2011 Electrical Insulation Conference, Annapolis, Maryland, 5 to 8 June 2011

Insulation Resistance and Polarization of Rotating Machines

S.A. Bhumiwat
Independent High Voltage Diagnostics Consultant
P.O. Box 18-062 Glen Innes
Auckland 1743, New Zealand
supatra@kea-consultant.com

Abstract—**This contribution explains insulation resistance and polarization of rotating machines through measurement results of Polarization Depolarization Current (PDC), or charging and discharging current, of machines having different types and conditions of insulation aging. It demonstrates why the Polarization Index (P.I.) cannot be used individually to judge insulation dryness and why the product of insulation resistance and capacitance is a better measure of insulation quality than the insulation resistance alone. But it is the combination of PDC, Capacitance ratio and Dielectric Dissipation Factor (DDF) which provides a decisive key in the diagnosis of global problems in machine insulation.**

Keywords- insulation; polarization; depolarization; resistance; capacitance; absorption; conduction; dissipation factor

I. INTRODUCTION

A. Conduction and Polarization

Problems in any electrical insulation are produced by the mechanisms of *conduction* or *polarization* or both. Table 1 shows classification of problems in machine insulation based on its basic properties. For decades, problems caused by *conduction* and *polarization* have been detected in combination through the measurement of insulation resistance [1]. Since this is the measurement during the charging of insulation by a constant direct voltage, the current consists of the steady-state conduction current (caused by *conduction*) and absorption current (due to *polarization*) which decays exponentially to zero at longer time. At initial time when the absorption current is high and dominant, the conduction current is hardly noticed. At longer time when absorption current decays to minimum, the steady-state conduction current then becomes obvious. In spite of the name, *Insulation Resistance*, which should have constant value and refer to problem caused by *conduction* only, it includes the time-dependent *Insulation Polarization* or *Dielectric Absorption* which refers to problem caused by *polarization*. Many efforts were reported (e.g. in [2],[3]) for the determination of absorption current from the values of Insulation Resistance in order to identify problems caused by *conduction* and *polarization* but none has been an easy task.

B. One-minute reading and Polarization Index (P.I.)

Carbon dust in old brush type machines and/or water can cause the charging current to be steady as early as one minute. So the one-minute reading of Insulation Resistance has been successfully used by maintenance people since the old days in the detection of *conduction* problems. To make it more handy, Polarization Index (P.I.), a ratio of the reading at ten minutes to the reading at one minute, was introduced as an indicator of *conduction* level. When P.I. =1.0, the problem caused by *conduction* is severe and needs action. Cleaning and drying decrease conduction current thus cause charging current to be steady at longer than one minute which means P.I. is higher. But *whether P.I. can be used individually to judge insulation dryness* will be answered later through a case study. Recommended minimum values of Insulation Resistance and P.I. of rotating machines are in [4]. Do higher values ensure that your machine has no risk of failure during operation?

TABLE I. CLASSIFICATION OF PROBLEMS IN MACHINE INSULATION

Polarization	Conduction
By-products of Partial Discharges	Surface humidity
Aging molecules at interfaces	Free water or droplet
Arcing by-products	Surface contaminants
Oxidation by-products	Tracking
Products of spilled lubricating oil & dust	Carbon dust
Chemical dust including salts	Metal dust
Corrosive products	Debris from fault
Thermal aging products	Leakage path
Moisture in adsorbed or molecular state	

C. Product of Insulation Resistance (R) and Capacitance (C)

For any insulation system, the product of insulation resistance and its capacitance is *the time constant of capacitor self-discharge*. The larger this time constant or the longer the capacitor self-discharge time, the better the insulation quality [5]. Therefore insulation resistance of any machine can be compared only with its sister units having the same design and same capacitance. It can be compared with its own previous records. Resistance of ground insulation cannot be compared with resistance of phase-to-phase insulation due to its much difference in capacitance. These will be demonstrated later in the case studies.

D. Polarization Depolarization Current (PDC) Analysis

All results of *Insulation Resistance* and other dielectric responses in this contribution are from commercially available PDC-Analyser[1] based on [6] which measures both polarization (or charging) current and depolarization (or discharging) in

---

[1] *PDC-Analyser from ALFF Engineering, Switzerland*

order to identify *conduction* and *polarization* in electrical insulation. The depolarization current represents absorption current since conduction current does not exist when external power source is switched off for discharging. This on-site instrument is able to measure current as low as one Pico-Ampere (10^{-12} A) with high precision which allows ground insulation of rotating machines to be tested at the voltage as low as 50V. In addition to the time-domain PDC measurement results, the instrument also provides the frequency-domain evaluation results of Capacitance (C) and Dielectric Dissipation Factor (DDF). Details of PDC diagnosis of machine insulation including test connection, factors affecting the measurement, interpretation and in-service criteria are in [7]. In that reference, the author proposed three diagnostic parameters from the Analyzer for interpretation of dielectric response results which are PDC shape, DDF and C ratio (the ratio of C at corresponding frequency to C at 50 Hz). While PDC shape identifies the type of problem, DDF tells how severe the problem is and C ratio indicates how much insulating materials have been deteriorated by *polarization*. When C ratio is unity, there is no deterioration in the insulating materials. Reference [7] does not include insulation resistance in the interpretation since it provides the same information as polarization current.

For each case study in this contribution, a plot of insulation resistance versus time is accompanied by the PDC so readers who are familiar with the plot of insulation resistance and P.I. results can better understand the characteristics of each aging type. A plot of RC versus time is also presented. RC is obtained by multiplying the 50-Hz capacitance value (given by the PDC-Analyser) to the insulation resistance. The value of RC at 60 s is presented in Table II together with capacitance, P.I. and insulation resistance at 15, 60 and 600 s. In addition, the results of DDF & C ratio are included in each case study together with the suggested limits (proposed in [7] and [9]) for safe operation of ground insulation (L-G) and phase-to-phase insulation (L-L).

II. PROBLEMS IDENTIFIED BY DIELECTRIC RESPONSES

A. No Problem

The dielectric response results of phase-to-phase (L-L) and ground insulation (L-G) of a new generator stator (not yet in service) in good condition are presented in fig. 1 for reference.

When the insulation system is good and dry, the polarization current (I pol.) and the depolarization current (I depol.) are nearly equal for about one-tenth of the charging time such as in fig. 1a. Both currents are straight in log-log scale, following inverse power law. The magnitude of PDC depends mostly on the capacitance and insulation condition. For any machine, L-G always has much higher PDC magnitude than L-L at the same test voltage and temperature no matter how good/bad the insulation is because L-G always has much larger capacitance than L-L. Since insulation resistance is the result of a constant test voltage divided by I pol., the insulation resistance of L-L is always higher than L-G, as shown in fig. 1b. *It does not mean L-L has better insulation quality than L-G*. The shape of insulation resistance for a good and dry machine is also straight in log-log scale but increases with time. So the ratio of insulation resistance between 1 and 10 minutes is more than 1. In another word, P.I. shows a good result.

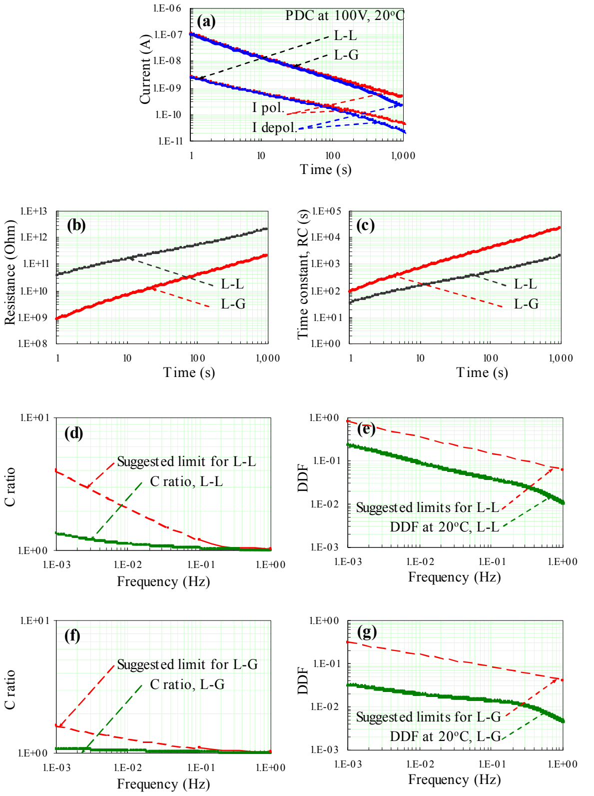

Figure 1. Dielectric response results of phase-to-phase (L-L) and ground insulation (L-G) of the good new machine in case IIA: (a) PDC at 100V (b) Insulation Resistance (c) Time constant, RC (d) C ratio of L-L (e) DDF of L-L (f) C ratio of L-G and (g) DDF of L-G

With the result of insulation resistance alone, someone can incorrectly interpret that L-L has better insulation condition than L-G. Therefore, the time constant, RC, as introduced on the previous page is the better measure of insulation quality. The RC-plot in fig. 1c shows that L-L has inferior quality to L-G. Actually the RC-plot of L-G in fig. 1c can be *a typical RC-plot for a machine having very good ground insulation*. Mostly, the phase-to-phase insulation of a new machine has inferior quality to the ground insulation. This can be confirmed by comparing C ratio of L-L in fig. 1d with C ratio in fig. 1f. The slight increase of C ratio at very low frequencies of L-L means slight deterioration of insulating materials due to *polarization*. Moisture in adsorbed state as described later in case IIB is the cause. While problems caused by *polarization* increase C ratio, problems caused by *conduction* do not.

DDF lower than suggested limit in fig. 1e and fig. 1g means acceptable condition. Both *conduction* and *polarization* increase the frequency-dependent DDF.

B. Problem with Moisture

This is the case of moisture in the adsorbed state (*Polarization*) without surface humidity, free water or other conductive contaminants (*Conduction*). It is the case which P.I. cannot be used individually to judge insulation dryness.

The dielectric response results in this case study are in fig. 2.

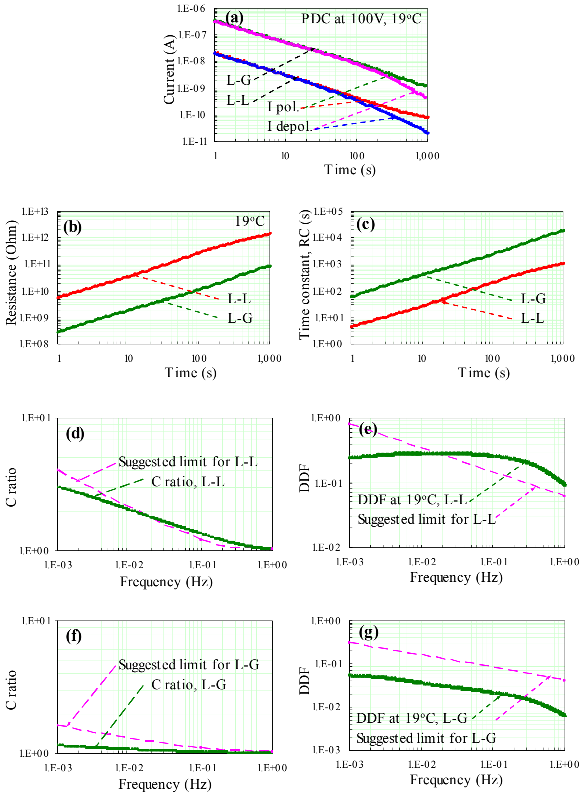

Figure 2. Dielectric response results of phase-to-phase (L-L) and ground insulation (L-G) of the machine having problem of mositure in L-L in case IIB: (a) PDC at 100V (b) Insulation Resistance (c) Time constant, RC (d) C ratio of L-L (e) DDF of L-L (f) C ratio of L-G and (g) DDF of L-G

A new generator stator in this case study was wet during storage before installation. The drying was done on site and the PDC analysis was applied to verify insulation dryness. The shape of PDC measurement results as presented in fig. 2a looks like a good and dry machine in case IIA (quite straight in log-log scale, following inverse power law). It is also difficult to judge from its evaluation results of insulation resistance in fig. 2b alone that only ground insulation (L-G) is acceptable but not phase-to-phase insulation (L-L), unless there is a sister unit to compare or there is a previous test record. The insulation resistance of L-L in fig. 2b is even higher than L-G. The P.I. of L-L (as shown in Table II) is 5.74, which is high like dry insulation. But it is not true. Moisture in adsorbed state is the case that insulation resistance and P.I. are not sensitive to. The RC plot in fig. 2c gives a hint that L-L is low and inferior to L-G. But the decisive answer of unacceptable L-L but acceptable L-G comes from the PDC evaluation results of C ratio and DDF (fig. 2d - fig. 2g) which include the suggested limits for safe operation (L-L and L-G have different limits).

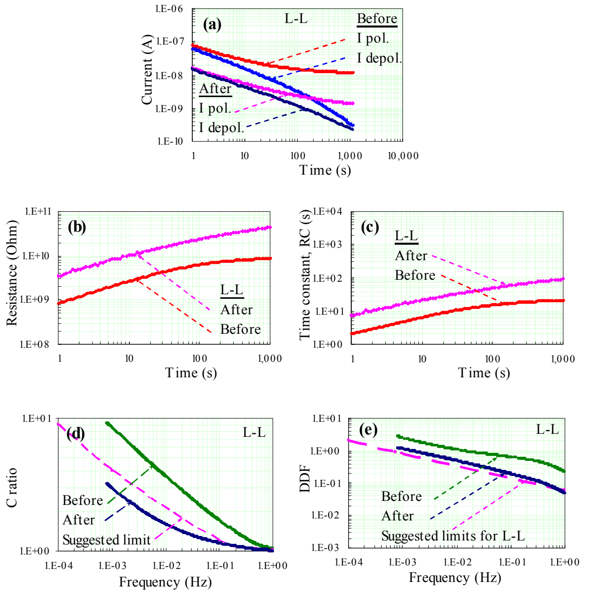

Figure 3. Dielectric response results of phase-to-phase (L-L) insulation of the machine in case IIC, before and after cleaning and drying: (a) PDC at 50V (b) Insulation Resistance (c) Time constant, RC (d) C ratio of L-L and (e) DDF of L-L

Unlike surface humidity or free water which are *conduction* problems and do not influence the absorption current, moisture in the adsorbed state increases absorption current without changing the PDC shape. It also increases DDF and C ratio. C ratio is very sensitive to this moisture problem.

C. Problem with conductive contaminants and mositure

Fig. 3 presents the dielectric response results at 32°C of phase-to-phase insulation of an old machine before and after drying & cleaning. The C ratio in fig. 3d and the DDF in fig. 3e reveal the successful drying by circulating short-circuited current which could decrease large amount of moisture in the adsorbed state thus decrease substantially C ratio, DDF and the magnitude of absorption current in fig. 3a (decrease both I pol.

TABLE II. CLASSIFICATION OF PROBLEMS IN MACHINE INSULATION

Reference	Fig. 1		Fig. 2		Fig. 3		Fig. 4	Fig. 5	
Insulation analyzed	L-L	L-G	L-L	L-G	(Before)	(After)	L-G	V-W	W-U
Winding temperature (°C)	20	20	14	14	32	32	18	30	30
Capacitance (pF)	951	107,860	770	213,400	2,422	2,113	301,175	295	1,328
R at 15 s (GΩ)	199	9.56	49	2.54	3.18	11.8	1.32	84.9	90.6
R at 60 s (GΩ)	401	27.2	172	7.41	5.36	19.8	3.10	144	135
R at 600 s (GΩ)	1,460	157	988	55	8.23	39.0	25.9	234	219
PI (between 15 and 60s)	2.02	2.85	3.51	2.92	1.69	1.68	2.35	1.70	1.49
PI (between 60 and 600 s)	3.64	5.77	5.74	7.42	1.54	1.97	8.35	1.63	1.62
RC at 60 s (s)	381	2,934	132	1,581	13	42	934	42	179

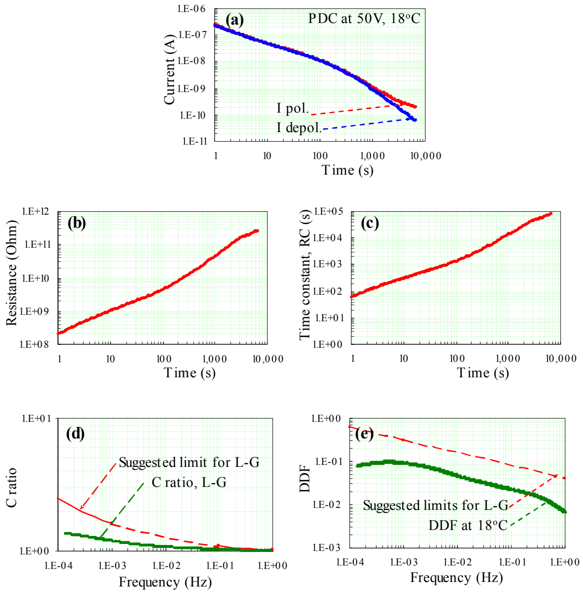

Figure 4. Dielectric response results of ground insulation of the machine in case IID which was overheated due to high load and poor ventilation: (a) PDC at 50V (b) Insulation Resistance (c) Time constant, RC (d) C ratio of L-G and (e) DDF of L-G

and I depol.). Insulation resistance in fig. 3b as well as in Table II therefore show a considerable increase. But there is no increase of P.I. between 15 and 60 s (see Table II) since conduction current has not yet influenced I pol. (or insulation resistance) in the first 60 s.

While removing conductive contaminants causes the separation of I pol. and I depol. to appear at longer time as in fig. 3a, it also causes the insulation resistance to be steady at longer time as in fig. 3b. In addition, P.I. between 60 and 600 s increases from 1.54 to 1.97 (see Table II). P.I. is a good diagnostic tool for the problem with conductive contaminants.

In spite of much improvement of L-L, the RC-plot in fig. 3c shows slight improvement because the value of 50-Hz capacitance also decreases with the decrease of moisture (see Table II). RC in this case especially before refurbishment is the lowest among all the cases presented here.

D. Thermal problem

Fig. 4 presents the dielectric response results at 18°C of ground insulation of a machine which was overheated due to high load and insufficient cooling. The similar shape of I pol. and I depol. in fig. 4a refers to absorption current which is dominant and has one prominent crook. Insulation resistance and RC versus time are presented to show the characteristics for this type of aging. The resistance curve in fig. 4b is steep and P.I. (between 60 and 600 s) in Table II shows the value of 8.35 which is very high. *Experienced from many cases, P.I.* (between 60 and 600 s) *higher than 7.0 reveals thermal aging or overheating.* This is another case to confirm that the high P.I. does not always mean good insulation.

(Note: The ground insulation of a new machine in case II B was thermally aged during drying. P.I. is 7.42 and the bending or prominent crook of PDC shape can be noticed in fig. 2a.)

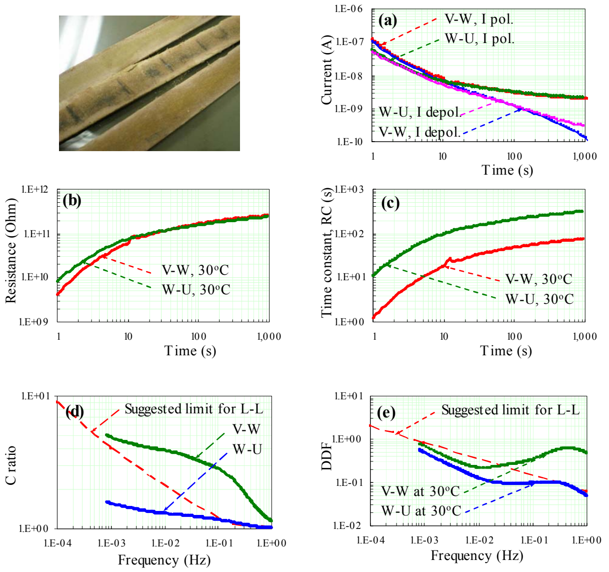

Figure 5. Dielectric response results of phase-to-phase V-W and W-U of the motor stator in case IIE with abrasion of insulation: (a) PDC at 500V (b) Insulation Resistance (c) Time constant, RC (d) C ratio of L-L and (e) DDF of L-L, in additio to a photo of abraded phase-to-phase insulation

The RC-plot in fig. 4c looks like those having good insulation except it is not in a straight line. The C ratio in fig. 4d shows deterioration of insulating materials but still acceptable. The DDF-plot in fig. 4e is also within suggested limit for L-G. The ventilation of the machine room was improved and the insulation condition has become stable.

E. Combination of polarization problems

Deterioration products due to heat, vibration and partial discharges which caused serious abrasion of insulation between two phases in the same stator slot (phase-to-phase slot packer) increase absorption current at initial time within 10 seconds, as shown in fig. 5a. The insulation between phase V and phase W (V-W) shows higher current (or lower insulation resistance) than the insulation between phase W and phase U (W-U) in the first 10 seconds. After that, I pol. of V-W and W-U have quite similar amplitude or similar shape. This means insulation resistance after 10 seconds of both pairs are also very similar, as shown in fig. 5b and Table II, in spite of more serious condition of V-W than W-U. The P.I. of V-W and W-U are also quite similar (see Table II). So this is an example that higher value of 1-min insulation resistance than IEEE Std. 43 recommendation does not always mean safe for opeartion.

The very abraded insulation of V-W can be clearly seen from the much lower capacitance value of V-W (only 295 pF) compared to W-U (1,328 pF) as shown in Table II, which leads to much lower time constant, RC of V-W compared to W-U in fig. 5c, much higher and unacceptable C ratio (fig. 5d) and DDF (fig. 5e). It is actually the very high and unusual shape of C ratio which characterizes the very deteriorated insulation of V-W. This large motor was stripped a few months after the PDC tests and rewound.

The deteriorated phase-to-phase slot packers are shown in the photo of fig. 5. The middle one is the very abraded V-W.

III. CONCLUSION

Like polarization current or charging current, insulation resistance detects problems caused by *conduction* and *polarization* of rotating machines in combination. Its value depends not only the insulation condition but also the capacitance. So it can be compared only with its sister units having same design or same capacitance. Insulation resistance of phase-to-phase insulation cannot be compared with ground insulation due to its much difference in capacitance. Without any fingerprint, the time constant or product RC provides better measure of insulation quality than the insulation resistance alone. This is demonstrated in most of the case studies particularly the case of abraded insulation in fig. 5 or case II E.

P.I. (between one and ten minutes) is sensitive to problems caused by conductive contaminants (carbon dust, surface humidity or free water) but not problems caused by *polarization*. P.I. cannot be used individually to judge insulation dryness since moisture in the adsorbed state (fig. 2 or case II B) decreases insulation resistance without changing PDC shape so P.I. can still be high in case of moisture if no conductive contaminants are included. When P.I. is higher than 7, thermal aging can be suspected.

In all case studies shown, C ratio and DDF together with PDC shape provide the most efficient and decisive indicator in the assessment of global problems in machine insulation. The accuracy of PDC in the first 10 seconds is very important.

ACKNOWLEDGMENT

Many thanks to my clients from whose machines the data presented here were collected.

REFERENCES

[1] J. S. Askey, J. S. Johnson, "Insulation resistance and dielectric absorption characteristics of large A-C stator windngs," AIEE Transactions on Electrical Engineering, vol. 64, June 1945, p. 347-351.

[2] W. McDermid, "Dielectric absorption characteristics of generator stator insulation," in 2000 IEEE International Symposium on Electrical Insulation, Anaheim, USA, April 2-5, 2000, p. 516-519.

[3] B. Milano, E. Eastment, B. Weeks, "New insights and complications in determining generator stator insulation absorption current exponents and constants from Polarization Index," in 2009 IEEE Electrical Insulation Conference, Montreal, QC, Canada, May 31- June 3, 2009, pp. 13-4, p. 254-258.

[4] IEEE Standard 43 Recommended practice for testing Insulation Resistance of electric machinery.

[5] B. Tareev, Physics of Dielectric Materials. Mir Publishers, Moscow.

[6] J. Alff, V. Der Houhanessian, W. S. Zaengl and A.J. Kachler, "A novel, compact instrument for the measurement and evaluation of relaxation currents conceived for on-site diagnosis of electrical power apparatus," in 2000 IEEE International Symposium on Electrical Insulation, Anaheim, USA, April 2-5, 2000, p. 161-167.

[7] S. A. Bhumiwat, "On-site non-destructive dielectric response diagnosis of rotating machines," IEEE Transaction on Dielectrics and Electrical Insulation, vol. 17, no. 5, October 2010, p. 1453-1460.

[8] S. Bhumiwat, "Application of polarisation depolarisation current (PDC) technique on fault and trouble analysis of stator insulation", in CIGRE SC A1 & D1 Joint Colloquium, Gyeongju, Korea, October 24, 2007, p. 79-87 [can be downloaded from www.kea-consultant.com].

[9] S. Bhumiwat, "Practical experiences on condition assessment of stator insulation using Polarisation / Depolarisation Current technique", in CIGRE 2008 Session, Paris, August 24-29, 2008, pp. D1-210.

[10] S. Bhumiwat, "Field experience in insulation diagnosis of industrial high voltage motors using dielectric response technique", in Electrical Insulation Conference, Montreal, Canada, May 30 – June 3, 2009, pp. 21-2, p. 454-457.