

Power-Factor Testing of Stator Winding Insulation: Understanding the Test Technique and Interpretation of Results

Power-factor testing of rotating machinery is another valuable test technique providing information about the integrity of the insulation system. This test technique has been in existence for many years, and Doble has been maintaining a database of results since the late 1950s. The database has been updated as recently as this year. The test is effective in detecting insulation contamination, the quality of the semiconducting and stress gradient coatings, the amount of void content, partial discharge damage, insulation delamination, and the quality of the impregnation process. This article is a review of the test technique and the interpretation of results. Also included are several case studies.

Theory

Power-factor testing of rotating machinery is a nondestructive ac test performed off line at apparatus frequency. When a 60-hertz voltage is impressed across the stator insulation, the total current that flows is similar to that of any capacitor. The total current has two components: a relatively large capacitive current (i_c), which leads the voltage by 90° , and a smaller resistive current (i_r) which is in phase with the voltage. The dielectric of this simulated capacitor is the insulation system which is embedded between two electrodes: the high-voltage copper conductors and the stator iron core. The power factor is the cosine of θ , the angle between the applied voltage and the total current.

$$\cos\theta = \frac{i_r}{i_t} = \frac{Ei_r}{Ei_t} = \frac{W}{Ei_t} = \frac{\text{Watts}}{\text{Volts} \times \text{Amperes}}$$



by Eileen Duarte
Doble

Power factor is a dimensionless quantity and, thus, can be compared with different volumes of insulation systems. It is a measure of the dielectric losses of the insulation and provides valuable information about the insulation quality.

Power factor is performed per phase at incremental voltages, starting at a voltage below corona inception and continuing up to the line-to-ground voltage rating of the machine and possibly 25 percent over. **Power-factor tip-up** is defined as the power factor measured at the line-to-ground voltage minus the low-voltage power factor (typically performed at 100 percent and 25 percent of the

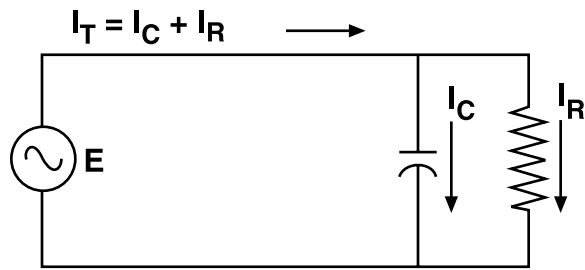


Figure 1 — Basic Dielectric Circuit

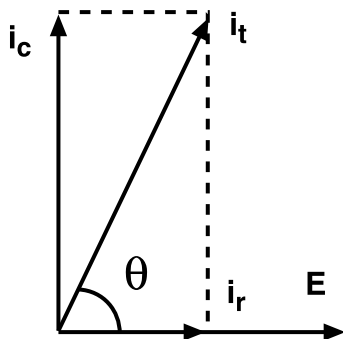


Figure 2 — Total Charging Current

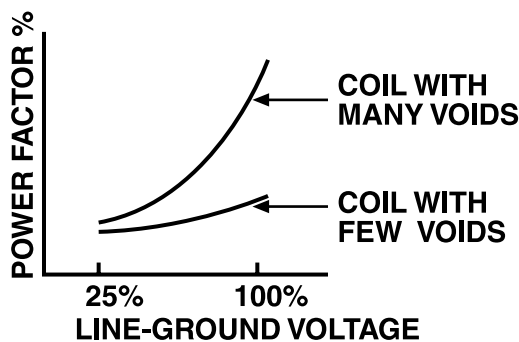


Figure 3 — A coil with few voids may have a PF of 2% at rated voltage. However with many voids a power factor of 5% to 10% may be measured at rated voltage.

line-to-ground voltage). Since all dry-type insulation systems contain voids, the power factor will increase with an increase in test voltage. The increases in power factor as a function of voltage are due to the ionization of the gas in the voids of the insulation system.

An insulation system with excessive voids will have a higher power-factor tip-up (see figure 3). Excessive voids may be due to the aging of the paper tape or of the bonding material in the insulation system. Aging of these materials leads to a reduction of physical strength and, thus, the production of voids. Once ex-

cessive voids are present, partial discharge will occur, which also damages the bonding materials. Degradation of the insulation system may occur internally or on the surface of the coil/bar due to loose coils within the slot, deterioration of the semiconductor grading paint, and/or inadequate coil spacing.

Capacitance and total charging current are also measured and recorded as part of the Doble power-factor test. These values provide important information about the physical condition of the insulation system. A change in capacitance may occur due to a change in the size, shape, or distance between the two conductors. As an insulation system cures or ages, the dielectric constant may change, causing a change in the measured capacitance and total charging current.

Applications

The power-factor test on stator windings is performed off line with either the rotor in or removed. The test may be performed in air or under sealed hydrogen at near-operating pressures. Hydrogen at pressures less than 15 pounds per square inch gauge (psig) has a lower breakdown level than air at atmospheric pressure. Water-cooled machines should be tested with the demineralized water flowing through the windings and when the conductivity of the water is less than 0.25 microsiemen per centimeter (micromho per centimeter). The dc losses associated with the water-cooling system must be subtracted from the ac losses using a specified test procedure. The test may be performed on low, medium, and high voltage machines. The initial test results may be compared with Doble's tabulated data and test results. Thereafter, test results should be compared with the previous results and the tabulated data.

The stator windings must be isolated and the neutral separated so that each phase may be tested individually. Each phase is tested to ground and then to the adjacent phase. If the neutral cannot be separated, all phases should be tied together and tested to ground.

Limitations

The power-factor test must be performed with the unit off line and with the stator winding isolated. For large machines the test set must be used with a resonating inductor in order to achieve the recommended line-to-ground test voltage. The resonating inductor extends the total charging-current range of the power-factor test set while minimizing the input current.

On a completed stator, the measured power-factor and capacitance results are an average value of the phase under test. Therefore, it may be difficult to determine if a high power factor, tip-up, or a change in capacitance is due to an overall condition or an isolated coil or coil set.

Interpretation

Power-factor analysis requires knowledge of both test circuits and the measured parameters. Each test mode involves a different portion of the insulation system. The phase-to-ground insulation test (grounded specimen test) involves mostly the coils/bars located within the slots. The interphase insulation test (ungrounded specimen test) primarily involves the end-winding insulation because the stator iron core shields the slot sections of the phases.

The recorded and analyzed parameters are:

- Total charging current
- Watts, Power Factor
- Capacitance
- Power-factor tip-up or tip-down.

The power-factor and watts values provide information about the quality of the insulation. The power factor measured at low voltage, below corona-inception voltage, is an indication of the inherent dielectric losses of the insulation system and its general condition. An acceptable power factor assures that the insulation system was manufactured with low-loss materials, processed properly, and free of contaminants. The low-voltage power factor will also provide information about the moisture content and the degree of overall cleanliness and curing of the insulation. It is common to have an elevated low-voltage power factor on a newly rewound insulation system due to uncured materials. In our experience, the power factor returns to normal typically six months later. Also, poor contact of the semiconductive slot coating with the core can be detected by an elevated low-voltage power factor.

The power-factor tip-up (or tip-down) is a calculated value, which is sensitive to the amount of void content within the insulation system. Thus, the power-factor tip-up reflects the quality of construction of the insulating system and the impregnation process. Power-factor tip-up will respond to excessive voids in the slot due to defective or deteriorated semiconductive slot coating. The continuity and condition of the stress-control coating is detectable by power-factor tip-up or tip-down. Often enough, the interphase test will exhibit a decreasing power-factor as the voltage is increased. This results in a **power-factor tip-down** and typically appears when the stress gradient paint or tape is applied on the windings as part of the insulation system. Power-factor tip-down is considered normal and should be compared with previous tests and the other two phases to monitor the condition of the stress gradient paint. Power-factor tip-up is also sensitive to delamination of the insulation due to thermal stresses and partial discharge damage.

In low-loss specimens (less than 20 percent power factor), the total charging current is nearly equal to the capacitive current. As a result, when the measured capacitance changes, the total charging current will change proportionally. Therefore, total charging current and capacitance provide valuable information about mechanical or physical changes in the insulation system. A change in capacitance with increasing test voltage of five percent or more or when compared to a previous test may indicate deterioration of the semiconducting paint or tape used to ground the coils in the slots.

Measured power factor, capacitance, and power-factor tip-up should be compared with the phases and with previous test results. For insulation in good condition, the per-phase results should be similar.

Case Study I: Power-Factor Slot Discharge

- Turbine generator: 13.8 kilovolts, 15.4 megavolt-amperes, manufactured in 1985, epoxy-mica
- Power factor: Initially very high, improved some after repairs, normal after rewind
- Power-factor tip-up: Initially very high, normal after rewind
- Capacitance: Increase with test voltage of approximately eight percent before rewind
- Analysis: Severe slot discharge, deterioration of semiconducting coating and stress gradient paint, with overall contamination.

Note: Machine rewound November, 1995.

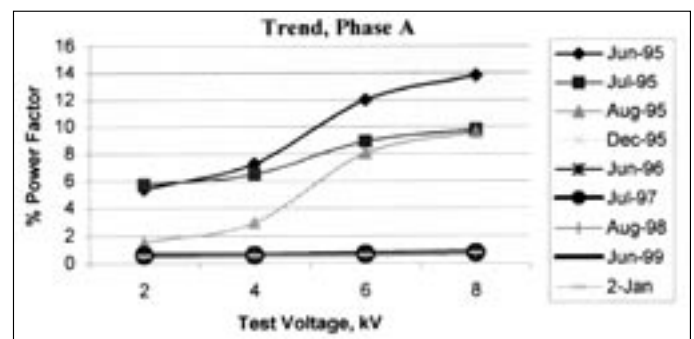


Figure 4 — Insulation to Ground Power Factor Trend, Phase A

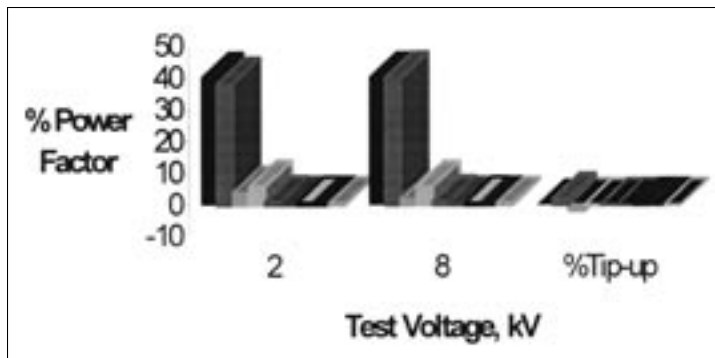


Figure 5 — Interphase Insulation Power Factor and Tip-Up Trend, Phase A

Case Study II: Power-Factor Insulation Delamination

- Induction motor: 4.16 kilovolts, 600 horsepower, manufactured circa 1980
- Initial power factor: High
- Initial power-factor tip-up: High
- After-rewind power factor: Normal
- After-rewind power-factor tip-up: Normal
- Analysis: Overall winding deterioration and delamination of insulation due to thermal stress or poor impregnation.

©OTA Field System - [Rotating Machinery Insulation Test - Overall Tests]

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Location: Special ID: ICW 20
Serial No: CCT Desig Date: May 22 2002

#	N	ENG	GND	UST	Test kV	Equip mA	10kV watts	SPF	Watt Cp(F)	SPF TipUp	RMV/C
1		WEG			2	346.10	334.23	5.66	91285		
2		WEG			2.4	346.50	353.23	10.19	91467	0.53	Before rewind
1		WOG			2	244.20	56.470	2.38	64753		
2		WOG			2.4	244.30	57.180	2.34	64789	0.01	After rewind

Figure 6 — Power-Factor and Tip-Up Results before and after Repairs

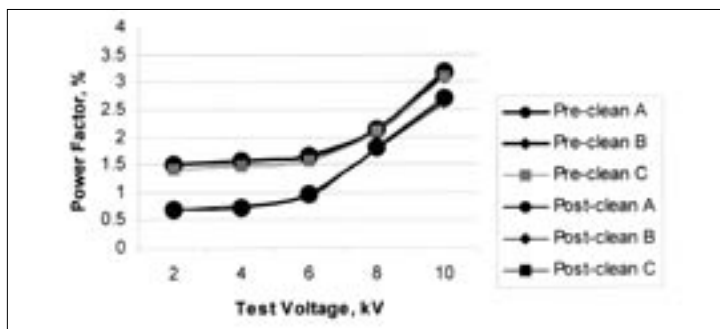


Figure 7 — Insulation to Ground Power Factor Before and After Cleaning

Case Study III: Power-Factor Effects of Maintenance

- Turbine generator: 13.8 kilovolts, 46.5 megawatts, manufactured 1972, epoxy-mica
- Percent power factor at two kilovolts before clean: Slightly high
- Percent power factor at two kilovolts after clean: Normal
- Percent tip-up before clean: Normal
- Percent tip-up after clean: Normal, but higher
- Percent power factor at two kilovolts tabulated: Less than 1.0 percent
- Percent tip-up tabulated: Less than 1.0 percent
- Analysis: Contaminated insulation

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Eileen M. Duarte received her BSEE from Northeastern University in Boston, Massachusetts in 1992. She worked for General Electric in the industrial and power services business for five years and was involved mostly with motor and generator repairs at several Apparatus Service Shops. She joined Doble Engineering Company in 1998 and is presently a Principal Engineer in the Client Service Department. She is a member of IEEE and is the Secretary of the Doble Rotating Machinery Committee.