Dielectric Losses Diagnostic Testing of Medium-Voltage Cables and Motors in Krško Nuclear Power Plant

Marko Pirc, **Klemen Grozina**
Nuklearna elektrarna Krško
Vrbina 12, Krško, Slovenija
marko.pirc@nek.si, klemen.grozina@nek.si

Nejc Friškovec
Elmont d.o.o. Krško
Cesta krških žrtev 135E, Krško, Slovenija
nejc.friskovec@elmont-kk.si

Renato Barbarić
Enconet d.o.o.
Zelinska ulica 3, Zagreb, Hrvaška
renato.barbaric@nek.si

ABSTRACT

Very low-frequency (VLF) dielectric losses or TanDelta (TD) testing is a well-established method for assessing the insulation condition of medium-voltage (MV) equipment and cables; however, conventional application requires disconnection of the cable from the equipment, increasing outage duration and testing effort. Following the publication of EPRI guidelines enabling VLF testing of motors and cables directly from cable terminations, comparative field measurements were performed at NEK to evaluate the diagnostic relevance and practical applicability of this approach. This paper presents operating experience and results from comparisons between VLF (0.1 Hz) TD measurements performed with the motor connected and conventional insulation measurements, including power-frequency (50 Hz) TD motor testing and standalone VLF cable measurements.

Measurements were conducted using full-circuit (guarded-in) and cable guarded-out configurations, allowing for the separation of cable and motor contributions without physical disconnection. Evaluated diagnostic parameters include tan delta, standard deviation of tan delta, VLF insulation resistance, capacitance, and voltage-dependent TD behavior. Due to various frequency-dependent dielectric loss mechanisms, absolute TD values measured at VLF and power frequency are not directly comparable; consequently, significance is placed on voltage-dependent indicators, particularly the tan delta tip-up value.

The VLF TD measurement method with the motor connected has been applied in a limited number of field cases. Comparison with standalone cable measurements indicates generally comparable results, with slightly higher TD values observed when the motor is connected. Provided that measured values remain within established acceptance criteria, the method is considered suitable for cable insulation assessment. Additionally, good correlation of tan delta tip-up values between VLF and power-frequency motor measurements indicates that VLF testing from cable terminations can provide a reliable and efficient approach for MV motor insulation condition assessment.

Keywords: *nuclear power plant, medium voltage cable, electric motor, testing, dielectric loss-tan delta*

1 INTRODUCTION

The VLF TD (0.1Hz) measurement method has been used at NEK for many years to check the insulation condition of MV cables. The method is well known and documented (IEEE 400.2), but its biggest drawback is that the measurement requires disconnecting the cable from the motor. Measurements of the loss angle (TanDelta) and the insulation capacity of the stator winding are also regularly performed, but at the operating frequency (50Hz). Since a very limited time is usually set in advance for testing motors and cables, sometimes due to time constraints it is not always easy to perform everything in the available time. For orientation alone, about 10 hours are usually available, 2 hours are required for disconnecting the motor, 4 hours for measuring the cable, 4 hours for revising the motor, 2 hours for measuring the motor, 3 hours for connecting the cable... And all this if there are no problems. Some activities can be performed in parallel, but it is still quite demanding to perform all as planned. Since EPRI issued document 3002013161, “Field Guide for Very Low Frequency TanDelta Testing of Medium-Voltage Motors and Cables from the Cable Terminations” [1] in 2018, NEK started testing the new method. We performed measurements with and without the motor in parallel to compare the results obtained.

This paper describes our experiences and attempts to compare the values TD measured at 0.1Hz and 50Hz.

2 TANDELTA , DISSIPATION FACTOR, LOSS ANGLE

TanDelta (tan δ, TD), also known as the loss angle or dissipation factor (DS) is defined as the ratio of the resistive (I_R) to capacitive (I_C) components of electrical leakage current is a parameter used to measure dielectric losses in insulating materials, indicating insulation health [2].

$$Tan\delta = \frac{I_R}{I_C} \tag{1}$$

Where:

I_R= resistive (loss) current
I_C= capacitive (charging) current

In an ideal insulator, the electric current passing through would only have a capacitive component, with no resistive component, due to zero impurities. Electrical energy is stored perfectly and returned without loss. TanDelta quantifies how much energy is lost as heat compared to how much is stored. It’s impossible to achieve 100% purity in insulators and over time with aging insulators accumulate impurities such as dirt and moisture. These impurities create a conductive path, introducing a resistive component to the leakage current from the line to earth.

The cable insulation can be modeled by a resistor *R* and a parallel capacitor *C*, and can be represented by an equivalent circuit as shown in Figure 1. [2]

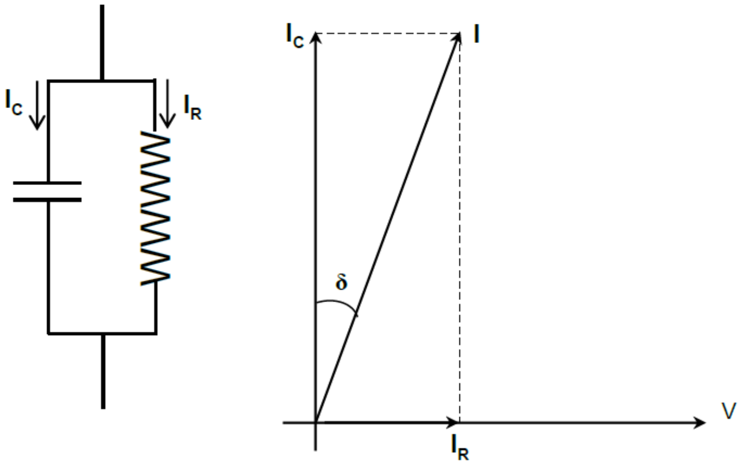

Figure 1: Equivalent Model of Cable Insulation

2.1 TanDelta for Cable

Cable insulation has low polarity and therefore exhibits little or no dissipation current. The TanDelta (TD) of a cable insulation system is given by [2]:

$$Tan\delta = \frac{I_R}{I_C} = \frac{1}{2\pi fRC} \tag{2}$$

Where:
F= frequency
R= insulation resistance
C= capacitance of the insulation.

For power cables, TanDelta is essentially independent of the applied voltage. In a good cable, TanDelta is also independent of cable length and insulation thickness because the resistance and capacitance remain in balance: as capacitance increases, insulation resistance decreases proportionally, and vice versa, keeping the TanDelta value constant so acceptance criteria are easily obtained.

2.2 TanDelta Attributes for Motors

Motor insulations are generally polar in nature and therefore exhibit significant dissipation currents. In addition, motor capacitances vary with design, as they depend on factors such as insulation thickness and type, coil and slot geometry, rated power, and operating speed. As a result of these variations and the increased influence of dielectric losses, the TanDelta expression for motor insulation systems becomes more complex than that used for cable insulation.

$$Tan\delta = \frac{I_R}{I_C} = \frac{1}{2\pi f(R_{dis}+R_{DC})C} \tag{3}$$

Where:
R_{DC} = DC insulation resistance
R_{dis} = V/dissipation current
C = Capacitance of a motor

2.3 Advantages and disadvantages of 50 Hz TD vs. 0.1 Hz TD

Medium-voltage (MV) cables operate at the industrial power frequencies (PF) of 50 Hz. In principle, dielectric dissipation factor (DS, TD) measurements on cable insulation systems should be conducted using power-frequency voltage to accurately replicate service conditions. Another advantage of power frequency TD measurements is that there are thirty years history in NEK of testing and trending results.

However, at power frequency the reactive power demand of long MV cables is exceptionally high, as it is directly proportional to the excitation frequency and cable capacitance.

To mitigate this limitation, very-low-frequency (VLF) techniques were introduced. Because the capacitive reactance of a cable varies inversely with frequency, the application of VLF test voltages results in a substantial reduction in the reactive power required for field testing. Additional bonus is reduced size, weight, and improved portability of VLF test. Additionally at low frequency, the TanDelta value is higher, and the measurement becomes easier.

3 VLF TESTING AND ASSESSMENT CONCEPTS

3.1 Test Method and Test Circuits

The VLF TanDelta testing is performed using three voltage steps 0.5, 1.0 and 1.5 times line-to-ground voltage U_0 (1,8kV, 3,6kV and 5,4kV).

To assess the insulation integrity of the entire motor circuit—including the cable, terminations, motor leads, and motor the VLF test set is connected to the cable terminations with the grounded cable shield. This arrangement ensures that the complete cable, termination, and motor insulation system is tested with respect to ground, as illustrated in Figure 2 [2].

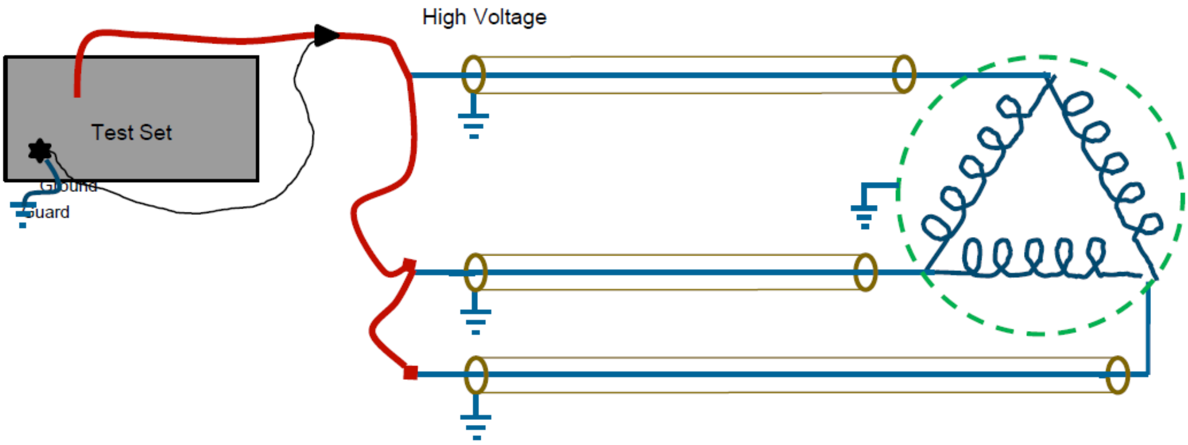

Figure 2: Guarded IN measurements, Test of entire circuit from cable terminations at circuit breaker (Cable shield grounds remain in place.)

By isolating the cable shields from ground and connecting the cable shields to the test set “guard,” the medium-voltage cable becomes part of the test set high-voltage lead and the cable insulation is removed from the test. Only the motor winding and terminations to the cable are under test. By isolating the cable from the circuit, we can get test results for the motor without disconnecting the motor. The configuration for using the medium voltage cable as a test lead ("cable guarded out") is shown in Figure 3.

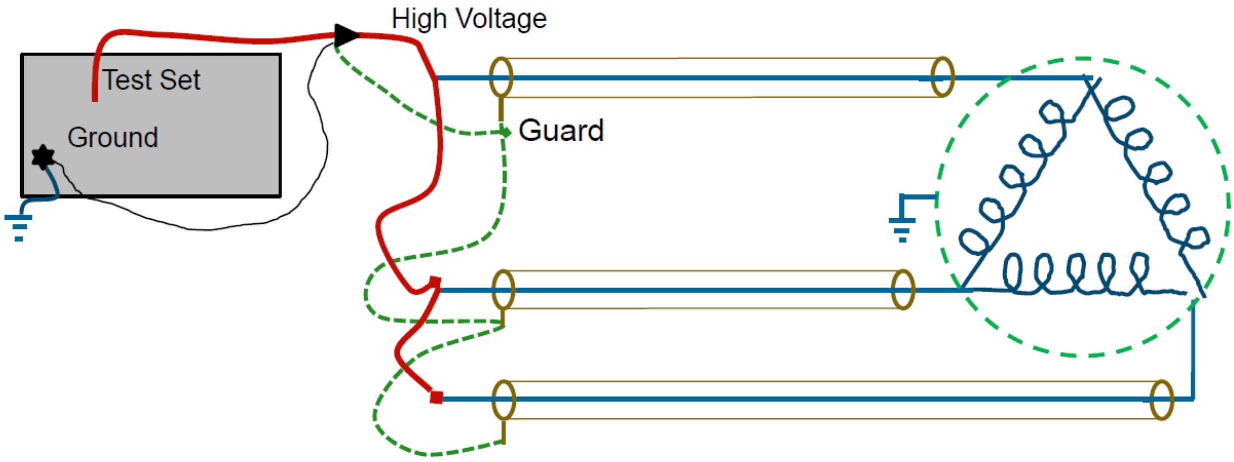

Figure 3: Guarded OUT measurements, Medium-voltage cable used as test lead, the cable phase shields are ungrounded and connected to the guard terminal of the test set.

3.2 Test result assessment

During the test several parameters are monitored: TanDelta, standard deviation of the TanDelta, VLF insulation resistance and capacitance. While each motor having a different power rating, speed, and insulation system will have a different base TanDelta because of differences in the insulation system, coil, and end turn configurations. Therefore, absolute and delta TanDelta acceptance criteria would have to be nearly motor specific so they are not used as assessment criteria.

An elevated percent standard deviation is indicative of partial discharge activity within the circuit. Even small increases in the TanDelta percent standard deviation are significant in motor circuit assessments, as cable capacitance can dampen and mask partial discharge or tracking effects that contribute to increased standard deviation values.

While the standard deviation obtained from the TanDelta test does not identify the specific location of partial discharge within the circuit, comparing results from a full circuit test (guarded IN) and a cable guarded-out test can help determine whether the source is located in the cable or in the motor leads, motor, or associated terminations. If the standard deviation is elevated during the full circuit test but remains low when the cable is guarded out, the partial discharge is likely occurring in the cable. Conversely, if a high percent standard deviation is observed in both tests, the partial discharge or tracking is attributable to the motor or its terminations.

3.2.1 VLF Insulation Resistance

VLF insulation resistance is not the same as DC insulation resistance. As the capacitive, absorptive, and polarization currents diminish during a DC insulation resistance test the value stabilizes. The variation in DC insulation resistance from one minute to ten minutes is used to get the polarization index. Under VLF conditions, the voltage is varying continuously during each 5- second half cycle. VLF insulation resistance provides valuable insights regarding the condition of motor insulation under AC stress. When AC stress is high, the VLF insulation resistance is mostly influenced by capacitive, absorptive and polarization currents. When low, the value is reflective of excessive leakage current through the insulation.

For cable insulation, the VLF insulation resistance value is closer to the DC insulation resistance value due to very limited absorption and polarization currents in the cable insulation.

Since cable and motor are in parallel connection cable VLF IR can be calculated:

$$\boldsymbol{IR_{CBL}} = \frac{\boldsymbol{IR_{MTR}} \times \mathbf{I}\boldsymbol{R_{CBL+MTR}}}{\boldsymbol{IR_{MTR}} - \mathbf{I}\boldsymbol{R_{CBL+MTR}}} \tag{4}$$

where:

$\mathbf{I}\boldsymbol{R_{CBL+MTR}}$ = VLF insulation resistance of the circuit (cable and motor) as measured

$\boldsymbol{IR_{MTR}}$ = VLF insulation resistance of the cable guarded out (essentially the motor result) as measured

$\boldsymbol{IR_{CBL}}$ = the calculated VLF insulation resistance of the cable.

VLF insulation resistance assessment criteria for motors and motor circuits:

Table 1: VLF insulation resistance assessment criteria for motors and motor circuits

Condition	**VLF Insulation Resistance with Cable Guarded Out**
Good	>25 MΩ
Further study required	20 MΩ< VLF IR <25 MΩ
Action required	20 MΩ<

3.2.2 TanDelta

Using the VLF insulation resistance obtained from both the circuit test and the "cable guarded-out" test, the cable insulation resistance can be calculated using:

$$\mathbf{C_{CBL}=C_{CBL+MTR} - C_{MTR}} \tag{5}$$

$$\boldsymbol{TD_{CBL}} = \frac{\mathbf{1}}{\mathbf{0{,}2}\boldsymbol{\pi C_{CBL} IR_{CBL}}} \ \mathbf{[10^{-3}]} \tag{6}$$

where:

$\boldsymbol{C_{CBL+MTR}}$ = capacitance of the circuit (cable and motor) as measured

$\boldsymbol{C_{MTR}}$ = capacitance of the cable guarded out (essentially the motor result) as measured

$\boldsymbol{C_{CBL}}$ = the calculated capacitance of the cable.

$\boldsymbol{TD_{CBL}}$ = the calculated TanDelta of the cable

This value represents the capacitance and TanDelta of all three phases.

If the motor VLF insulation resistance is equal to the circuit VLF insulation resistance, the calculated cable insulation resistance will be infinite, indicating that the cable insulation is in good condition. However, in this case, the tan delta value cannot be determined.

If the motor VLF insulation resistance is slightly higher than the circuit VLF insulation resistance, a finite value of cable insulation resistance can be calculated. The cable capacitance is then determined by subtracting the motor (cable guarded-out) capacitance from the total circuit capacitance.

By inserting the calculated cable VLF insulation resistance and cable capacitance into Equation (6), the TanDelta value for the cable can be obtained. However, this result may not be entirely accurate, as small errors in the VLF insulation resistance can lead to significant variations in the calculated tan delta value.

3.2.3 Standard Deviation Assessment

During tan delta testing of a motor circuit, an elevated percent standard deviation is indicative of partial discharge within the circuit. Even small increases in the percent standard deviation are significant for motor circuit assessment, as the cable capacitance can dampen and mask partial discharge or tracking effects that contribute to this increase.

It is important to note that the standard deviation of the tan delta test does not identify the exact location of the partial discharge. However, by performing both a full circuit test and a cable guarded-out test, it is possible to determine whether the source is in the cable or in the motor system (including motor leads, the motor itself, and its terminations).

If the percent standard deviation is elevated during the full circuit test but not during the cable guarded-out test, the partial discharge is likely located in the cable. Conversely, if a high percent standard deviation is observed in both tests, the partial discharge or tracking is likely occurring in the motor or its terminations.

Condition	**E-3 Standard Deviation of Tan Delta Measurements at a Particular Test Voltage**
Good	≤0.2
Further study required	0.2+ < standard deviation <0.4
Action required	>0.4

4 POWER FREQUENCY TESTING AND ASSESSMENT CONCEPTS

4.1 50 Hz motor testing

Dielectric loss measurements are routinely performed on medium voltage electric motors as part of the periodic assessment of stator insulation condition. The main objective of these measurements is to verify whether the insulation system exhibits any indication of degradation over time and to ensure consistent long-term monitoring of insulation parameters. In the observed practice, each motor is tested once every two years, which enables comparison of results between inspection cycles and supports maintenance decisions based on insulation condition trends.

Two different measurement approaches are used in practice, corresponding to two different measuring systems. Although the instrumentation differs, both approaches are based on the same diagnostic principle, namely the evaluation of dielectric losses and capacitance of the stator insulation system under applied AC test voltage. From a theoretical point of view, the insulation of a high voltage motor behaves predominantly as a capacitive system. However, real insulation is not ideal, since it also contains resistive and polarization related loss components as discussed for cable measuring. As a result, part of the electrical energy supplied during the test is dissipated in the insulation, which can be expressed through dielectric loss quantities such as dissipation factor or loss angle. These quantities are commonly used as diagnostic indicators of insulation condition. A significant increase may indicate aging, moisture ingress, contamination, void formation, or other changes in the insulation structure.

The measurements are performed at five voltage points: $0.2U_0$, $0.4U_0$, $0.6\ U_0$, $0.8\ U_0$, and U_0, [5] where U_0 is 6000 V. The use of several voltage levels enables observation of insulation behavior under gradually increasing electrical stress. This is important because certain insulation irregularities may not be equally visible at lower and higher voltages. The stepped voltage procedure therefore provides a more informative picture than a single point measurement and allows evaluation of possible voltage dependence of dielectric losses.

The voltage dependence of dielectric losses may also provide useful diagnostic information regarding the nature of insulation ageing or deterioration. If elevated dielectric losses are already observed at lower voltage levels, this may indicate the presence of more general and uniformly distributed insulation problems, such as moisture ingress, surface contamination, thermal ageing, or increased conductivity of the insulation material. In such cases, the insulation exhibits higher losses even under relatively low electrical stress, which may suggest that the deterioration affects a broader portion of the insulation system rather than a localized weak point.

In contrast, if dielectric losses remain relatively stable at lower voltages and begin to increase more significantly only at higher voltage levels, this may indicate defects that become electrically active only under stronger stress. Such behavior can be associated with localized insulation irregularities, internal voids, delamination, partial discharge inception, or other defects that are not strongly expressed at low voltage but become more pronounced as the electric field increases. An increase in dielectric losses at higher test voltages is therefore often considered more indicative of field dependent insulation weaknesses, which may require closer monitoring or further diagnostic investigation.

For this reason, it is not only the absolute value of dielectric losses that is relevant, but also their trend across the applied voltage range. A stable response over all voltage points generally indicates consistent insulation behavior, while a nonlinear increase with voltage may lead to developing insulation defects. The interpretation must nevertheless consider the specific motor design, measurement configuration, and historical measurement records, since reliable assessment is based primarily on comparison with previous results obtained under similar test conditions.

In practical field conditions, the measurements are not always performed under the same connection arrangement. In some cases, the test is carried out directly at the motor terminals, while in other cases it is performed from the switchgear cell, with the cable section included between the measuring system and the motor. This distinction has an important influence on the measured capacitance values. When the cable is included in the test circuit, the total measured capacitance is higher, which is expected due to the additional capacitive contribution of the cable. On the other hand, deviations in dielectric losses are generally not observed in regular testing practice, regardless of whether the measurement is performed directly at the motor or through the cable. This indicates that the tested motors usually do not show pronounced insulation deterioration in terms of dielectric loss behavior, while the difference in capacitance is mainly a consequence of the measurement arrangement itself.

From the diagnostic perspective, the value of these measurements lies primarily in their repeatability and comparability over time. Since noticeable deviations in dielectric losses are usually not present, the method serves mainly as a periodic confirmation of stable insulation condition and as a means of identifying possible future changes. At the same time, the results clearly show that the test configuration must be considered during interpretation, especially in relation to capacitance values, which are systematically higher when the cable is included in the measurement circuit.

5 COMPARISON OF RESULTS

The VLF tan delta (dissipation factor) cable measurement method with the motor connected has been applied approximately twenty times to date. A comparison of tan delta values obtained from standalone MV cable measurements (with the motor disconnected) shows good alignment with the values measured with the motor connected. The measured tan delta values are typically 10–30% higher, which remains within a conservative margin and therefore acceptable.

It should be noted, however, that when measurements are performed with the motor connected, the result represents an average value of all three phases. Consequently, there is a theoretical possibility that a defect or degradation in a single phase may be masked by the phase averaged result, but until calculated values are way below the acceptance criteria are considered acceptable.

At present, NEK is considering the option that, for selected MV power cables that are not installed in an adverse environment and do not supply safety related (SR) loads, standalone cable testing may be discontinued. Instead, measurements would be performed using a combined cable and motor test configuration, with the objective of optimizing MV cable diagnostic activities.

If the evaluated measurement results exceed the defined acceptance criteria, a standalone cable measurement (with the motor disconnected) will be required to precisely localize and determine the source of the insulation issue.

Since the two measurement methods are performed at different test voltages and with a different number of voltage steps, the 50 Hz power frequency tan delta results were interpolated so that the dissipation factor values could be evaluated at the same voltage levels as those applied during the VLF (0.1 Hz) tan delta measurements.

When comparing motor tan delta values, it must be considered that the measurements are conducted at different test frequencies. According to the frequency dependency expressed in Equation (1), tan delta values measured at VLF would theoretically be approximately 500 times higher due to the 500 times lower frequency compared to power frequency testing. In practice, however, due to complex dielectric behavior, winding losses, and additional loss mechanisms within the motor, the observed differences are significantly smaller[4]. For this reason, a direct comparison of absolute tan delta values is not meaningful. As stated in [3], the standard deviation of tan delta and the VLF insulation resistance are considerably better indicators of the condition of motor insulation systems.

Because motor measurements are sometimes performed directly at the motor terminals, and in other cases at the breaker or switchgear termination points, measurements that include the MV cable tend to attenuate the motor response and result in lower measured tan delta values. Therefore, particular care must be taken when interpreting the results. While absolute dissipation factor values may vary significantly, the tan delta tip up value (Δtan δ between 20% and 100% of rated test voltage), which is used as the primary acceptance criterion, is substantially more stable and reliable.

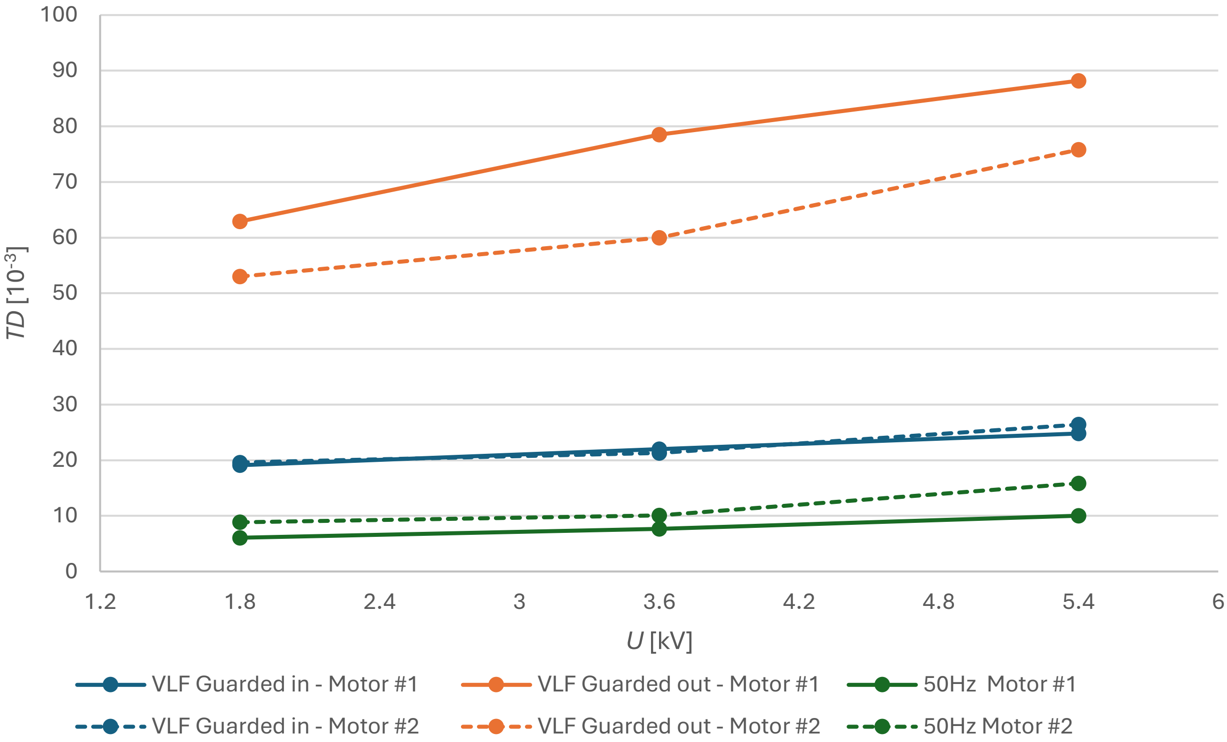

Figure 4: Comparison of VLF and PF TD results for two motors that are connected by cable with measurements taken at the breaker box.

In figure 4 is clearly visible that although TD values differ in absolute values for VLF Guarded in and 50 Hz, the tip-up is similar because results in both cases are “dumped “with cable capacitance. In figure 5 there is also visible similarity between tip-up values of VLF Guarded out and 50 Hz measurements.

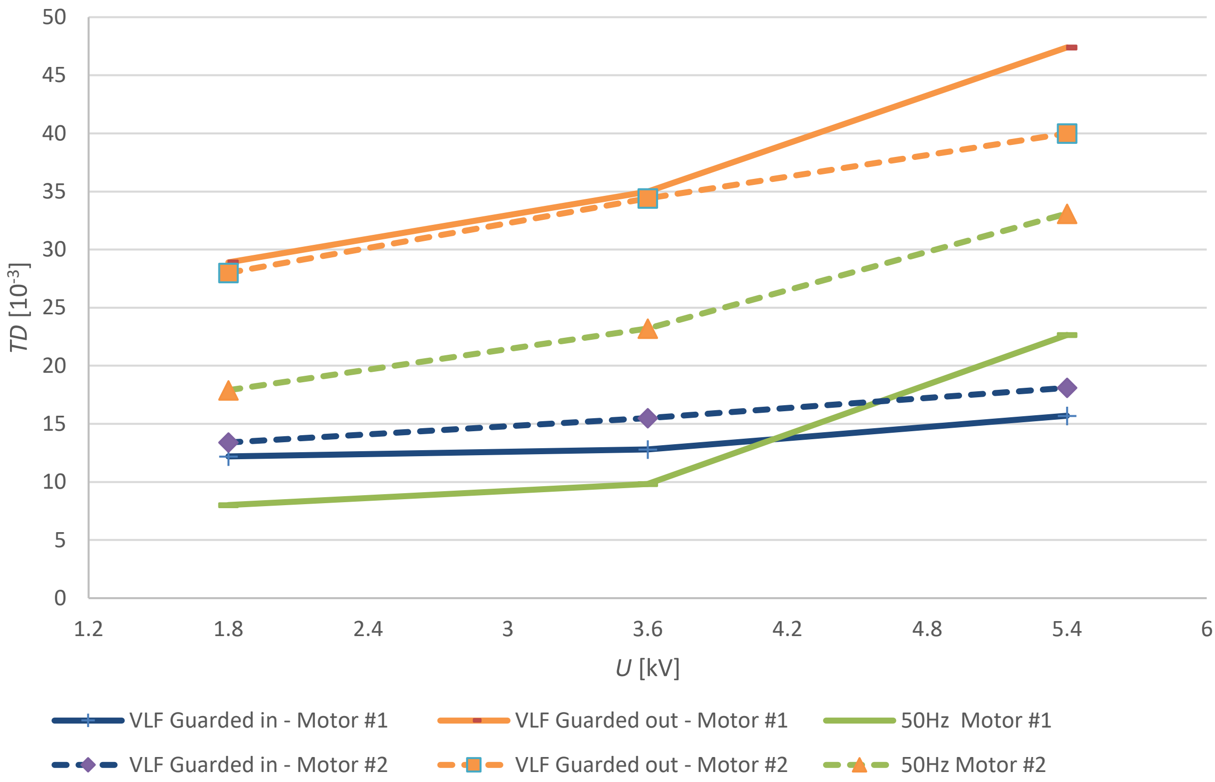

Figure 5: Comparison of VLF and PF TD results for cables with connected motor and two disconnected motors.

A comparison of VLF and power frequency measurement results leads to several conclusions. When comparing measured capacitance values, good agreement is observed provided that comparable measurement configurations are used - Guarded IN measurements compared with motor measurements performed from the breaker cubicle and Guarded OUT measurements compared with measurements conducted directly at the motor terminals.

6 CONCLUSION

It is anticipated that the tan δ (TanDelta) values measured at very-low frequency (VLF) will be relatively higher, as the capacitive charging current is generally lower at such frequencies. This is because capacitive reactance experiences a substantial increase as frequency decreases. Additionally, the resulting tan δ values are influenced by the fact that polarization loss in insulating materials tend to decrease at extremely low frequencies. Consequently, the tan δ value measured at 0.1 Hz does not scale linear to the higher measured frequency at 50 Hz.

The relationship between tan δ and frequency is not a simple inverse proportionality, as it is influenced by frequency-dependent polarization loss, which are notably prevalent in motor insulation systems. Additionally, the frequency-dependent breakdown mechanisms and the applied electric field both influence the ionization losses associated with dielectric breakdown.

The capacitance measured at both frequencies is identical in the limited scope of all measurements that have been conducted. However, it is important to exercise caution and compare the correct values, as the 50 Hz motor is occasionally measured with the cable connected and sometimes without, depending on the available configuration. The absolute TanDelta values' ratio is highly dependent upon the motor type and the measured configuration, ranging from 1.2 to 3.5. These figures are consistent with the comparison of TD measurements on VLF and power frequency, which showed that the results on VLF were 2-3 times higher than results at 50 Hz.

As of today, we have a limited amount of data (approximately 20 measurements have been conducted) and approximately half of them can be compared to measurements at 50Hz solely on the motor and the other half to measurements from the breaker cell. In the future, when a greater number of measurements are collected, an attempt will be made to establish a direct quantitative correlation between the overall dielectric losses measured at VLF and those at power frequency for each type of motor.

These preliminary findings demonstrate that the primary parameter utilized to evaluate the insulation condition of a motor (the tip-up value) is in good alignment with the results of VLF measurements, as determined by 50 Hz TD motor measurements.

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