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Using a Disturbance Monitoring IED When in Transition to a Fully Digital Protection System

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Tomás Yebra Vega
Application Engineering department
ERLPhase Power Technologies, Ltd.
Winnipeg, Canada
tyebra@erlphase.com

Anderson Oliveira
Application Engineering department
ERLPhase Power Technologies, Ltd.
Winnipeg, Canada
tyebra@erlphase.com

Adam Gernhard
Asset Management
Duquesne Light Company
Pittsburgh, USA
agernhard@duqlight.com

***Abstract*—We have one**

***Index Terms*—Digital Fault Recorder, electromechanical relays, Retrofit Substation**

I. Introduction

The present paper describes how to use a disturbance monitoring IED (Intelligent Electronic Device) when in transition to a fully digital protection system. This topic is important because there are many substations in North America that are starting the transition to digital or planning to start soon, and one of the best ways to reduce the economical and technical risk of these projects is to use Disturbance Data Recorders. The purpose of the paper is presenting digital recorders as a tool to find answers to the problems that substations with electromechanical relays have.

The paper is divided into five sections. The first section presents an overview of the challenges that electromechanical relays create in a substation when transitioning to digital. Then second gives an overview of the advantages of transforming those old substations into digital ones. The fourth section is about digital disturbance recorders which are a fundamental part of a modern substation. The fifth section brings Duquesne Light Company real cases that demonstrate the benefits of installing digital recorders. The conclusion summarizes the most important points that are described in the paper.

II. Electromechanical relay substation

Electromechanical relays have features that still allow them to be present in the twenty-first century. Digital solutions have overpowered many of these features that were problems when first digital relays appeared, but the principle of not touching anything that it works still applies to many situations.

A. Advantages and disadvantages of electromechanical relays

Electromechanical relays are robust and perform well in harsh environments. Historically, these relays have shown sturdiness in environments with high levels of electromagnetic, radio frequency interference and with extreme temperatures. In general, EID's are not so sturdy in this type of working conditions, but with good grounding and wiring, operating IEDs should not be a problem. Moreover, proper conformal coating of the electronic boards can make IEDs work in a temperature range between -40^{0}C to 85^{0}C. A second advantage is retrofitting. It is always easier to replace a component by an exact copy of it. So, if an electromechanical relay fails and an identical unit is available in your warehouse then the solution is easy and inexpensive. Unfortunately, that is not the situation in most cases, and it is frequent to end up searching for equivalents that do not fill the requirements completely. Moreover, manufacturers will give a long list of benefits for replacing the old electromechanical relay with an IED. The third advantage is that electromechanical relays do not need an auxiliary power supply to be operative. Most utilities do not see this as an advantage because it is an exception not to find an uninterrupted power supply or battery system in a substation, but in some small industries or places in which such a facility is not possible a self-power protection relay is a solution. Finally, it is obvious that Electromechanical relays are times superior to any IED from the cybersecurity point of view.

On the other hand, considering replacing the old electromechanical relays of a substation might be done for two main reasons. The first could be that the relay has failed, and there is not an alternative in the market. The second is that the benefits of new technologies are clear in the application. Focusing on the second point of view it is possible to compare a few weak points of the electromechanical relay with the advantages that IEDs offer. First, an electromechanical relay does not have a great deal of features, and its performance is poor when speed is required. Opposite IED's combine multiple protection devices in one single box which can be activated and deactivated by uploading a file and they operate very fast. But what is more important is that when the operation happens the electromechanical relay does not give any information of what has happened. Recording capabilities are critical to learn lessons and implement a continuous improvement program. Another group of problems that electromechanical relays have is that they are difficult to maintain. It is well known that operation characteristics change as the relays become old. Furthermore, the reliability of mechanical contacts drops quickly after hundreds of operations, and old equipment suffers from voltage isolation problems. The last point is that there is less space in the control building of the substation due to the expansion and addition of equipment in the yard and its associated equipment. IEDs make the design of switchgears and racks simpler. Thus, electromechanical relays score low when comparing their footprint and energy consumption with IEDs.

B. Evaluation and planning of electromechanical relays replacement

The result of making a decision about modernizing a substation is based on the cost, and technology aspects are critical. Simplifying the problem, it is possible to define two paths. The first is to make a full replacement of all the old equipment. Here, equipment refers to the switchgear and associated devices. The second path is to retrofit the substation. In a retrofit solution the switchgear is not touched and only active devices are replaced. The economical evaluation of each path is based on many variables, but three can be considered as more relevant. The first is the downtime that usually is measured in days and it is the most difficult to calculate. It depends on the case, but a full replacement will have higher downtime because more hardware has to be removed. The second is the material cost that should be easy to estimate, but it has high variability based on the vendor. Finally, the site work which competes with downtime in terms of the most expensive part of the project although in some cases in-house expertise can execute the job saving money.

Another point that should be taken into consideration from the cost point of view is the maintenance because many electromechanical relays have reached the end of commercialization in their product life as it is shown in Fig 1. It does not mean that the relay can not be replaced or repaired because manufacturers commit to having spare units and parts after that day, but the uncertainty of when those parts will be available increases monotonously. At some point the cost of maintaining those relays will be so high that a retrofit or full replacement will be the only viable economical solution.

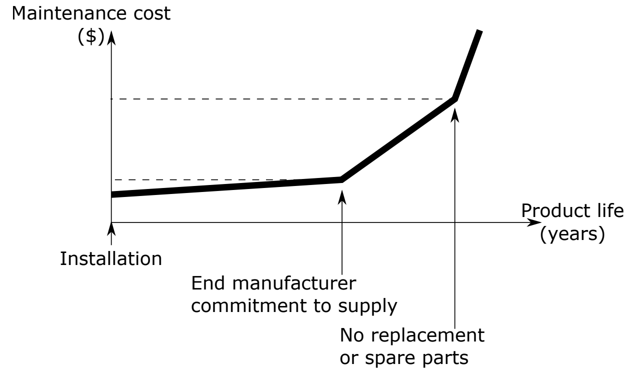

Fig. 1. Typical shape of Product life vs Maintenance cost curve of a device in a substation.

There are many ways to look at the problem to estimate when electromechanical relays have to be replaced, but all of them require reliable information. A summary diagram is shown in Fig. 2. A suggestion is to divide the process in four steps. The first could be to assess the risk of failure. The role that the manufacturer has in the process is crucial. The manufacturer should provide information about different critical points in the product life and estimates of when those points are reached. Internally, the user should collect data about the maintenance of the electromechanical relays. Given that the electromechanical relays do not have record capabilities it is time to add a digital recorder that is able to monitor the performance of the substation and individual units. The next section is dedicated to this matter. The output of this step is to find how close the substation is from an upgrade. The second step could be to estimate the cost that the old substation is incurring because the reliability is being compromised. Several iterations of these two points will tell when the upgrade is unavoidable. Before that happens, a plan has to be defined. Fig. 2 enumerates a few aspects that have to be considered during the planning. It is desirable to evaluate at least three different engineering solutions technically and economically before going into detail engineering. Once the project is concluded a recorder should be in place to measure that the objectives have been reached. The recorder will provide invaluable information to improve the solution and to optimize the operation as a whole.

III. Transformation towards digital substations

This section describes what many stakeholders expect from a digital substation. The main promise of the digital substation is that it will save cost and increase reliability for many years to come. How it achieves the target is by using Ethernet to connect IEDs. The first effect is visible. Hundreds of analog cables that are populating the substation are substituted by a few fibre optic cables. But everyone agrees that having communication does not mean that the substation is digital. It is necessary for devices that can exchange data to allow operation. The promise is that all manufacturers will

Risk assessment

- Manufacturer
- Evaluate maintenance history
- Monitoring performance of the substation
- Monitoring performance of individual units

Cost estimates

- Find downtime and maintenance cost

Planning

- Define possible solutions: retrofit or replacement
- Evaluate engineering designs
- Define project (cost and time)

Project execution

- Track material, contractors and quality

Monitoring new installation

- Proactive monitoring
- Optimization of the engineering solution

Fig. 2. Stages that are involved in the planning process of electromechanical relay replacement.

Goals

- Reduce the amount of cables and connections
- Allow integration of equipment from different vendors
- Increase the amount of data available from operation and events
- Increase controllability of the substation
- Simplify design: centralized, decentralized
- Long term stability

Obstacles

- Complex communication network: bandwidth, redundancy, protocols.
- Time synchronization protocols: SNTP, IRIG-B, PTP
- Standards evolving: IEDs with full implementation, new digital current transformers
- Software engineering tools: multiple vendor tools, unified design tools.

Fig. 3. Goals and objectives of the digital substation.

constraint their devices to a few standards, and all of them will be able to execute their functions independently of the brand that is on the other side of the line. Another straightforward consequence is that more data will be available. Hopefully, that also means better maintenance and control of the substation. Moreover, a well-defined standard means that the design of a substation is easy. Finally, the constraints of the standard should not stop the evolution of technology. The communication language should allow the user to integrate equipment that has technology that it is unknown today, but keeping operative what is already installed. What it has just described is not an easy task, and Fig. 3 lists some of the points that can be considered more problematic. It also stresses that there is a long path for technology before IED's and tools can make the digital substation design a simple task.

A. Role of network communications

The technological evolution of communication networks is what allows us to talk about the digital substation today. Fig. 4 lists a few factors that have been crucial for reaching this point. The first is that the popularization of the Internet has reduced the prices of TPC-IP technology. Switches, routers, fiber optics are a few examples of communication devices that have reduced their prices thanks to economies of scale. However, it is not possible to think about transmitting the big amount of data that a substation generates without fast communication. The bandwidth available nowadays is sufficient to design a protection relay that operates based on digital quantities collected by other devices (Merging units). Once the combination of cheap hardware and fast connection has been achieved the next logical step is to think about reliability. Fortunately, the market offers mature redundancy communication protocols that allow the user to reroute the packet and manage failures in the communication network effectively. The last piece of the system is to define a language that every device can understand. IEC 61850 defines that language, and it has been positioned as the world leader standard in substation automation. The last row in Fig. 4 shows that digitalization of data allows the transfer of data to all the layers that make use of that data seamless. It implies that is possible to create applications that before were unimaginable.

B. Providing a digital solutions to analog substations

Returning to the old electromechanical relay substation that probably has not changed significantly in the last fifty years it might look like another fifty will be necessary to transform the substation or that it is necessary to rebuild it from scratch if the benefits of digitalization want to be effective. A more positive approach to the previous view is that many digital devices do not make a digital substation, but if a digital device is present in the substation the transformation has already started.

A logical way to introduce digitalization is to monitor what is happening in the substation. The idea is that a single digital recorder gives the user a big amount of data of how the substation is performing. It means that many electromechanical relay actions are being reported, events and incidents are captured to estimate risk, and long-term

Hardware cost
- Internet has make TCP/IP hardware cheap

Bandwidth
- Serial technologies (1200 -56kB)
- LAN technologies (1MB – 1GB)

Reliability
- Redundancy protocols: PRP, HSR, RSTP

Architecture
- Client / Server
- Peer to peer

Substation automation protocols
- IEC 61850
- DNP3
- Modbus

Layers
- Power system equipment
- Merging Units
- IEDS
- Operation Applications
- Corporate applications

Fig. 4. Diagram of communication features and components in the digital substation.

performance can be evaluated.

Once the user has monitored the substation for a period of time, he will be able to establish a retrofit plan. The digital recorder will give the necessary data to evaluate the changes that have been made and optimized the whole design.

IV. Recorders for monitoring electromechanical relays

The name of digital disturbance recorder condenses well what this type of IED should do, but it does not give a good picture of the complexity inside the box.

A. *Balancing amount of data and post-processing*

The need for a complex system comes mainly from a balance between the amount of data that it is possible to capture and the usefulness of analyzing that data as it is shown in Fig. 5. In an extreme case it could stream hundreds of analog, digital and calculated signals instantaneously at a very high sampling rate, and then tries to post-process that information to find what it is valuable. The amount of resources and the time analyzing signals will make this case costly and impractical. On the other hand, it can be programmed with a few simple rules that will capture only a short period of time when a condition happens. The result in this other case would be that the system will not get the most fundamental objective that is to capture the disturbances that are relevant. Even in the case that the event is captured you might end up missing parts that are crucial for understanding what has happened.

The point is that a good digital fault recorder should have functionalities that allows the user to program the triggers that he needs so that the created records contain the information that he requires for the analysis and nothing more. In fact, a good recorder provides calculated channels such as sequence components or harmonics that reduce the post-processing time and simplify the analysis.

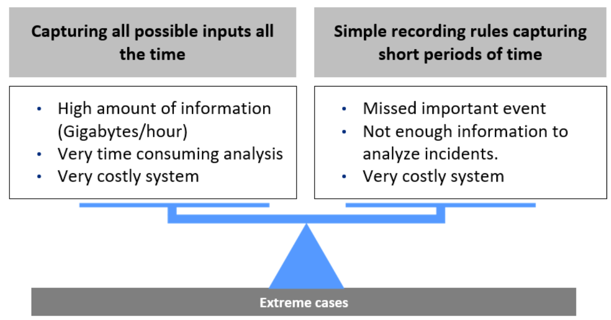

Fig. 5. Diagram that represents the balance that digital disturbance recorders have to achieve.

B. *NERC Standard compliance*

The issues mentioned before are enough to justify the installation of a digital recorder in an electromechanical relay substation, but there are other forces such as NERC (National Electric Reliability Council) that have made clear what data needs to achieve its analysis objectives. Since 2006 NERC has published PRC-002 that defines what data they request from utilities, and in some cases specifies the storage period, sampling frequency and accuracy. NERC has been increasing the requisite levels. PRC-002-02 has been enforced since December 2016, and NERC is planning to enforce PRC-002-03 in January 2024 [1].

This regulation applies to any type of substation, and of course electromechanical relay substations are not an exception. The following list remarks some of the essential aspects of PRC-002-02.

- Requested data retention of 10 days.
- Storage breaker status.
- Continuous data recording of voltages and currents
- Frequency and rate of frequency variation detection.

C. *Installation of digital fault recorders*

When installing a digital disturbance recorder there are several factors that should be considered. Here a few of them are discussed when the recorder is monitoring a substation with electromechanical relays. The first step is to consider what mechanism is used to inject the analog signal and translate them to digital. Voltages and current are injected into the recorder using different methods such as input modules, split core current transformer or merging units. Special attention is required when considering how recorders capture analog current signals. The first approach is to connect the secondary of current CTs to the recorder. This is a delicate operation that might need an outage. An alternative is to clamp split core CTs to the wires in the secondary side. This second alternative simplifies the installation and does not need an outage. It can be decided to inject only digital signals. In that case the user needs merging units and a recorder with at least one sampled value port. Second is to consider the distance between the recorder and sensors. If input modules are chosen, they will allow transmitting low voltage signals far from where the recorder is installed. It is also possible to install the module close to potential transformers if an advantage is found. This design decision simplifies the installation and helps to deal with electromagnetic compatibility problems. Some input modules can be installed up to 1200m from the recorder, accept conventional substation voltages and currents levels and there is no necessity of previous conversions. It is clear that there are many possibilities and all of them have advantages and disadvantages which can not be defined well until it is applied to a specific case.

D. Record types, channel and triggers

Once signals are injected inside the recorder it is necessary to specify the periods that the recorder is going to report. Fig. 6 shows four different types of records that the user finds in a recorder usually. The main differences between records are the length of the period they can capture and the frequency sampling rate. It is clear that a fault should not generate a 100s record length because it is a waste of memory and makes the postprocessing complex, but a voltage sag might need such length. On the other hand, analysis of the operation goes in the range of minutes or hours. They do not need any fast transient information. Thus, sampling rates are in the order of one per second. If what the user is looking for is to evaluate the performance of the substation in the long run then it is necessary to consider ways to store a reasonable amount of values which capture what he wants to measure for several days. The user should have flexibility to configure multiple types of records which operate simultaneously. The user might want to use all of them, but he should be careful about how to set up those records because wrong settings mean high volume of data which is not useful and a reduction of resources. In summary, if the interest is faults then Transient records should be used. If slow transient recording is the objective such control actions Swing records should be set up. If the goal is to study the operation of the substation, Continuing Data Recording is the solution. This is also the type of record that the user should submit to comply with NERC PRC-002. Finally, if the user needs to evaluate the performance of the substation for a very long period of time Trend record is a useful tool.

	Transient	Swing	CDR	Trend
Sample Rate	32 – 512 s/c	Configurable @ 1 or 2 s/c	6 – 60 sample per second	10 – 3600 seconds
Recording Length	Up to 30 seconds	Up to 30 minutes	10 – 412 days depending on number of channels and sampling rate	Up to 60
Recording Storage	Up to 1000 records (combined)			90 days Unlimited
Measured Value	Oscillography	RMS	RMS	RMS

Fig. 6. Summary of different record types.

Once the type of recorder has been selected it is necessary to specify what the record should capture. This part is in which the technical knowledge of the facility is added to the recorder. A brand-new recorder does not make any assumption about what to measure or calculate. The first step is to set up the channels which is an engineering work that has many parts. A channel can be made of data in a very straightforward way as a voltage measuring or a complex calculation such as the 50th harmonic of voltage in phase A. Moreover, the user has to define how to trigger the defined channel. The user can define a simple high current magnitude trigger so that the recorders will capture overcurrent events exclusively by measuring the current, a more advanced trigger such as rate of change of frequency which it will allow to see when sharp changes in the operating frequency has happened or combination of multiple simple and complex triggers. Table I shows a list of possible channels and triggers that can be uploaded to a recorder. It is clear by the amount and types of channels and triggers that an idea of what to expect in the facility is critical if the user wants to be able to use the recorder efficiently.

TABLE I
CHANNELS AND TRIGGERS

Channels	Triggers
Direct measured Voltages and currents Digital inputs Calculated Frequency Symmetrical components Power: P and Q Power factor Impedance Fault locator Boolean logic	High magnitude Low magnitude Positive rate of change Negative rate of change Power detectors Impedance circle Capacitive Inductive

E. Automatic record retrieval

The next step after defining the type, size and content of the record is to transfer that record to the office so that data can be analyzed. The process of sending the records to a PC is usually as simple as a few clicks. The challenge is that the user does not want to be clicking periodically. What many users want is an automatic system of record retrieval. Fig. 7 shows a list of features that the system should have. The first is that the user should be able to program when the retrieval has to happen. The network can be busy during some hours of the day or day of the week, and it is better to program the retrieval during time when the network has less traffic. Furthermore, the system should connect with multiple IEDs simultaneously. A well-designed system should allow connections of more than hundred devices. The system should also have a central database which has enough searching capabilities to identify the day that records were generated, and the IED that created it. Finally, the user might want to be notified when a type of record has been created or to have a daily digest of what has been captured.

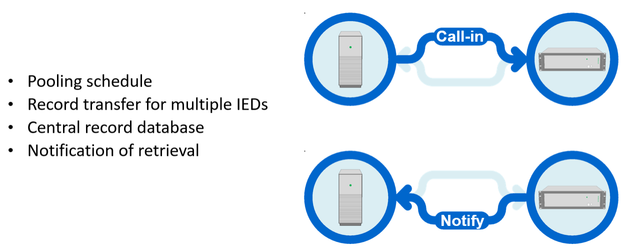

Fig. 7. Pooling scheduling process.

F. Analysis tools

After the records are in a PC with the right data ready for the analysis the next step is to find tools that extract from the data the information that allows making conclusions about what has happened in the system. Similar to what was discussed when introducing digital recorders, any analysis tool has to deal with a balance between how much flexibility and the time it is necessary to accomplish the analysis (Fig. 8). In general, more flexibility means that there are more options and that the calculations that it can solve are more complex. On the other hand, a reduction in flexibility means that the user needs less training and the full report might be available in a few clicks. For example, in a fault analysis you can start by getting the instantaneous values of currents, and the user could implement his own analysis algorithm using a mathematical package or programming language. It will take a lot of time to develop the script, but it will output exactly what the user needs. If the user does not have the time and skills to learn those mathematical packages, he can use a tool that can easily help him to find values such as maximums, RMS values and duration of the fault by moving markers dynamically on a graph. There might be some complex operations that he might want to perform to have better insight on the event that are not available in the tool, but he will have some answers quickly.

G. Communicating with a digital fault recorder

The final thought of this section goes back to the communication aspects of the digital substation. It has

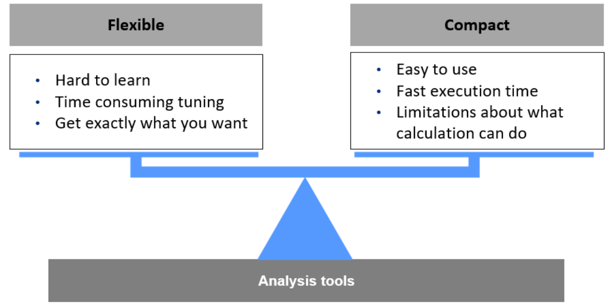

Fig. 8. Diagram that represents the balance that analysis tools should achieve.

been discussed about how records are downloaded from the recorder to a PC or a central database, but many recorders can do more than that. Indeed, they are real-time monitoring equipment. They have metering screens, support many SCADA protocols such DNP3, IEC61850 [2] or PMU (Phasor Measuring Unit) and more. Therefore, a single digital recorder is the link between the old electromechanical relay substation and the cutting edge of SCADA technology in the control center.

It is necessary to make clear that a digital recorder is a complex piece of equipment with a lot of hours of engineering inside. It might not be perceived as a critical IED such as protection relays, but in many cases have a lot more functionality and capabilities. In an electromechanical relay substation means to have remote access to information that was not available before, and make smart economical retrofit decisions. So if a recorder has been decided to be installed in an electromechanical relay substation it should be considered getting the communication network inside. It is not absolutely necessary, but it will improve your productivity.

V. Duquesne Light Co. Experience

A. DLC Overview

Duquesne Light Company (DLC) is a transmission owner and distribution provider of electric energy in the Pittsburgh region, and has been for more than 140 years. We consistently rank among the most reliable utilities in the state and part of that reliability is our commitment to upgrading our infrastructure. Across our 817 sq-mile service territory, DLC maintains 345 substations with voltages ranging from 4kV to 345kV. While DLC had installed a variety of disturbance monitoring equipment (DME) from magnetic tape models in the late 1960s, early digital recorders in the 1980s, and modern recorders in the early 2000s. Around 2004, DLC standardized on one manufacturer line of DMEs for permanent installations. In addition to permanently installed DME, DLC has used portable DME equipment to assist with operation investigations and for equipment energizations of transformers or capacitor banks to provide energization data. In 2020 DLC decided to standardize on a portable version of the same DME, which operates the same as the permanent DME to meet this need.

B. Subtransmission Event

The portable DME is helping troubleshoot the line protection at a customer substation, and the sub-transmission lines that feed it. The customer substation is feed from two lines from one company substation, two 4kV transformers feeding off the substation bus. The line protection for the lines is an electromechanical directional (CR) relay, while these devices are not 'new' the periodic maintenance testing and age would not have suggested replacement. Also near the substations there are line-sectionalizing and reclosing devices. Recently an apparent fault caused a short outage (restored by SCADA switching in ¡3min) for the customer. This outage perplexed the protection coordination design team as three of the four-line breakers operated at the same time, with one of the sectionalizing devices. Based on settings review this should only occur for two concurrent faults [very rare] or in-secure device failure [also rare]. Upon testing the customer substation line protection relays, the directional functionality, including the secure loss of voltage function operated correctly. A portable DFR was connected to receive bus voltages, line currents, and breaker statuses. Given that station AC may be briefly interrupted during fault conditions, and it was undesirable to connect to station DC, the portable DFR was powered from a commercially available UPS. The records collected by the portable DME at this station will help determine if there need for relay replacement.

C. Capacitor Bank / Transformer Energizations

Transformers and Capacitors both exhibit inrush phenomena upon energization which can produce harmonics, and may be susceptible to harmonics from other sources. Due to the critical system performance impact, potential for dramatic failure mode, and expense for repair or replacement DLC often performs brief test energization of transformers or capacitor banks after significant repairs or replacement. During these test energizations, if there is no permanent substation equipment capable of recording significant oscillography (DME, or certain advanced microprocessor protective relays), DLC will use the portable DME to capture the energization.

1) Capacitor Relay Troubleshooting & Energization: The portable DME unit helped troubleshoot issues with a capacitor bank. A several decades old capacitor bank (individual cans may be same-model though newer) had a relay that was continually alarming despite bank-level measurements being satisfactory. On the alarms it was noted that no fuses blew, but the capacitor controller would not allow the bank to be closed, indicating excessive neutral voltage on the bank. The banks were re-measured without any indication of problematic cans, and no fuses had blown. A portable DME was set-up and configured to record bus voltages, capacitor neutral voltages, and capacitor currents. The event record was analyzed to confirm that there was no issue with the capacitor bank and confirm that the controller was appropriately reading the neutral voltage. While the solid-state relay was operating appropriately, it was replaced with a modern microprocessor capacitor protection relay.

D. Key Take-Aways from Use Cases

Portable DME provides a flexible and easily deployable platform for collecting fault and non-fault data for major equipment installations, or to assist operation analysis. Some key points from the experience of DLC with these devices:

- Split-Core CTs are essential for quickly being able to deploy a portable DFR to EMRLY or SSRLY site. This allows installation without disturbing the equipment and without requiring another outage. The run length of the secondary modules will likely not limit the placement of the DME within the control house.
- DME Live/HMI software allows for observing analog values 'real-time', helping on-site personnel ensure proper configuration of ratios and polarity prior to departure.
- DME Event records provide detailed information at very high frequencies required for transformer capacitor bank applications. The event records can be converted to COMTRADE for use with alternate software if needed.
- The number of analog and digital channels make a single unit capable of capturing most small distribution substations – and hardware or software cross triggering is available – between portable or permanent DME if needed.

For locations where installing a permanent DME may not be economical, portable DME helps to provide valuable information about primary equipment health and secondary equipment performance.

VI. Conclusion

The conclusions are summarized in four points. First the electromechanical relay substation will have to be replaced. It does not matter how robust the relays are or how much investment is necessary to keep the facility operating there will be a day that it will not make economic sense to have them running. The second point is that the transformation from an electromechanical relay substation to a digital substation starts at the moment that an IED is present, but to get a full digital substation is a process that can take a long time. Third, digital disturbance recorders are the first logical IED that many users consider when they are writing a modernization plan. A digital recorder provides invaluable information about the performance of the substation and allows better maintenance and economical decisions. Finally practical experience has shown the advantages of installing digital recorders in electromechanical substations.

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