

# Simulating Insulation Systems Under Various Environmental Conditions in the Laboratory

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**Abstract** – Over the last century as electrical motor testing became prominent in industry, little research has been published on simulating insulation systems in various environmental conditions such as moisture and contamination that are found in the field. In this paper, summary results of research performed using simulation software to simulate insulation systems in various environmental conditions that may be experienced in the field are presented. All simulations are based on actual nominal Insulation Resistance Profiles (IRP) obtained during a standard Polarization Index (PI) Test on motors (not containing stress graded systems). Once a nominal profile is obtained, the effects of changing various parameters of the standard insulation system model such as resistance-to-ground, and capacitance-to-ground, to simulate various environmental conditions are examined. Lastly, simulation results are compared to actual field case studies using some of the four basic Insulation Resistance Profiles (Nominal, Moisture, Contamination, and Embrittlement).

**Key Words:** *Insulation Resistance, Polarization Index, Megger, Resistance-to-Ground, Insulation Resistance Profile (IRP)*

## I. INTRODUCTION

Insulation systems are typically represented using the schematic as found in the IEEE 43 Standard. Recent research has led to modifications of the equivalent circuit to better represent the complex system of absorption currents by adding multiple current paths (R4-R6 / C2-C4 as shown in Figure 1). For practical purposes, only three branches of absorption currents are shown and will be discussed later in this paper.

Using the modern equivalent circuit, we will examine the Insulation Resistance Profile (IRP) and how various insulation system conditions may be simulated by modifications made to it. To study these, a nominal profile which represents a system with no degradation will be simulated. Once a nominal profile is obtained, various parameters will be modified to represent various conditions.

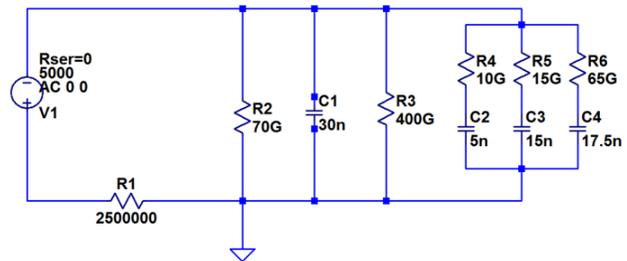


Figure 1. Insulation System Equivalent Circuit simulating a system with a Nominal Profile.

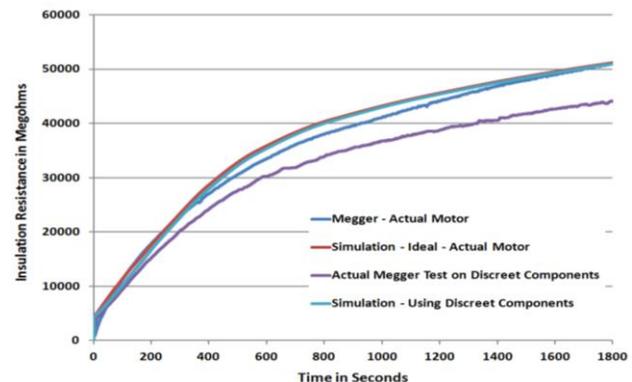


Figure 2. IRP comparison of field test data with that from a simulation.

In our study of what effect various conditions have on the profile, it is important to note that one property of all insulation system measurements is that they will resolve (exponentially approach an asymptotic resistance level equivalent to the parallel combination of R2 and R3 of Figure 1) to that of an RC charging circuit. Examination of the equivalent circuit demonstrates the currents in the absorption current branches and the capacitive branch all approach zero in the time limit. Given sufficient time, the remaining branches are the leakage and conduction current branches. Together, these determine the final current, and thus, the final (asymptotic) resistance the IRP will approach in the time limit.

Using an asymptotic approach concept, and in contrast to the IEEE 43 standard, IRP analysis may be applied to small integral horsepower motors with random windings, whereby,

the IRP may resolve within one or two minutes rather than the standard 10 minutes which is typically used to calculate the PI value. Large motors of hundreds to thousands of horsepower may require much longer time periods such as one or more hours for the IRP to resolve. Thus, when obtaining an IRP as an initial baseline, a user should take into consideration the time frame involved in resolving the IRP.

To determine a time frame for resolution we must first define resolution. Resolution will typically be assumed to be equivalent to the engineering standard of five time constants (from charging circuit theory), which represents a system charge to within 1% of the final resistance value. For example, in the IRP shown in Figure 2, the IRP continues to approach its asymptotic value even after 1800 seconds (30 minutes). Although preference is given to new or newly reconditioned insulation systems, a full profile may be done at any time and only involves applying the Insulation Resistance (IR) test long enough for the resistance measurement to approach a final value (assumed to be five time constants).

## II. COMPONENTS OF THE SIMULATION CIRCUIT

Insulation Resistance Profiles of healthy insulation systems consist of four primary components of the current. These four components are: Surface Leakage ( $I_L$ ), Geometric Capacitance ( $I_C$ ), Conductance ( $I_G$ ), and Absorption Current ( $I_A$ ). These components are affected in different ways by the presence of moisture, contamination, embrittlement, temperature, and the insulation condition itself. See Figure 3.

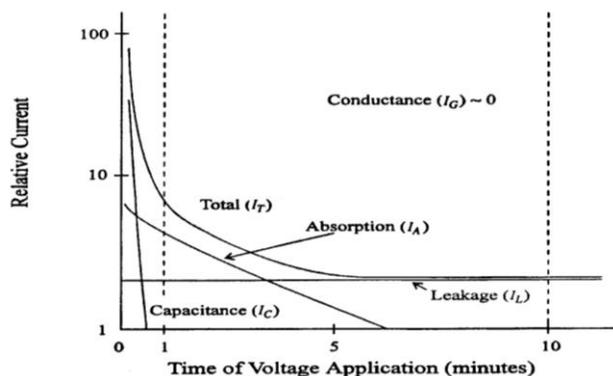


Figure 3. Four Primary Components of the Test Current

### A. Series Resistance

Series Resistor ( $R1$ ) – Internal impedance of test equipment and will vary between testers. For our simulations, we will use 2.5 Megohm.

### B. Surface Leakage Current ( $I_L$ )

Shunt Resistor ( $R2$ ) — represents leakage current across the surface of the insulation system. This shunt resistance is the dominant factor in determining the overall asymptotic

(final) resistance. Presence of surface moisture and/or contaminants will reduce the overall insulation system resistance seen as a reduction in the value of  $R2$ . To select a value for simulation, use the final system resistance to start with and modify as necessary.

### C. Geometric Capacitance ( $I_C$ )

Shunt Capacitor ( $C1$ ) – represents the geometric capacitance of the insulation system and is fixed with respect to the structure of the system. Although variations in surface moisture, contamination, and temperature changes may appear to change this component in the profile, the capacitive branch will only vary due to changes in its dielectric permittivity given the assumption there are no changes in either the dielectric thickness ( $d$ ), surface area ( $A$ ), or number of plates ( $n$ ). In practice, a change in capacitance only tends to happen when an insulation system becomes embrittled. Although not presented in this paper, our simulations show that modifying the capacitance (without changes in the other branches) has only a small affect on a profile and that it typically takes orders of magnitude changes to have a significant effect on the overall profile. For simulations, start with a value near the measured capacitance to ground. Typically, this will be in a range of 1nF to 1000nF.

### D. Conductance ( $I_G$ )

Conduction Component ( $R3$ ) – Represents the insulation system conduction current. On a molecular level, this current represents the infinitesimal charge migration through the insulation system itself. This component is typically very high in value and is typically a negligible component of the insulation system. For simulations, use a value at least 10 to 100 times that of the leakage resistance.

### E. Absorption Current ( $I_A$ )

Absorption Components ( $R4-R6/C2-C4$ ) represents the absorption current and has a dominant affect on the IRP. Absorption current modifies the rising part of the nominal profile. Although actual insulation systems should be represented by many “branches” of absorption currents, it was found that, typically, three components are the minimum required from a practical point of view needed to simulate the absorption current due to their affect on the Slow, Medium, and Fast portions of the profile. For simulations, start with values approximately 1/10 of those used for the leakage resistance and capacitance.

### F. Adjust Component Values

Once initial values for these components are chosen, modify the values so the IRP of the simulation fit that of the actual measured IRP. For moisture or contamination, addition of voltage (or current) sources in some of the branches may be necessary (as shown throughout this paper).

### III. SIMULATING ENVIRONMENTAL CONDITIONS

#### A. Moisture

When surface moisture is present, the apparent overall insulation system resistance decreases as shown in the comparison graph of a nominal profile versus an IRP of a system containing moisture (Figure 4). This decrease in the overall insulation system resistance is represented by a decrease in the resistance of the moisture component (R2). As the insulation system charges, the IRP will approach the parallel value of R2 (leakage) and R3 (conduction) far more quickly than when there is no moisture present. It should be noted the conduction component (R3) has a negligible affect due to it being much higher resistance than the leakage current component (R2). The absorption branch (R4, R5, and R6) is also heavily affected due to the inability of the insulation system to polarize, the absorption currents decrease as shown in Figure 5. As seen in the simulation circuit (Figure 6), which is a modified version of the circuit shown in Figure 1, the absorption current component (R4-R6 & C2-C4) values are dramatically decreased, and thus, represent a significant decrease in the absorption current in the presence of surface moisture. Note that voltage sources V3-V5 were added to account for the variability in the absorption currents with the final simulation being shown in Figure 7.

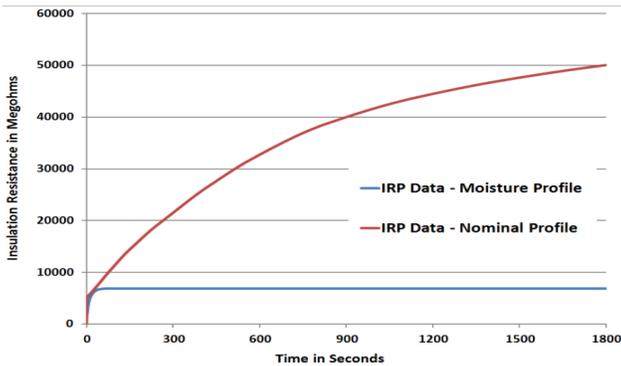


Figure 4 – Nominal vs. Moisture Profile.

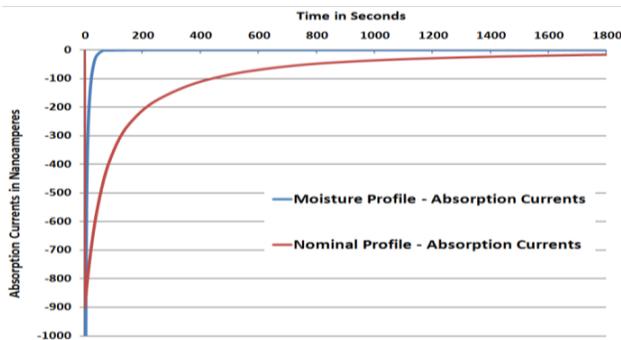


Figure 5. Absorption Current comparison between an insulation system with a nominal profile and one that represents moisture.

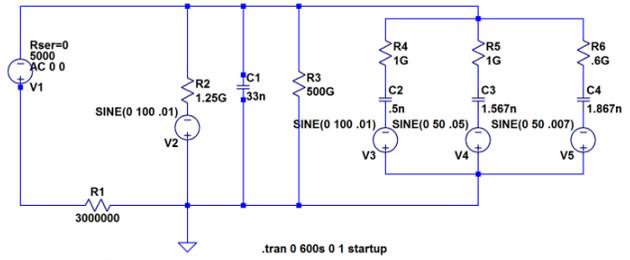


Figure 6. Simulation Circuit of Moisture

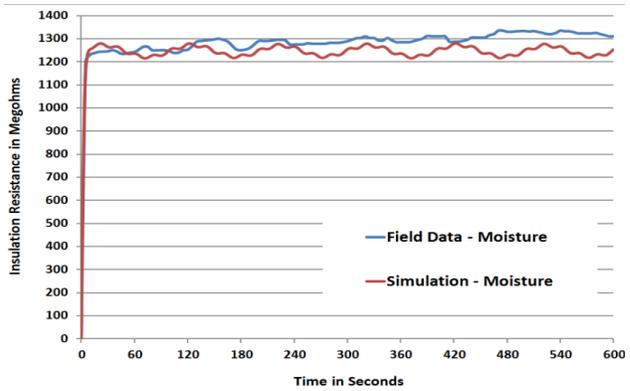


Figure 7. Simulation Plot of Moisture with voltage sources.

#### B. Contamination

Due to limitations of the simulation software, mild contamination is represented by an additional AC voltage (or current) source in series with the leakage current component R2. To model insulation systems with heavy, highly erratic, contamination requires voltage sources in the absorption current branches (Figures 8 and 9). It should be recognized that due to software limitations only sinusoidal sources were available for the simulations presented in this paper. In a more properly represented simulation, a white noise source would be used instead of an AC voltage source. Physically, the white noise source would represent the randomness of charge movements and polarizations/de-polarizations and their affect on the IRP.

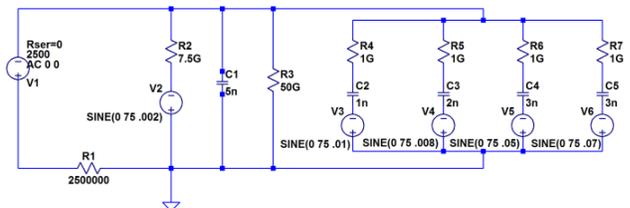


Figure 8. Simulation Circuit of Contamination with an additional voltage source due to variability in the IRP.

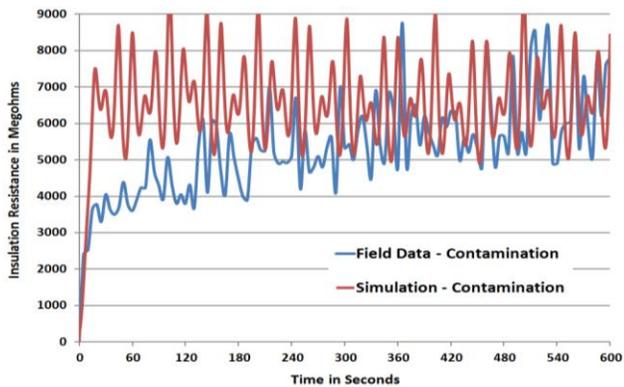


Figure 9. Field data compared with simulated data of a system containing heavy Contamination.

### III. FIELD CASE

In March 2005, an Induced Draft (ID) fan motor tested in the field had an IRP showing moisture and slight contamination. A simulation was performed and presented on the same chart as the original data (Figure 10). To more closely model this situation, two additional leakage current branches with voltage sources were added due to the fact that modifying the absorption current branches had little effect on the IRP in this case (Figure 11).

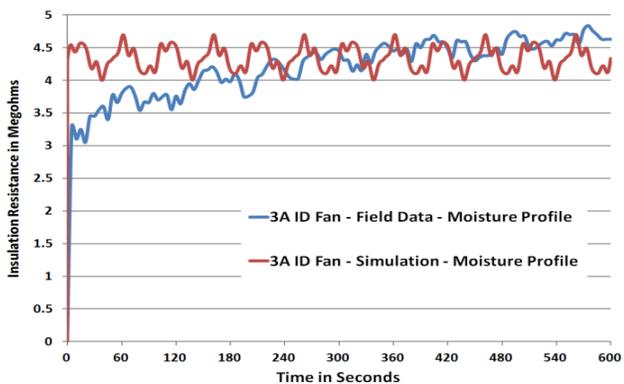


Figure 10. 3A ID Fan – Moisture Profile

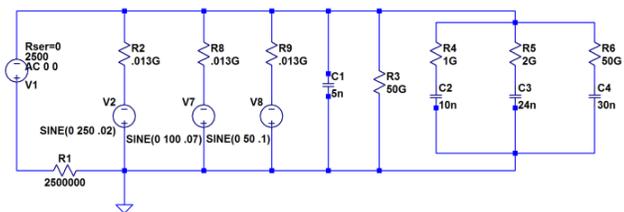


Figure 11. 3A ID Fan – Moisture Profile



Figure 12. Condition that caused the unacceptable IRP

Causal analysis determined that condensation around a cable entrance was the culprit (Figure 12). The area around the cable entrance was dried and resulted in the IRP shown in Figure 13 which resembles a nominal profile. The system was then simulated using the nominal profile with the results shown in Figure 14. Note the removal of the additional leakage current paths and voltage sources, yet, the absorption current branches remained the same for both simulation models.

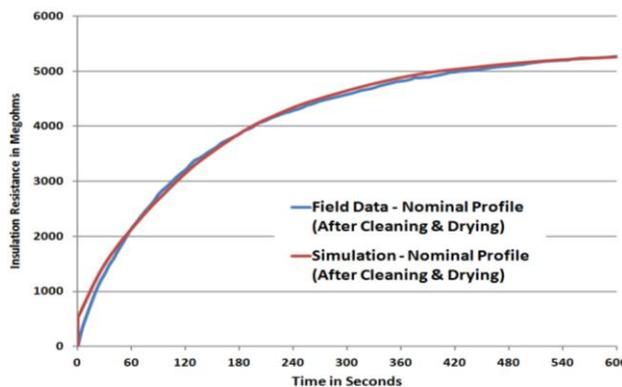


Figure 13 – 3A ID Fan – Nominal Profile

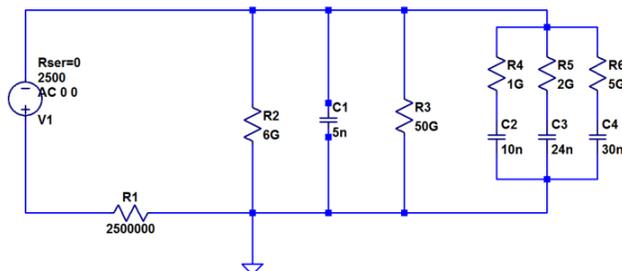


Figure 14. 3A ID Fan Simulation Circuit – Nominal Profile

#### IV. SUMMARY

Simulation of insulation systems under varying conditions may aid in developing or further developing new diagnostic techniques such as the frequency response. Simulation techniques and use of the RC time constant may also lead to optimizing IR measurements from a time and cost benefit viewpoint.

Although three absorption current branches may be used for many models, additional branches may be needed to better model highly erratic situations such as heavy contamination.

In contrast to the IEEE 43 standard, IRPs may be applied to all sizes of motors and insulation systems. A major consideration is the asymptotic approach to a final value represented by a combination of the leakage resistance and the conductance of the insulation system.

Our simulations and case studies involved steady state temperatures during the measurements or simulations. Variations in temperature will also affect the profile requiring future research into additional modifications of the equivalent circuit to represent their affect on the IRP.

It is not a recommendation of this paper to extend PI/IRP testing until reaching five time constants for all cases; the intent is only to create awareness of this property when testing and during the analysis of the insulation system condition.

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#### AUTHOR



**David L. McKinnon** received his BS in Electrical Engineering from New Mexico State University in 1991 and a MBA from the University of Phoenix in 2002. He has worked in the field of magnetics for over 20 years. During the past ten years, he has worked for PdMA Corporation as a Project Manager for product development of motor test equipment. He is currently chair of the P95 Working Group and actively participates in over a dozen standards working groups and the materials subcommittee.