{1I}, so the deviation between C_{1M} and C_{1I} is negligible.

C_1 PF_M changes with C_C PF but not with C_C value. C_1 PF_M is exactly equal to C_1 PF_I if C_C PF and C_1 PF_M have the same values. If C_C PF is higher than C_1 PF_I, C_1 PF_M by the UST is slightly lower than C_1 PF_I but C_1 PF_M by the GST is slight higher than PF_I as shown in Tables 2 and 3.

This finding allows us to measure C_1 PF of RG bushings with the following way: (1) grounding the whole surface of the RG porcelain, (2) measuring C_1 PF with the regular UST or GST methods at a reduced voltage. The deviation between C_1 PF_M and C_1 PF_I is within 15% of the measured C_1 PF_I.

Table 2. C_1 PF_M measured by the UST method with different C_C PF (900kV BIL POC bushing)

INTRINSIC C_{1I} & C_1 PF_I		C_C PF = C_1 PF_I		C_C PF = 0		C_C PF = 2* C_1 PF_I	
C_{1I} pF	PF_I %	C_{1M} pF	PF_M %	C_{1M} pF	PF_M %	C_{1M} PF	PF_M %
356	0.250	308	0.250	308	0.285	308	0.215
356	0.500	308	0.500	308	0.570	308	0.430
356	1.000	308	1.000	308	1.139	308	0.861
356	1.500	308	1.500	309	1.709	308	1.291
356	2.000	308	2.000	309	2.278	308	1.721

Table 3. C_1 PF_M measured by the GST method with different C_C PF (900kV BIL POC bushing)

INTRINSIC C_{1I} & C_1 PF_I		C_C PF = C_1 PF_I		C_C PF = 0		C_C PF = 2* C_1 PF_I	
C_{1I} pF	PF_I %	C_{1M} pF	PF_M %	C_{1M} pF	PF_M %	C_{1M} pF	PF_M %
356	0.250	457	0.250	457	0.212	457	0.288
356	0.500	457	0.500	467	0.424	467	0.576
356	1.000	457	1.000	457	0.848	457	1.151
356	1.500	457	1.500	457	1.273	457	1.727
356	2.000	457	2.000	457	1.697	457	2.302

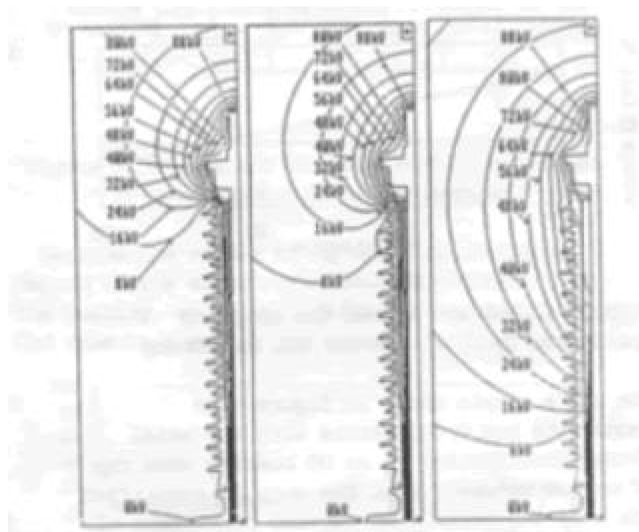
PROPOSED TEST METHOD

The best method of measuring C_1 and C_1 PF of an RG bushing is lifting the top clips and grounding the whole surface of the RG porcelain by conductive foils or bands, and then measuring C_1 PF with the UST or GST measurement.

It is difficult to ground the whole surface of RG porcelain because of the petticoat shape.

An alternate method is grounding all the body sections (the narrow straight portions between petticoats) of RG porcelain. Because this method may influence the electrical field distribution significantly, we performed electrical field analyses as shown in figure 8.

We found that the electrical field distribution on the bushing with all the body sections grounded is almost the same as that with the whole surface grounded. Therefore, the alternate method should not cause significant deviation in C_1 PF measurement. An electrical field plot of a regular bushing is shown as a reference.



Left: Bushing with the whole surfaces grounded
Middle: Bushing with all body sections grounded only
Right: Bushing without ground foils

Figure 8. Electrical field distributions of a 550kV BIL bushing

The test setup for measuring power factor of RG bushing is shown in figure 9. All the body sections of the RG porcelain must be grounded with conductive foils or bands. When using the UST method it is not necessary to lift the top clips, but when using the GST method the top clips must be lifted.

From Tables 2 and 3, we know the power factor of the coupling capacitance influences C_1 PF_M. If the power factor of the coupling capacitance C_C is higher than C_1 PF_I, C_1 PF_M measured by the UST will be lower than C_1 PF_I. So a bad contact between the ground bands and RG surface will cause C_1 PF_M to be less than C_1 PF_I. So great attention should be paid to keeping all the ground band contacts tight.

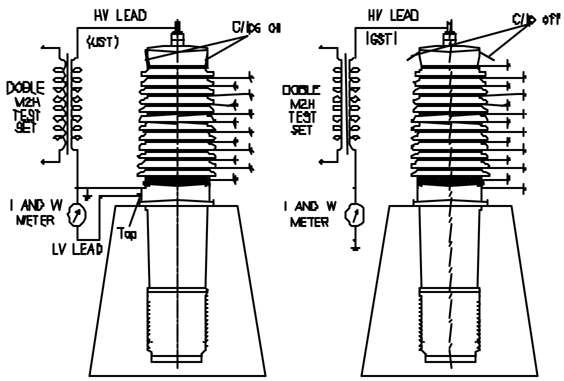


Figure 9. Recommended test hook up

TEST RESULTS

Tables 4, 5, 6 and 7 show the test results using different methods. The test results indicate C_1 PF_M measured by the recommended method (bold-faced in the tables) agrees most closely with the intrinsic C_1 power factor.

C_1 PF_M measured by the recommended method deviates only slightly from the intrinsic C_1 PF_I. Our test results on two RG bushings show that the deviation of C_1 PF measured using the UST method is -0.16%. The deviation of C_1 PF_M measured using the GST method is in the range of -0.30% to +0.16%. As the accuracy of Doble M2H test set in measuring power factor is ±0.1% PF or 5% of the measured value, whichever is greater, the results obtained are very good.

The test results show it is possible to measure C_1 PF with the top clips on and with all the body sections grounded except the top one. This is because the first foil of the condenser core is always lower than the first petticoat. The coupling capacitive current from the bushing conductor to the RG surface does not flow through the measuring circuit, so it does not influence measurement. In this case the very top petticoat holds the test voltage.

Table 4. UST tests at 10kV with DOBLE M2H test set on a 900kV BIL RG bushing B-567680-EXP2-70

Test	Description	C1, pF	PF, %
0	Design value. Core spec. BC-253DC and RG resistance (measured) = 80MΩ	437	
1	*Core only*	*470*	*0.32*
2	**Top clips off, ground all the straight surfaces of RG porcelain**	**359**	**0.31**
3	**Top clips on, ground all the straight surfaces except top one**	**326**	**0.26**
4	Top clips on, no grounded foil on RG surface	370	0.81
5	Top clips off, no grounded foil on RG surface	371	-0.14
6	Top clips on, ground all the odd straight surfaces of RG porcelain	320	-0.17
7	Top clips off, ground all the odd straight surface of RG porcelain	322	-0.10
8	Top clips off, ground the top, middle and bottom straight surfaces only	323	1.43
9	Top clips off, ground the top and bottom straight surfaces only	336	5.03

Table 5. UST tests at 10kV with DOBLE M2H test set on a 900kV BIL RG bushing B-567670-70

Test	Description	C1, pF	PF, %
0	Design value. Core spec. BC-650 and RG resistance (measured) = 80MΩ	356	
1	*Core only*	*359*	*0.31*
2	**Top clips off, ground all straight surfaces of RG porcelain**	**313**	**0.15**
3	**Top clips on, ground all the straight surfaces except top one**	**313**	**0.13**
4	Top clips on, ground all the odd straight surfaces of RG porcelain	341	3.18

5	Top clips off, ground all the odd straight surface of RG porcelain	339	5.33

Table 6. GST tested with DOBLE M2H test set on a 900kV BIL RG bushing B-567680-EXP2-70

Test	Description	C1, pF	PF, %
0	Design value. Core spec. BC-253DC and RG resistance (measured) = 80MΩ	437	
1	*Core only*	*410*	*0.42*
2	**Top clips off, ground all straight surfaces**	**406**	**0.29**
3	Top clips off, no grounded foil on RG surface	678	1.51
4	Top clips on, no grounded foils on RG surface (estimated: PF=7.58%)	570	7.00

Table 7. GST tests with DOBLE M2H test set on a 900kV BIL RG bushing B-567670-70

Test	Description	C1, pF	PF, %
0	Design value. Core spec. BC-650 and RG resistance (measured) = 80MΩ	356	
1	*Core only*	*406*	*0.29*
2	**Top clips off, ground all straight places**	**548**	**0.59**
3	Top clips off, no grounded foils on RG surface	499	4.73
4	Top clips on, no grounded foils on RG surface (estimated: PF = 9.31%)	477	26.10

From our tests and analyses, we estimate that the accuracy of C_1 PF_M is ±0.3% PF or 15% of the measured value, whichever is greater. We believe that C_1 PF_M of the RG bushing measured by our recommended method can detect the change of the power factor caused by insulation deterioration easily.

CONCLUSION

We studied why the power factor C_1 PF_M differs from C_1 PF_I when we measure the power factor of an RG bushing with regular method, and then we present a correct method.

The correct method of measuring C_1 power factor of RG bushings is grounding all the body sections of RG porcelain with conductive foils or bands and then performing the UST measurement. If we use the GST method, the top clips need to be lifted before testing.

The results are very close to the intrinsic C_1 power factor of the bushing core with an accuracy of ±0.3% PF or ±15% of the measured value, whichever is greater. We believe that this power factor reading can be used to identify whether the internal insulation of an RG bushing is deteriorated.

ACKNOWLEDGMENT

The author appreciates Lapp Insulator Company’s permission to publish this paper.

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BIOGRAPHY

He received a BS in high voltage engineering in 1964, an MS in electrical measurements in 1967 and another MS in high voltage engineering in 1981 all from Tsinghua University, Beijing, China.

From 1968 to 1978 he worked at Xi-an Power Rectifier Company in China and developed AC-DC and DC-AC energy conversion systems. From 1981 to 1985 he worked at the Electrical Engineering Institute of Chinese Academy of Sciences to develop high-voltage impulse generators and work on high-voltage insulation projects.

In the US, he worked as a visiting scientist at the Plasma Lab of Stevens Institute of Technology. Since 1990, he has been with Bushing Division of Lapp Insulator Company. His responsibilities include bushing design, bushing development, thermal physics, electrical field analysis and development of measuring method.