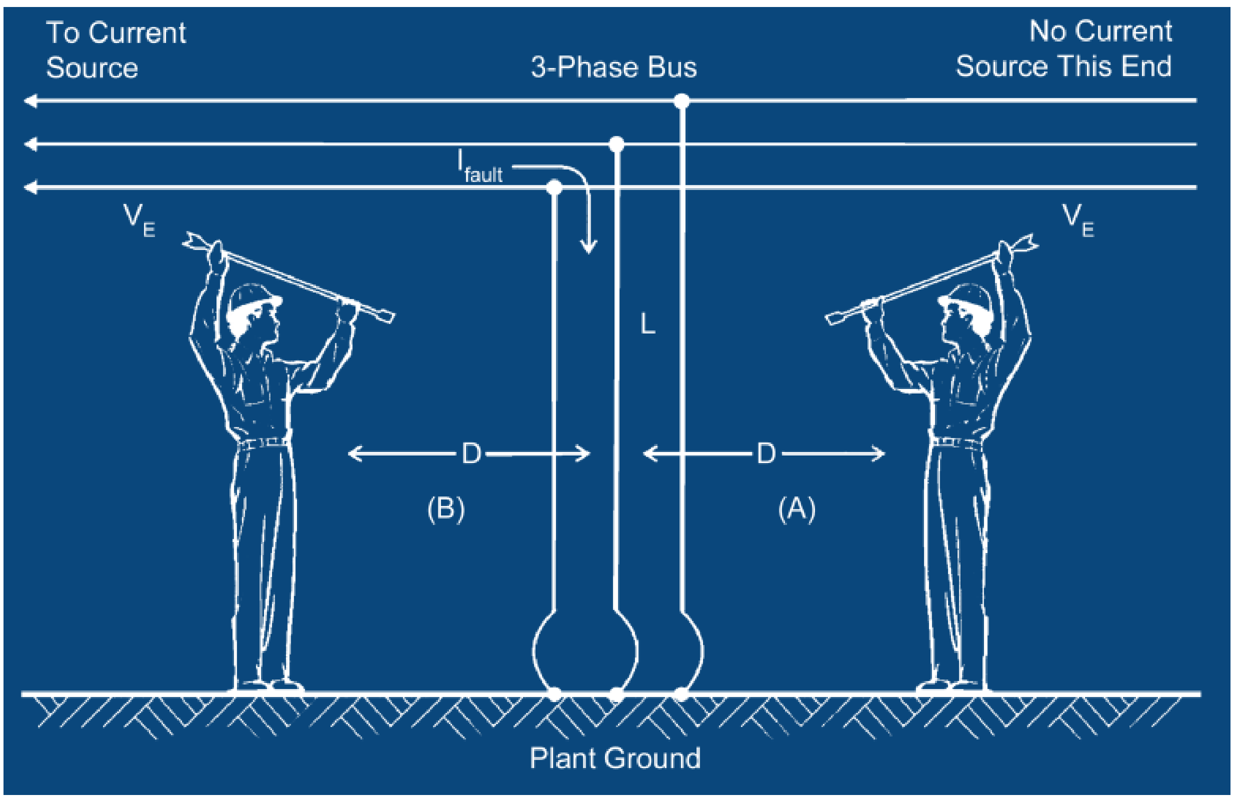
RECLAMATION

Managing Water in the West

Power System Safety

Research and Development Office
Science and Technology Program
(Final Report) ST-2017-613-00



U.S. Department of the Interior
Bureau of Reclamation
Research and Development Office

September 29, 2017

Mission Statements

Protecting America's Great Outdoors and Powering Our Future

The Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

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14. ABSTRACT Power system safety is formulated to develop solutions for personnel safety in Reclamation electrical power generation and other supporting facilities. The research is aimed at preventing personnel injuries and reducing/eliminating potential damage to equipment. Specific task included looked at personal protective grounding procedural improvements, improved worker safety for hands-on electrical maintenance work, and the prevention of the misoperation of ground switches.

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Power System Safety

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Executive Summary

Recent injuries at Bureau of Reclamation (Reclamation) powerplants demonstrate the dangers plant personnel face when working with high power, high voltage electrical systems found at Reclamation facilities. These incidents demonstrate that there is room for improvement in Reclamation's safety program, specifically safety related improvements to Reclamation's maintenance program as well as additional engineering barriers to prevent misoperation of equipment. This research program looked at personal protective grounding (PPG) procedural improvements, improved worker safety for hands-on electrical maintenance work, and the prevention of the misoperation of ground switches.

The Hydropower Diagnostics and SDADA Group (86-68450) actively supports Reclamation field personnel in the application of PPG used during electrical maintenance work. This includes nearly two decades of research into the optimal placement of PPG. This research program helped complete technical transfer efforts outlining the engineering equations and calculation methods used to determine the optimal placement of PPG. Two summary papers where published in IEEE Power and Energy Technology Systems Journal and a detailed hard cover book was published and made available on Reclamation's Science and Technology internet site.

The recent burn injury at a Reclamation Powerplant demonstrated the dangers of manual operation of ground switches in powerplants. If a ground switch is closed into an energized circuit, the resulting arc flash can injure employees and damage equipment. This research looked into additional engineering barriers that could be implemented to help prevent this type of incident in the future. Specifically it examined the use of a passive voltage detection device that can be used to indicate if a bus is energized as a final safety check before a ground switch is closed.

A contributing cause of the incident referenced above was that the protection circuits were disabled. This demonstrated a weakness in Reclamation's safety program in that often times hands-on maintenance work is being performed on equipment at the same time protection system testing or maintenance is being performed. Hands-on maintenance work requires that PPG be installed. The sizing of these grounds is based on the magnitude of fault current and that the protection system quickly senses the fault and opens the fault source. Herein lies the problem; if the protection system is disabled to do maintenance, it will not quickly sense the faults and thus the personal protective grounds will not adequately protect the workers. This research project developed additional safety procedures that were published in Reclamation's Power Equipment Bulletins to help prevent this type of incident in the future. A PowerPoint training module was developed and a webinar for Reclamation personnel was conducted to help plant personnel understand the issue.

The program research goal is to improve the safety and reliability of Reclamation powerplants and bring solutions to industry via technology transfer. Avoiding personnel injury(s) or death(s) is the highest priority of any organization. Improving personnel safety and reducing facility operation and maintenance (O&M) costs are all an evolving problem set and additional research looking into improving power system safety will continue to be necessary.

Contents

Introduction

Recent injuries at Bureau of Reclamation (Reclamation) powerplants demonstrate the dangers plant personnel face when working with high power, high voltage electrical systems found at Reclamation facilities. These incidents demonstrate that there is room for safety related improvements to Reclamation's maintenance program as well as additional engineering barriers to prevent misoperation of equipment. This research program looked at personal protective grounding (PPG) procedural improvements, improved worker safety for hands-on electrical maintenance work, and the prevention of the misoperation of ground switches.

Personal Protective Grounds

The Hydropower Diagnostics and SDADA Group (86-68450) actively supports Reclamation field personnel in the application of Personal Protective grounds (PPGs) used during electrical maintenance work. This includes nearly two decades of research into the optimal placement of PPG. This research program helped complete technical transfer efforts outlining the engineering equations and calculation methods used to determine the optimal placement of PPG. A brief summary to this topic is as follows:

> The electric power industry has, for a long time, recognized the need for grounding de-energized, high voltage power lines and equipment for bare-hand contact during maintenance or construction activities. Grounding of the line or equipment conductors is typically accomplished by applying PPG according to the utility's procedure to create a safe, equipotential work zone. However, in practice, the various conductive parts of the work zone are rarely at the same potential when an accidental re-energization occurs. This is due to voltage drops in the fault current carrying conductors, both PPG and the grounded equipment, which cannot be avoided.
>
> As stated in the Institute of Electric and Electronic Engineers Standard No. 1246-2011 [1] (IEEE 1246), historically, the PPG cable resistance was placed in parallel with the worker's body to calculate current through the body during an accidental energization of a grounded worksite. The PPG cable resistive *(IR)* voltage drop resulting from the alternating current (ac) power system available short-circuit current was the key factor in determining worker touch voltage and body current. Recent modeling of grounded worksites, and laboratory and field testing (see IEEE 1246, Section 7, "Model Comparison with Field Test Data"), demonstrated that the PPG cable reactive *(IX)* voltage drop often is a significant component of the worker touch voltage and body current.
>
> Grounded worksites inherently produce a reactive voltage drop (touch potential) when PPGs conduct ac short circuit current. Induction ground loops are typically formed by the PPGs, grounded line or equipment conductors, and a current return path between PPG and worker. The worker completes the ground loop circuit by touching a grounded conductor (intentionally grounded by PPG) and another grounded object at the worksite. The induction ground loop creates the reactive *IX* voltage drop exposure to the worker.

The combined resistive and reactive voltage drops of a PPG cable can be several times higher than the resistive voltage drop alone. Therefore, the PPG effective ac impedance (not only resistance) should be considered for realistic worker exposure evaluation. This situation led to the development of PPG composite impedance, which accounts for the physical layout of the PPGs at the grounded worksite. To simplify the calculation of the PPG impedance, the PPG impedance K-factors were introduced. The use of the K-factor to predict worker touch voltage modifies the historic method of calculating PPG resistive (IR) voltage drop by including the additional effects of reactive voltage drop of the PPG cable. Worker touch voltage may be approximated using the following equation:

$$Vt = If\ x\ Rc\ x\ K$$

where

Vt is the touch voltage, Vrms
If is the available short-circuit current, kA rms sym.
Rc is the PPG cable resistance (excluding clamps and ferrules), milliohm
K is the PPG impedance multiplier

Application of K-factors for the worker touch voltage calculation procedure is covered in IEEE 1246. However, explanation of magnetic induction concepts and derivation of equations is limited, and additional explanation is provided in the following three references published under this research project:

1. *Temporary Protective Ground Cable Impedance K-Factors for Predicting Worker Touch Voltage* [2],
2. *Temporary Protective Ground Cable Impedance K-Factors for Predicting Worker Touch Voltage–Basic Single-Point Grounding (1 of 2)* [3], and
3. *Temporary Protective Ground Cable Impedance K-Factors for Predicting Worker Touch Voltage—Bracket Grounding (2 of 2)* [4]

Passive Voltage Detection

Powerplants present many hazards to the people working in them. In the vast majority of accidents, hindsight shows that most incidents could have been avoided. Many such accidents around high-voltage equipment often arise due to the mistaken belief that the equipment is no longer energized. At first glance, these seem to be the easiest accidents to avoid, yet they still persist within the power industry and within Reclamation. For example, the recent burn injury at a Reclamation Powerplant demonstrates this danger. Passive voltage detection devices have been used in recent years to hedge risks of accidents such as these. The goal of such a device is to give clear indication of the presence of voltage, while being self-contained (bird on a wire), passive (no batteries or external source, and no need to tap into conductor for power), and reliable.

One such device that meets this goal and is commercially available is the VisiVolt™ by ABB Group. The VisiVolt™ is completely passive and consists only of an LCD screen and a single surface mount antenna. The antenna produces a voltage and activates the liquid crystals in the LCD screen in the presence of a strong electric field. LCD crystal activation controls light reflection from the back surface of the display producing the image of a lightning bolt. Because the strong electric field that causes the image to be produced is a result of high-voltage potentials, the lightning bolt only appears when equipment is energized. It is important to note, however, that while the VisiVolt™ is good evidence of energization, it should not be used as proof of de-energization for switching or maintenance work. For switching and maintenance work, de-energization can only be obtained following the facility Hazardous Energy Control Program (HECP) as described in FIST 1-1. For maintenance work, proof of de-energization can only be established by testing for the absence of nominal voltage using a recently tested indicating type detector, and the application of personal protective grounds as described in FIST 5-1.

A project notes report developed under this research project entitled *ABB VisiVolt™ Applications and Limitations* [Appendix A] explores some of the advantages and limitations of the VisiVolt™, specifically in relation to power system safety.

Protective Relaying and Hands On Electrical Work

Electrical equipment rated above 600V is not considered de-energized and safe for work until proper personal protective grounding is applied. PPGs are sized based on available fault current and relay clearing time to isolate any energy sources in the event of inadvertent energization. The equipment is not properly grounded if the relay protection scheme utilized in sizing the grounds is disabled. Guidance to avoid this situation was developed under this research project is provided in *Power Equipment Bulletin No. 57- Safety Issues Associated with the Configuration Management of Protective Relaying and Hands on Electrical Work* [5]. A PowerPoint training module was also developed and a webinar for Reclamation personnel was conducted to help plant personnel understand the issue. An internal copy of this material can be found at http://intra.usbr.gov/power/training/index.html.

The purpose of this document is to provide Reclamation Power Facilities with information concerning the safety risks associated with performing electrical 'hands-on' work that requires the installation of PPGs concurrent with activities that may impact the correct operation of the protection system. To avoid a potential electrocution safety hazard, activities that impact the correct operation of the protection system should not be scheduled or performed concurrent with electrical 'hands-on' work. If this is not possible, alternative clearance and grounding procedures are available that avoid this hazard, but additional engineering analysis may be required.

Recommendations for Next Steps

The program research goal is to improve the safety and reliability of Reclamation powerplants and bring solutions to industry via technology transfer. Avoiding personnel injury(s) or death(s) is the highest priority of any organization. Improving personnel safety and reducing facility operation and maintenance (O&M) costs are all an evolving problem set and additional research looking into improving power system safety will be necessary. Suggested new areas for research into power system safety include the following:

1. Improved worker safety while turning rotors - There are various situations when the rotor of a generator must be slowly turned (such as during generator tests or unit alignments). Presently, this is typically accomplished by personnel entering the generator rotor area and physically pushing on the spider arms. This places personnel in a hazardous location as the rotor is being spun, and exposes personnel to stress and strain related injuries. The rotor momentum, even at very slow speed, will crush anything that gets in its way. Severe injury or death could occur if a person pushing on the rotor were to slip or get stuck in a pinch point. This research task will focus on improving an electrical method to slowly rotate the rotor, without the need for personnel inside the machine. Preliminary tests performed in 2017 showed that by injecting a small, slowly pulsed DC current into the stator, the rotor will spin due to reluctance torque. By controlling the magnitude of the DC current, and when the pulses are applied, the rotor can be accelerated and then held at a slow rotational speed. Similarly, the pulses can be controlled such that the rotor can be brought to a complete and controlled stop as well. This task will look into automating this method, and developing a standalone system that can be implemented by plant personnel. The described standalone, automated system could be the subject of intellectual property patents as well.

2. DC and AC arc flash reduction - Industry guidance regarding AC and DC arc flash requirements for personnel safety has been rapidly evolving for the last several years. Plant personnel struggle to keep up, understand, and implement safe working procedures. This research task is aimed at removing or reducing the potential for a DC or AC arc flash incidents to safe levels. A prototype DC disconnect was finalized and lab tested in 2012 under a previous research project. This task will look into improving the electronic design of this prototype, and then conduct lab and field tests of this new design. If results are favorable, technical transfer will be pursued in cooperation with the Science and Technology (S&T) office. Reduction of AC arc flash energy can be accomplished by modifying relay settings when maintenance work is performed. This research task will focus on new engineering solutions such as implementing “maintenance mode" relay settings to reduce arc flash levels when hands-on work is being performed.

3. The prevention of the misoperation of energized equipment - This research task will explore additional engineering barriers in additional to the VisiVolt™ that could be implemented to help prevent misoperation on energized equipment.

4. Evaluating the use of CO_2 for generator fire suppression systems - Fire protection of generator windings in Reclamation has relied almost exclusively on the use of CO_2. However, the safety and environmental concerns of CO_2 has lead a number of utilities in North America to re-evaluate the use of this gas within their powerplants, and a significant number of utilities have decided to remove CO_2 systems. These utilities typically either replace the CO_2 system with a water mist or deluge water system, or do not implement any type of generator fire suppression. A major driver to remove CO_2 is the presumption that the newer Class F insulation in generator windings have a self-extinguishing behavior, and will not actively burn. This research task will start the CO_2

evaluation process by participating in a CEATI study that will involve performing a series of tests on stator winding coils in a controlled laboratory environment to investigate and evaluate Class F winding combustibility and self-extinguishing characteristics.

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1. *IEEE Guide for Temporary Protective Grounding Systems Used in Substations*, IEEE Standard 1246, 2011.

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3. Atwater, Philip; DeHaan, James. *Temporary Protective Ground Cable Impedance K-Factors for Predicting Worker Touch Voltage–Basic Single-Point Grounding (1 of 2),* IEEE Power and Energy Technology Systems Journal, April, 2016. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7536176.

4. Atwater, Philip, DeHaan, James, *Temporary Protective Ground Cable Impedance K-Factors for Predicting Worker Touch Voltage—Bracket Grounding (2 of 2),* IEEE Power and Energy Technology Systems Journal May 2016. http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7536199.

5. DeHaan, James. *Power Equipment Bulletin, No. 57- Safety Issues Associated with the Configuration Management of Protective Relaying and Hands on Electrical Work*, Bureau of Reclamation, Sept., 2016. http://intra.usbr.gov/power/FIST_PEB_PRCB/PEB/PEB_57_Release_9-23-16.pdf. Internal document.

Appendix A – ABB VisiVolt™ Applications and Limitations

Hydropower Diagnostics & SCADA Group
Project Notes 8450-2016-05

Author:
Jacob Lapenna

Introduction

Power plants present many hazards to the people working in them. In the vast majority of accidents, hindsight shows that most incidents could have been avoided. Many such accidents around high-voltage equipment often arise due to the mistaken belief that the equipment is no longer energized. At first glance, these seem to be the easiest accidents to avoid, yet they still persist within the power industry [1] [2]. Passive voltage detection devices have been used in recent years to hedge risks of accidents such as these. The goal of such a device is to give clear indication of the presence of voltage, while being self-contained (bird on a wire), passive (no batteries or external source, and no need to tap into conductor for power), and reliable.

One such device that meets this goal and is commercially available is the VisiVolt™ by ABB Group [3]. The VisiVolt™ is completely passive and consists only of an LCD screen and a single surface mount antenna [4]. The antenna produces a voltage and activates the liquid crystals in the LCD screen in the presence of a strong electric field. LCD crystal activation controls light reflection from the back surface of the display producing the image of a lightning bolt [5]. Because the strong electric field that causes the image to be produced is a result of high-voltage potentials, the lightning bolt only appears when equipment is energized. It is important to note, however, that while the VisiVolt™ is good evidence of energization, it should not be used as proof of de-energization for switching or maintenance work. For switching and maintenance work, de-energization can only be obtained following the facility Hazardous Energy Control Program (HECP) as described in FIST 1-1. For maintenance work, proof of de-energization can only be established by testing for the absence of nominal voltage using a recently tested indicating type detector, and the application of personal protective grounds as described in FIST 5-1. In this report, we explore some of the advantages and limitations of the VisiVolt™, specifically in relation to power system safety.

Physical Characteristics

The VisiVolt™ is comprised of a 2.25 x 1.4 inch liquid crystal display, which is adhered to a hard plastic base for mounting, and is encapsulated in high-visibility orange silicone for environmental resistance (see Figure 1) [3]. There are two models available: VV-A and VV-B as described in Table 1 [3].

Main Specifications	Unit	Model VV-A	Model VV-B
Nominal Voltage	kV	3.0 – 6.0* 6.0 – 15.0	13.8 – 36.0
Maximum Voltage	kV	3.6 – 17.5**	17.5 – 40.5**
Operation Temperature	°C	-40 to 85	
Physical Dimensions	mm	H: 92 x W: 63 x D: 38	
*- Lower threshold is on bare, un-insulated conductor with a mounting surface less than 30 mm wide. **- Exact maximum threshold depends on clearance between nearest phase-to-phase and phase-to-ground reference.			

Table 1: Table showing manufacturer specifications for both models VV-A and VV-B. Note that the lower end indication thresholds of model VV-A only apply when installed directly on un-insulated conductor of width less than 30 mm to ensure sufficient field concentrations.

Figure 1: Image of ABB Group's VisiVolt™ passive voltage indicator. The lightning bolt image appears in the presence of strong electric fields (left). Image courtesy of www.abb.com. VisiVolt™ shown in hand for scale (right).

The image is formed by either reflecting or not reflecting light through a liquid crystal, which means that if there is enough ambient light to see the VisiVolt™, there is enough light to see the image on the display as well. The only energy consumed by the unit is the work done by the electric field to twist the liquid crystal pixels within the display, which is negligible when compared to the potential energy within the electrical equipment being monitored. Also, because the VisiVolt™ operates off of the equipment's electric field, indication will work whenever there is voltage potential present, which is independent of load current. The only major limitation when using the VisiVolt™ is that it cannot be installed on components shielded by a ground plane (e.g. mounted on surrounding bus cabinets or shielded cable). For this reason, the VisiVolt™ may not be a preventative measure in accidents that involve shielded conductors [6]. Also, equipment with voltages below the VisiVolts™ indication thresholds may still present a life threatening hazard in both shock and arc flash potential [6].

Electrical Characteristics

Several high-voltage experiments were performed with the VisiVolt™ in our laboratory to test its performance under a variety of voltage levels and physical layouts. Overall, we found an indicating voltage of several kilovolts AC for the VV-B model. Moreover, because the indication threshold is set by the electric field flux per area (i.e. field density), we found threshold sensitivity increased when in a field of higher density. This means that the VisiVolt™ showed positive indication of voltage presence at lower voltages when installed on smaller conductors with less surface area. This was shown by mounting the VisiVolt™ on a large plate (Figure 2) and measuring at what voltage the indication image was present, and then comparing this to the indication voltage when mounted to a much smaller area conductor (e.g. the head of a needle, Figure 3). In the case of the large plate, voltage indication was present at approximately 4 kV AC. For the electric field produced at the end of a needle, voltage indication was observed at approximately 2.5 kV AC.

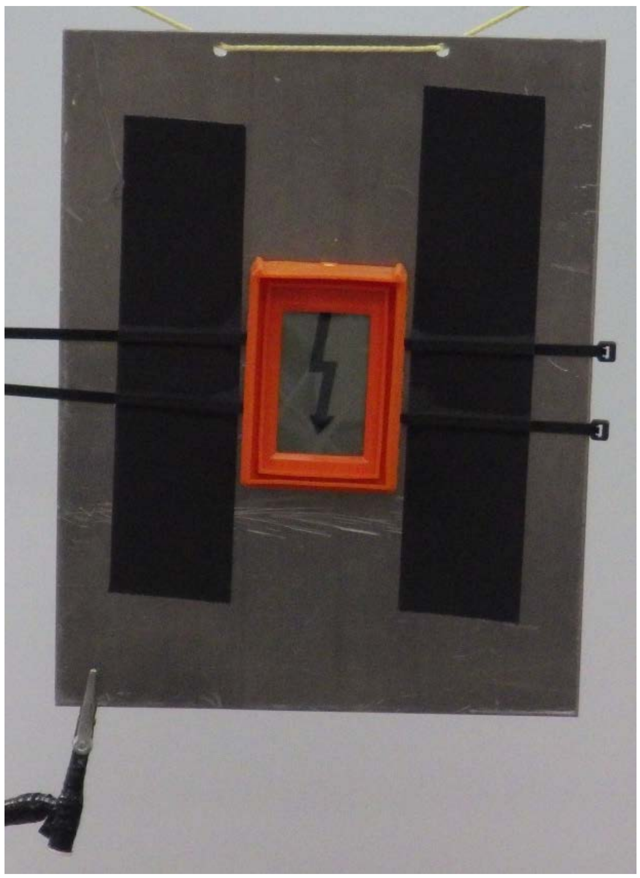

Figure 2: Image showing the test setup for large area conductor. The plate measures 8.5 by 11 inches and is 27 times bigger than the LCD in the VisiVolt™. First sight of voltage indication was observed at approximately 4 kV AC. This test was performed on model VV-B.

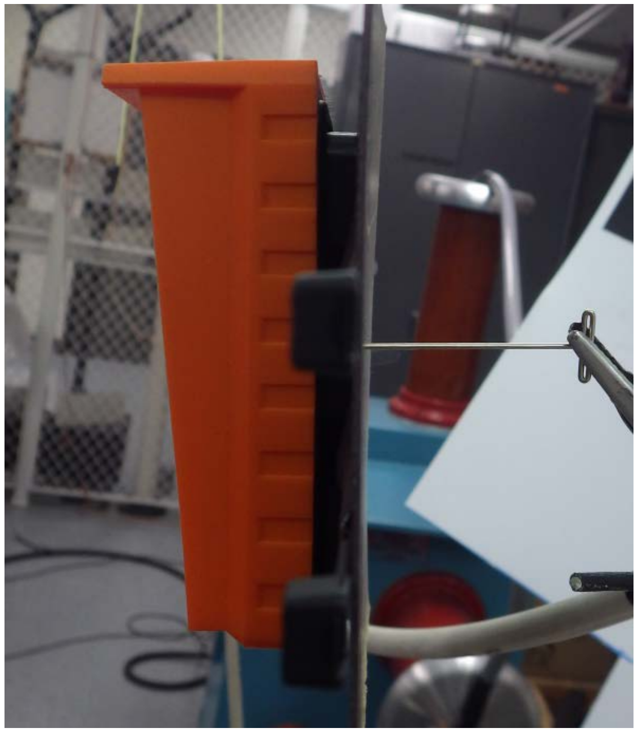

Figure 3: Image showing the test setup for concentrated electric field test. The VisiVolt™ unit was mounted to a non-conductive paper, and a sharp T-pin needle was inserted through the paper until it was touching the back mounting plane of the VisiVolt™. First voltage indication was observed at approximately 2.5 kV AC. This test was performed on model VV-B.

Instillation on insulated bus is a possible application in many power plants. Because insulation effectively increases the distance from the conductor, and therefore decreases the field density at the VisiVolt™, we tested threshold sensitivity at relatively large thicknesses from the conductor. Figure 4 shows the setup with approximately 1.15 inches of insulating material between the VisiVolt™ mounting plane and the conductor. The voltage indication threshold was observed to be about 7 kV AC on model VV-B, or about 75% higher than when mounted to the high-potential plate.

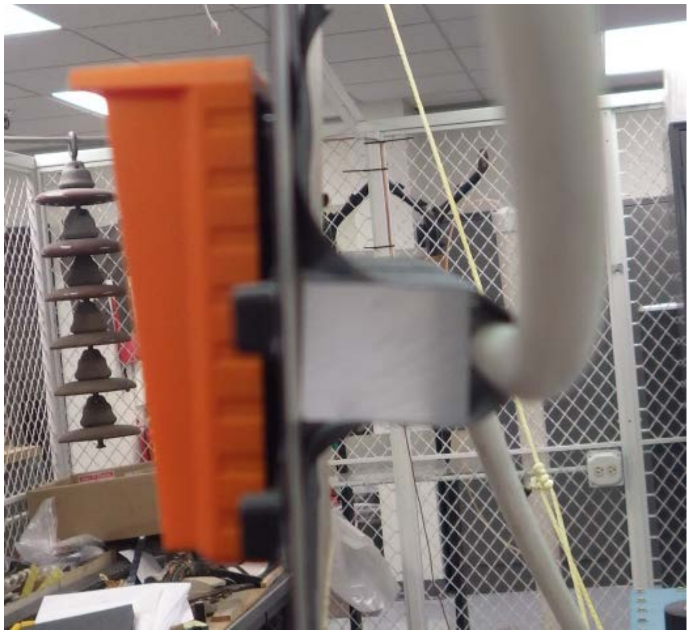

Figure 4: Image showing the test setup for determining the effect of insulation thickness on sensitivity. The VisiVolt™ was again mounted on non-conductive paper, and an insulating block was placed between it and the conductor. Total thickness between the VisiVolt™'s mounting plane and conductor was a little over one inch. First voltage indication was observed at approximately 7 kV AC. This test was performed on model VV-B.

Voltage withstand and image persistence was also tested. With the setup shown in Figure 2, voltage was set to 50 kV AC on the VV-B model. This voltage level was held for more than 15 minutes. No adverse effect was observed. The setup was monitored with a corona camera during the 15 minutes and no corona was observed coming from the VisiVolt™ itself.

Liquid crystals can also exhibit physical memory if left in a constant electric field for long periods of time. In displays, this crystal memory can result in image persistence, which results in the LCD image remaining on the screen even after the DC electric field is turned off. Because the VisiVolt™ is intended for installation on AC electrical equipment, it should never see a strong DC electric field in normal use, and should therefore never exhibit image persistence (which could lead to a false positive indication).

VisiVolt™ model VV-A was also tested. This unit showed greater sensitivity than VV-B as expected, and first visible signs of positive indication was observed at approximately 2.5 kV AC, or 1.5 kV lower than the less sensitive model VV-B. We hypothesize that the sensitivity difference is attributed to the surface mount antennas in both models, with VV-A's antenna having physical dimensions that make it more sensitive than VV-B's. Also, because it is the voltage from the antenna that activates the indication mechanism, and because antenna's only couple AC voltages, the VisiVolt™ does not indicate for DC voltages. This was tested in the lab with the setup shown in Figure 2, DC voltage up to 10 kV, and no indication of voltage from the VisiVolt™.

Model VV-A was also verified to operate in extreme physical conditions. The unit was submerged in water for 48 hours, cooled to -7° C, and heated to 50° C and, for each of these conditions, re-tested as shown in Figure 2. No change in sensitivity was observed. Icing conditions were also tested (e.g. an ice coating surrounding the VisiVolt™ and conductor), and VisiVolt™ failure was observed by no voltage indication present past 40 kV AC. We hypothesis that this is due to the ice coming to the same potential as the bare conductor, thereby significantly reducing the electric field inside the ice shell at the VisiVolt™'s antenna. Normal operation of the VisiVolt™ was verified after thawing and removing it from the ice.

Conclusions

For Reclamation purposes, the VisiVolt™ has been shown to be a robust and reliable choice that meets desired requirements of a passive voltage indicating device. It is completely powered via the electric field produced by the monitored equipment, and needs no galvanic connection to said equipment. It is resistant to environmental influence, and can be installed inside or out. For AC voltage applications, on bus rated between 3 and 36 kV AC, this device is a good solution for live equipment indication, and is a step toward preventing future accidents. The device is activated once a specific electric field density at the antenna is met or exceeded. The electric field density at the antenna is determined by the geometry and physical characteristics of the specific mounting situation, though we found this dependence does not vary outside the typical unit's nominal voltage levels. It is recommended to select VisiVolt™ models based on threshold information provided in Table 1 for a particular application (e.g. insulated or non-insulate bus, specific bus voltage, etc.)

While the VisiVolt™ is good evidence of energization, it should not be used as proof of de-energization. This is because the lack of visual evidence could mean multiple things: 1) the VisiVolt™ is faulty and the equipment is still energized, 2) voltage is still present but below the indication threshold, or 3) the equipment is indeed de-energized. Thus it should never circumvent the established HECP for de-energized equipment, testing for the absence of nominal voltage using a recently tested indicating type detector, and the application of personal protective grounds. Despite this limitation, at $500 per unit in low-quantities, this device can be an effective way of providing one more level of protection; particularly during switching procedures in providing evidence of energization. For these types of foreseeable applications, the VisiVolt™ may be a step toward increased safety in Reclamation power plants by indicating bus energization at rated voltage.

The next step for evaluating the effectiveness of the VisiVolt™ will be to install several devices in Reclamation power plants and to evaluate their effectiveness. Analysis of the device should include functional evaluation (ease of installation, long term reliability, etc) as well as how it is utilized (how well it is received, when and how it is used, are its limitation clearly understood, etc.).

Plant personnel who would like to be involved in testing these units should contact:

Jacob Lapenna @ 303-445-2829 or jlapenna@usbr.gov.

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