PRACTICAL USE OF PROTECTIVE RELAYS TO ENHANCE PERSONNEL SAFETY IN PROCESS INDUSTRIES

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Abstract – The combination of electrical equipment, flammable chemicals and high-pressure processes in the process industries has placed greater importance on the safety of employees and equipment. Protection relays used for providing reliable power to plant processes can further be utilized to create safe process operations. This paper highlights the enhancement of safety using a protection relay with specific applications of: Thermal-electrical monitoring of critical assets to detect connection hotspots or any intermittent arcing, which can potentially cause a hazardous arc flash event; Enabling the automatic setpoint group changes when personnel are in close vicinity of switchgear or enter into the electrical room; Lowering the sensitive and high-speed protection setpoints during the maintenance around the switchgear; Use of color LCDs to provide users with configurable single line diagrams and customized warning messages to activate when safety measures are enabled. This paper will provide guidance and deployment of safety technologies into the facilities.

Index Terms — Industrial Safety, Arc Flash, Safety by Design

I. INTRODUCTION

Personnel safety in process industries are of paramount importance, and it should not only be enabled but enhanced on all equipment/devices operated in the plant. According to reference [1], Industrial safety in the context of occupational safety and health refers to the management of all operations and events within an industry, for protecting its employees and assets by minimizing hazards, risks, accidents and near misses. In a study by the Institution of Engineering and Technology (IET) [2], for 151 incidents in East and South East England from January 2001 to December 2008, the fundamental causes were divided as such:

- Procedure: 55%
- Maintenance: 36%
- Design: 9%

Where procedure causes were non-compliance with, and unsuitability of, procedures and systems of work. Maintenance causes were related to how inadequate resources and lack of competence can adversely affect performance of both the individual and the equipment. Design causes go back to poor, and unsuitable, standards of design for equipment and systems. By improving the equipment design such as protection relays, the maintainability can be increased, procedures can be made simpler, and safety related incidents can be reduced.

Increasing safety does not mean choosing every option available but, rather, it is an optimization of feature selections for a specific installation.

There is a new IEEE draft P1814 *Recommended Practice for Electrical System Design Techniques to Improve Electrical Safety* [3], that is currently under development that will address some of the common safety related design concerns. The design techniques mentioned in its scope may fall under several basic categories.

- System design techniques
- Equipment features
- Protective coordination strategies
- Remote controls

In this paper, the practical measures and experience of utilizing protection relays features related to safety design points along with the thermal and dust sensors application to enhance personnel safety within the plant is discussed.

When electrical equipment is installed in an industrial environment with protection, control, and monitoring relay, safety can be further enhanced by built-in design features which aligns with the safe practices of the specific company deploying the device. Historically, protection relays have evolved from electromechanical to digital devices. Recent developments have introduced proactive monitoring and diagnostics in addition to protection and control. The advanced digital protection relays can be used to enhance safe workplace practices in an industrial environment, and the presented designs can be included in any digital device for enhanced safety of the industrial environment.

II. Background of Paper Mill Plant for the Case Study

The installation takes place at a large paper mill that is a producer of specialty grade papers for flyers and magazines. The plant produces over 400,000 tons of paper annually. The plant uses a mix of virgin fibers made on site by processing chips through a thermo mechanical pulping process, market purchased Kraft, clay and recycled fiber. The electrical substations involved with this study are connected to a

138kV incoming supply and is stepped down to 13.8kV. The process runs on a complex arrangement involving, multiple buses with more than 50 switchgear cells feeding over 40 LV/MV transformers and 13.8kV motors, as shown in Fig.1.

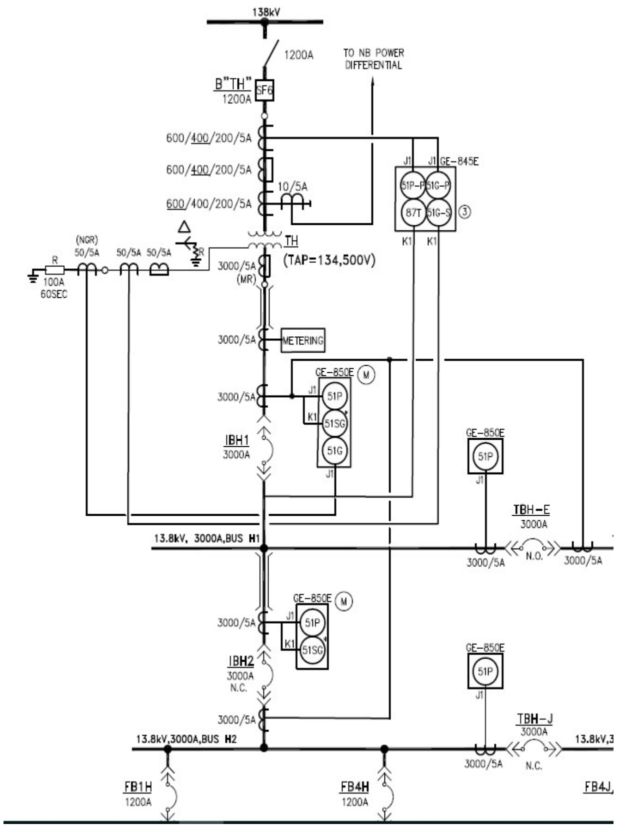


Fig.1 - 13.8kV Substation SLD at the Paper Mill

III. DESIGN POINTS Related to Safety Process in Plant

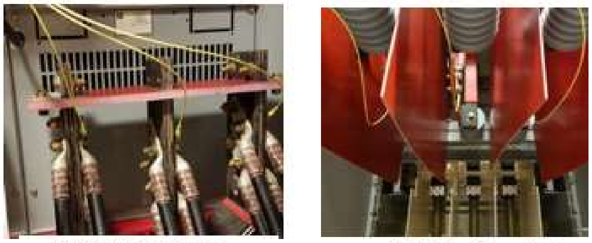
It is not enough to just comply with safety standards, companies should strive to eliminate any potential for injury or fatality. In the process industries, cognitive design, communications interface, and human errors are among the key human factor issues related to personnel safety [4]. To prevent behavior that gives opportunity for electrical hazards, designs can be improved by keeping the human factors in mind from the beginning of product development. From the IEEE IAS Electrical Safety Workshop in 2006 Human Factors in Electrical Safety, one of the key themes included simplicity. Simplicity in design, planning, implementation, communication, language, graphics, organization, or construction reduces the likelihood of error [5]. Using protection relay features which include graphical display visualization, setpoint groups in conjunction with environmental sensors increase the focus of safety management. The proceeding subsections will provide further details.

A. Thermal Monitoring with Electrical Correlation

Electrical connections points exist in numerous locations throughout a power distribution system found in industrial plants. These connections can be found throughout switchgear bus work, cable terminations, transformer windings, breaker and motor terminals. Unfortunately, the connections can become a point of failure that can lead to arc flashes and fires. Loose joints due to vibration or poor torqueing cause a thermal avalanche effect that deteriorates the insulation. Currently there are thermal inspection methods such as Infrared (IR) scanning which requires a window to be installed on the asset or continuous monitoring which requires sensors to be installed to measure potential hotspot locations. For thermal inspections, a maintenance schedule was must be created and properly followed. A person must physically go to the asset and perform the IR scan and then interpret the image produced which includes a comparison with previous images. For continuous monitoring there are several different sensor types that are available, all with the common characteristic of high voltage isolation. Continuous monitoring has the advantage of continuously collecting the thermal measurements. Connecting the thermal monitor to a protection relay can allow for trending of the temperature. Multiple alarms limits can be set by using logic equations in the protection relay. When a temperature exceeds a threshold an alarm can be made available remotely through many communication protocols such as IEC 61850, DNP, Modbus or OPC-UA. To increase the security of alarm conditions, correlations with current measurements can allow for discrimination of expected thermal heat fluctuations versus evolving insulation degradation. By setting logic equations that alarm only if a differential of current and temperature is exceeded provides a more secure status. Differential comparisons of thermal measurements between phases are available with logic equations in the protection relay which can provide more granularity of anomalies.

The Paper Mill plant had a connection failure on a flex link cable that was feeding a 30,000 hp motor due to overheating. At the time of the failure there wasn't any thermal checking performed on the motor terminals. Afterwards, an IR window was installed in the junction box for periodic maintenance. Due to the criticality of the motor, the company decided to move to continuous thermal monitoring sensor that feeds the data into the motor protection relay. This will provide continuous thermal monitoring and ensure any anomalies will be detected well before a safety issue occurs.

They have also installed another continuous thermal monitoring sensor on a transformer which is situated in the warmest area of the electrical room. A protection relay that was already installed for transformer protection now collects the thermal parameters as well. The company had identified this transformer as a higher risk due to the elevated temperature so collecting real-time information can provide an early warning. In the past the paper mill had a breaker failure in sub transformer unit in the same electrical room due to corrosion. This was detected as extreme heat in and around the breaker. With the online continuous thermal monitoring on the connections on the back of the breaker combined with AC current correlation, any changes in normal operation will be quickly identified. 9 sensors have been installed, 3 per LV breaker and 3 on the MV switch. Installation picture of the monitor sensors are shown in Fig.2 at transformer and Fig.3 at motor location.



600V cables on breaker 13.8kV Transformer Feed

Fig.2 - Transformer Installation

Existing IR window next to flex links 13.8kV Motor Feed Cables

Flex Joints Top View Measured Thermal Values

Fig.3 - Motor Installation

B. *Humidity and settled dust detection*

Accumulation of dust and humidity in switchgear can cause corona discharges. These discharges leave carbon deposits called tracking. Once there are enough deposits then corona discharge can potentially evolve into an arc flash event causing safety issues. One method of preventing corona discharge is to perform scheduled maintenance of cleaning the dust for all the switchgear in plant. This method is time consuming to cover all equipment and may not target the higher risk assets. The amount of dust accumulation can greatly increase when ventilation systems move air within the electrical room. In several areas of the plant, this was the case where higher circulation of air was required to regulate temperature. One specific piece of switchgear was severely damaged due to tracking from dust. During the composition of this article the paper mill was in the process of installing sensors that measure the dust density and humidity level. When installed the sensor is calibrated in the location and then dust accumulation is measured through a window. The sensor data will be read by the protection relay and the levels can be trended within the relay. Using collected data between the humidity and dust levels the protection relay can alarm the user to schedule a cleaning cycle on the asset.

C. *Annunciator Panel*

The standard for Basic and Safety Principles for Man-Machine Interfaces, Marking and Identification – Coding Principles for Indications Devices and Actuators IEC 60073 Chapter 4.2.1.1 [6] describes in detail the recommended visual codes, colors, and indications to be used for consistent human interaction with machines across the electrical equipment.

Annunciator panels are used to indicate an abnormal status defined by the user. The status can be for functional or safety indications. In the context of safety, having the ability to digitize the annunciator panel provides enhanced functionality: customization, maintenance and visualization are key factors.

Table I
MEANING OF COLORS – GENERAL PRINCIPLES [6]

Color	Meaning		
	Safety of Persons or Environment	**Condition of Process**	**State of Equipment**
Red	Danger	Emergency	Faulty
Yellow	Warning/ Caution	Abnormal	Abnormal
Green	Safe	Normal	Normal
Blue	Mandatory Significance		
White Grey Black	No specific meaning assigned		

With digital annunciator panels the user can customize the severity of the alarm using the Table 1 (above). The size of the annunciator panels can be classified according to the critically of the process. As company standards are updated, the text can be adjusted to closely reflect these changes. Obsolete statuses can be dynamically updated immediately without cumbersome blanking out of individual panels.

To minimize human factor related errors and for objective decision making, the alarm indications are defined by the ISA-18.1-1979 (R2004) Standard for Annunciator Sequences and Specifications [7]. The standard defines the sequences for automatic reset mode, manual reset mode, and ring back mode. IEC 60073 Chapter 4.2.3.2 states two flashing visual frequencies *f1* and *f2* for indications with set ranges and allowable ratios between two frequencies [6].

Operators can mimic their control room alarms and controls on the relays as well. Larger displays can show alarms and statuses in various sizes (2x2 grid or 3x3 grid), colors, and flashing sequence modes.

Table II
FLASHING VISUAL FREQUENCIES

	Visual	**Frequency Range**
F1	Slow Flashing (alarm cleared)	0.4 Hz to 0.8 Hz (24 to 48 flashes per minute)
F2	Normal Flashing (alarm given)	1.4 to 2.8 Hz (84 to 168 flashes per minute)

After an event has occurred, this design inclusion eliminates the need to download the records from the relay which saves precious time. The annunciator panel display can be set as a home screen so that active alarms always stay on top. It helps the operators in understanding the situation quickly and hence reacting quickly. Additionally, it serves as a training tool for operators.

Protection relay displays are used for metering, trip and control status so having one single point of focus for process and safety enables the user to assess the situation.

Like the electromechanical relays, migrating to a digital annunciator alleviates the concern of burnt out lamps, missing windows or faded text. Additionally, annual lamp testing is not required.

The paper mill migrated their existing lamp-based annunciator to a digital version that was available in a modern protection relay (see Fig.4). They were able to reduce the amount of annunciator lamps by utilizing the target message functionality for protection tripping and use the annunciator panel for critical statuses.

While configuring the annunciator, the standardized colour coding was applied with Red for “Danger” and Yellow as “Caution”. LOW SF6 PRESSURE was programmed as Red since this would be indicating a leak of the SF6 gas. If not fixed the breaker could fail to operate when it is supposed to. The annunciator will provide indication for personnel who are in the vicinity of the protection relay. Since it is a digital status as well, this can provide a remote alarm to a server. The current is that the paper mill collects the status from the protection relay using a data historian and created a script to forward a message to their on-call personnel to notify them of any issues.

Fig.4 - Conventional and Digital Annunciator Panel

D. Configurable Single Line Diagram

Typically, portions of a Single-line diagrams (SLDs) are drawn on the front of every switchgear with pushbuttons, switches, etc. It provides an easy and quick reference for the electrical system concept, interconnections, load flow, and circuit-isolating devices. SLDs also assist during commissioning, operations, and maintenance. SLDs can be simplified for operations with only isolating devices shown for lockout/tagout purposes [8]. Lockout/Tagout is a part of practice and procedure to safeguard employees from unexpected energization or startup of machinery and equipment during service or maintenance activities. If a breaker or disconnect switch is tagged, the open and close controls are inhibited.

To benchmark safety in the industrial environment, a survey of 13 entities (24 individuals representing 11 industrial companies, one retired consultant, and one health professional) was carried out with multiple scenario-based questions. One such scenario was regarding the use of SLDs. The breakdown of the SLD usage is not

Table III
SLD USAGE [8]

Entities	Usage
11	Require SLDs that contain operating data such as diagrams with isolating/disconnect switches, equipment identification, nameplate data, sizing, CT/VTs, etc.
8	Utilize computer aided drafting to develop SLDs in two layers. One for operation and one for engineering or maintenance.
11	Agree that SLDs must be perpetually maintained and that they must be updated for any change or addition to the electrical installations.
2	Revalidate the SLDs every 3 to 5 years regardless of changes
13	Utilized for engineering, commissioning, operations (lockout/tagout), maintenance, and production.
1	Standardized development process for SLDs
6	Utilize a combination of SLDs and panel schedules to maintain the knowledge of voltage levels

It is a common practice in the industry to display SLDs physically on the switchgear for operations and maintenance, to increase safety a critical electrical equipment protection relay should also have the capability to show the SLD. The color graphical display can be leveraged to aid the operations and maintenance crew to provide bay control and automation. The SLD should have the following capabilities:

- Ability to have multiple pages of SLDs
- Ability to show live values for SLD related CT/VTs, metering, status, and labels
- Ability to show custom messages and labels
- Ability to show tagging (lockout/tagout) and interlocking (blocking/bypassing)
- Ability to control open/close operations on breakers and switches

See Fig.5 for a comprehensive SLD example

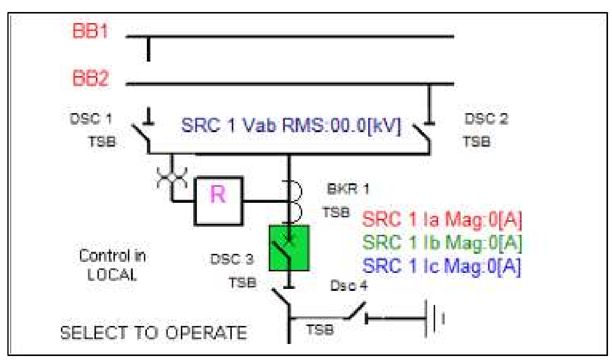


Fig.5 - Single Line Diagram Page

The OSHA standard for The Control of Hazardous Energy (Lockout/Tagout), Title 29 Code of Federal Regulations (CFR) Part 1910.147 [9], addresses the practices and procedures necessary to disable machinery or equipment, thereby preventing the release of hazardous energy while employees perform servicing and maintenance activities.

Inside the protection relay, breaker or switch is tagged by pressing the SLD pushbutton “Tag”. If the selected switching device is tagged, a letter “T” appears under its symbol. Tagging can be achieved in local mode using the front panel control from the configurable SLD screens. “Tag” when active, will work as software interlock, and both remote and local control commands (typically closed operations) are blocked for the selected breaker or switchgear respectively. However, it should be noted that this isn’t a replacement for a LOTO procedure and a physical lock on the isolating devices.

E. Programmable Pushbuttons

Several control actions are required to be executed on switchgear for operation and maintenance of a typical industrial plant. Typically, most of these switchgear related actions are available to the plant operations team at the front of the switchgear, such as switches and pushbuttons. These switchgear controls can be embedded into the faceplate of the advanced protection relay with multiple programmable pushbuttons. These protection relay pushbuttons can be configured with logic and delays, for example earth switch status of open before closing the circuit breaker; and earth switch closing followed by breaker operations, etc.

The intentional delay in the control actions can be programmed to allow the working personnel to clear from a safer distance. Using time delays for intended pushbutton activation adds a security measure. When local control is required, an operator can program a delay that gives enough time for the operator to move to a safe location before the activation occurs. The figure below (Fig.6) shows the configurable safety delay that was programmed in the relay at the paper mill plant, which is applied after arming the faceplate pushbutton and delays the control actions. Within this configurable safety delay, the personnel can move to a safer place away from the switchgear.

Accidental button presses can cause unintended actions with sometimes dangerous consequences. The United States Department of Energy’s Handbook for human factors/ergonomics design for ease of maintenance [10] indicates several physical controls, guarding, or logic controls for example cancel pushbutton within the programmed delay can be put in place to avoid accidental energization (or de-energization) of electrical equipment. Therefore, the use of touchscreen based Push-button with no guarding or logic controls should be avoided to prevent accidental energization.

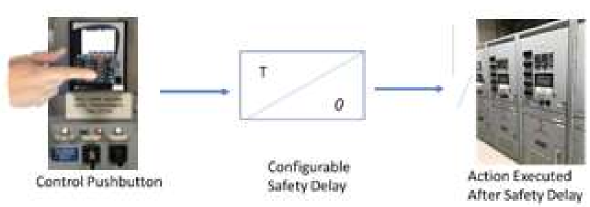


Fig.6 - Safety Delay Logic Example

The user can program a required time period in which the pushbutton is required to be in the depressed state. This prevents accidental activation of the pushbutton when working in the local proximity of the device. To prevent further accidental activation of the pushbuttons, an internal pushbutton locking functionality can be implemented which can be automatically triggered when the relay switches from local to remote mode.

F. Proactive Arc Flash Protection

Proactive arc flash method is to prevent arc flashes by using hotspot location with temperature as discussed in Thermal monitoring section. In addition, the arc flash detection and mitigation should be executed as fast as possible.

Modern digital protection relays allow integration of arc flash protection embedded into the relay with integration of light sensors. These point sensors are installed at different locations of the switchgear shown in the figure below. Light only or Light-and-current arc flash protection can be used to detect the arc flash within 2-4 milli-seconds and to reduce the incipient energy level, which in turn reduces the PPE class requirements. Sensors mounted at strategic locations within the switchgear collect light intensity and provide a trip output to the breaker based on the programmed threshold light level.

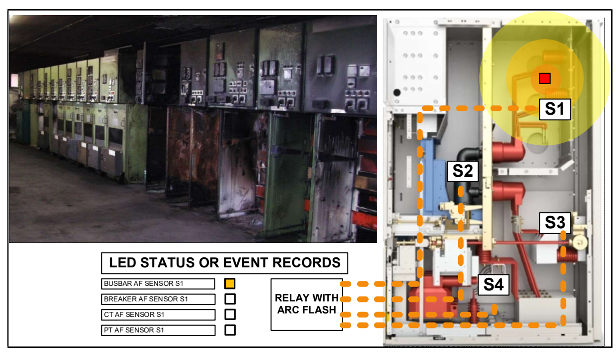


Fig.7 - Arc Flash Location from Sensors

When an arc flash event occurs, it is generally followed by an investigation for its root cause and the need for improvements to prevent it from happening again. During an investigation, it can sometimes be difficult to pinpoint the location where the arc had initiated.

With arc flash protection enabled on a protection relay, the point sensors placed at various locations throughout the switchgear compartments can help in identifying the source of the arc flash as shown in Fig.7. LEDs can be assigned to each sensor to identify which sensor had triggered the arc flash protection. Alternatively, event recorder can also be used to track the light pickup event from one or multiple sensors.

G. Setting group Change

The American National Standards Institute (ANSI) standard Z10 [11] for occupational, health and safety management systems have set hierarchy of hazard control measures and they are ranked for guidance on best method for potential hazard mitigation actions.

1. Elimination of the hazard
2. Substitution of less hazardous equipment
3. Engineering controls
4. Warnings, signs, and other communications
5. Administrative controls
6. PPE

The engineering controls refer to selection of equipment, protective settings, and automated control. To limit the arcing duration, the protective device settings can be switched to be more sensitive for faster tripping times.

Setting groups within the relay allow the user to have a multiple set of settings with different pickup levels. One setting group can be at a normal level and another at a sensitive level. The setting group changes are instantaneous so that there is no time in the middle where the equipment or system is unprotected. This switch can also be automated by assigning an appropriate change trigger.

Example 1: Motion sensors which upon detecting a presence in the switchgear room, switches the settings group to a more sensitive one.

Example 2: A smart mat that when stood upon, activates the setting group change to have sensitive settings when a person is present in front of the switchgear.

Fig.8 shows an example of smart mat is configured to the protection relay contact inputs to latch to sensitive setting group and allows manual reset command.

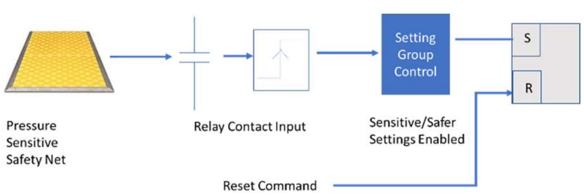


Fig.8 - Smart Mat Logic Example

When the setpoint group has been changed, visual indications can be displayed on the front panel using customized color display messages that can be clearly seen from a distance. (See Fig.9)

Fig.9 - Safety Delay Logic Example

H. Wireless for Remote User Interface and Cybersecurity

Wireless communication has been slow in being adopted in industrial plants. When associated to safety, there should be a more thorough review on the resistance of acceptance. When the network infrastructure is available, the preference for operating the breaker should be done remotely. But this is not always practical when maintenance or troubleshooting is involved. Therefore, the use of wireless communications through a secure WPA2 connection can provide the isolation needed for safety but also the convince of being relatively close to the breaker. There are remote actuators that provides 100ft distance between the pistol grip actuator and the user. Similarly, the same principle can be applied for the use of a protection relay for opening and closing the breaker. Instead of cumbersome lengths of communications cables, the user can conveniently connect to the device wirelessly. An isolated network can be used for more local control over connection management or if more security measures are needed then use of existing IT wireless network can be used. Fig.10 shows the level of clearance that is achieved using the wireless method.

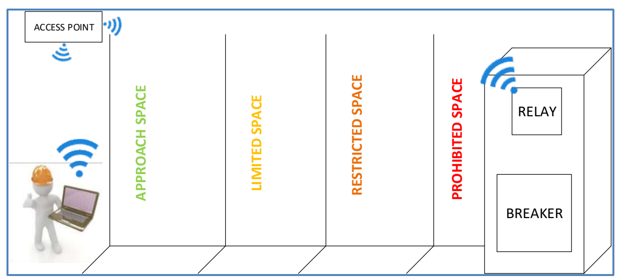


Fig. 10 - Secured Wireless Communication

Breaker and switch operations are mostly performed by qualified and adequately trained individuals. With all the training and procedures defined, it still does not stop someone unqualified from approaching the relay and operating it. With proper security measures in place, this can be avoided. Normally, the relays have multi-tier role- based security access which allows read-only access to observers, control access to operators, and administrative access to the engineers. Such role-based access ensures that settings and controls are available only to the users with proper access rights, training, and qualification. This means that the operator does not have access to change settings while in service for protection elements. The operators do have access to operate the breakers and switches. The observers do not have access to change the settings or to operate any switchgear. This limited access ensures no unauthorized change occurs which can cause false operations. Centralized role-based access can be implemented using a RADIUS server at the plant. Any user access can be removed or added centrally to all digital devices connected to the RADIUS server.

Appropriate access in all critical devices (such as relays) enhances the safety and security of the overall plant.

IV. CONCLUSIONS

Electrical safety is not limited to mitigating arc flash hazards only, it can also be improved by applying advanced features of the electrical devices. This paper presents a case study of a large paper mill with the application of several safety measures using advanced digital protection relays. Prevention of arc flash hazard is presented with the combination of active thermal monitoring, humidity and settled dust detection with electrical data available in the protection relay. IR inspections have been historical used to manage hotspot temperatures, but the reliance of scheduled inspections can be unreliable. Evolving issues may not be detected before a failure occurs due to delayed or missed inspections. Continuous thermal monitoring that is available remotely can be included with other electrical parameters of the asset for anomaly detection. The paper mill discussed in this article recognizes the advantages of continuous monitoring and plans to migrate to the option across their plant. A larger portion of design improvements can also be made in the human factors for the protection relays. Using a larger graphical color display, more information can be displayed on customized annunciator and configurable single line diagram as seen with the examples implemented at the paper mill. The application of programmable pushbutton to add safety delay and smart mat to apply sensitive settings are also presented in this paper. Preventing direct contact of the personnel with the help of secure wireless interface to the relay can further enhance the electrical safety. These design features outlined for electrical safety and human factors should be utilized in the control procedures and should be embedded in the training for qualified personnel.

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VI. VITAE

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