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Experience with Optical PT's and CT's at 500kV for Relaying and Metering

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1. INTRODUCTION

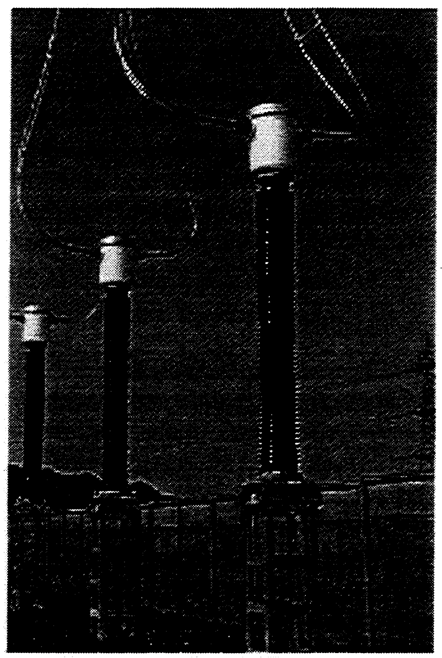

Figure 1

For most of this century, the measurement of transmission voltages and currents have been accomplished with magnetic or capacitive devices that transform primary power system quantities to 115 and 67 volts and 5 amps, secondary. The secondary currents are capable of transmitting 5 kW of power during system transients, and that demands long runs of #12 wire to reduce burden and prevent saturation. This cabling is expensive to purchase and install requiring substantial design expertise to provide the electrical isolation. Also, the failure of these devices is often explosive, creating unplanned outages and subjecting personnel to potential injury when failures occur.

This paper discusses the evaluation of 500 kV optical voltage and current transducers that are a part of the Advanced Substation Project (please reference Figure 1). One objective of the project is to incorporate all substation control, protection and metering into one optical communication bus. All substation functions and equipment will be remotely accessed via telephone modems or dedicated communications. The overall project goal is to reduce the cost of substation equipment and design. Operation and maintenance schedules will be reduced with equipment that is self diagnostic, automatically signaling component failures as they occur.

The equipment from two manufacturers was purchased for evaluation. The optical transducers are a General Electric Corporation (GEC) Alstom, combined optical PT and CT unit and Asea Brown Boveri (ABB) optical CT unit. The GEC equipment consists of three single phase optical transducers that transform primary voltage and current into meter and relay secondary low level voltages. The ABB equipment consists of three single phase optical transducers that transform primary current into meter and relay low level voltages. ABB does not have an optical voltage transducer involved in this project.

Low power input relaying and metering, designed to accept these low power input signals, were tested and evaluated. The relaying used was Schweitzer Engineering Laboratory's (SEL) 321 and General Electric DLP microprocessor based single pole trip relays. The relays will also be monitored for power flow to evaluate the need for maintenance. The metering used was the Scientific Columbus JEM I (BPA standard), ABB 2200, and Square D 2000 meters. The metered quantities are watts and vars in and out.

A data acquisition system (DAS) was designed and built to monitor all optical outputs and inputs to all relaying and metering to determine signal fidelity and drift over time.

The optical transducers, relaying, metering and data acquisition system were put into service at Keeler Substation in Southwest Portland in late September, 1994. Staged power system faults were initiated separately on each phase, at 500 kV, as part of the static var compensation evaluation installed at Keeler substation at the same time. This provided important transient data to evaluate the dynamic performance of the optical devices during actual power system disturbances. The optical transducers will be in service for approximately two years.

2. SPECIFICATIONS

2.1. **Optical voltage transducers** (General Electric Corporation)

Metering

- accuracy 0.3 percent of full scale (4.0 volts peak secondary).
- range - 0.8 to 1.2 per unit (525 kV = 1 per unit).
- bandwidth - 0.1 Hz to 2 kHz.

Relaying

- accuracy 0.3 percent of full scale (2.0 volts peak secondary).
- range - 0.0 to 1.5 per unit (525 kV = 1 per unit).
- bandwidth - 0.1 Hz to 2 kHz.

2.2. **Optical current transducers** (General Electric Corporation and Asea Brown Boveri)

Metering

- accuracy 0.3 percent of full scale (2.0 volts rms secondary).
- range - 0 to 2.0 per unit (2000 amps primary = 1 per unit).
- bandwidth 0.1 Hz to 2 kHz.

Relaying

- accuracy 3.0 percent of full scale (0.2 volts rms secondary).
- range - 0 to 10 per unit (2000 amps primary = 1 per unit).
- 0.1 Hz to 2 kHz.

2.3. **Relaying** (General Electric and Schweitzer Engineering Laboratory)

Voltage

- 0.2 volts rms full scale (2000 A).

Current

- 0.2 volts rms full scale (2000 A).

Protection criteria

- standard BPA three zone protection with time delayed back up, single pole trip with no transfer trip.
- metering, phase monitoring and event reporting via RS 232 serial interface
- 3.0 percent accuracy.

2.4. **Metering** (low voltage)	(standard voltage)
(Scientific Columbus, Asea Brown Boveri, Square D)	(Scientific Columbus)
Voltage	
• 4.0 volts peak full scale (525 kV).	120 volts full scale (525 kV)
Current	
• 2.0 volts rms full scale (2000 A).	5 amps full scale (2000 A)
Meter criteria	
• watts and vars, in and out	(same)
• 0.3 percent accuracy	(same)

3. OPTICAL PROPERTIES

The following concepts are to give the reader some background concerning optical transducers to complement the presentation at this conference[1].

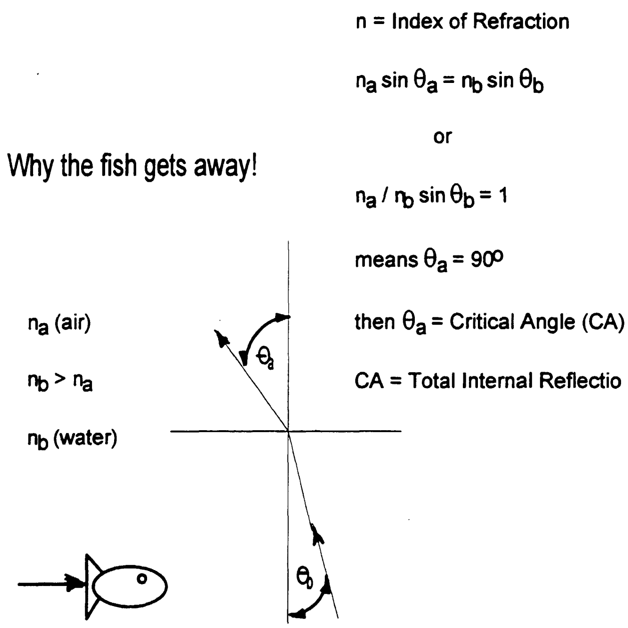

Figure 2

3.1 Snell's Law

According to Snell's law, when light passes from a medium (such as air) into a more dense medium (such as water), the angle of the light transmitted (please see Figure 2) is related by the expression:

n(a)sin(angle a) = n(b)sin(angle b),

n = refractive index of optical medium

A critical angle must be overcome before light can be transmitted from one media to another. Reflection occurs when the angle of light is above this critical angle. Any fisherman who has gone trout fishing on a mountain stream soon realizes that the fish see you coming long before you see them. This is due to the fisherman needing to get above the water to see into it. For the fish looking into the air from the water, this angle is much smaller. Light injected into optical fibers follows Snell's law.

From a power system point of view, optical fibers in a substation will still have to run through conduits. If the optical cable were to be bent, this critical angle would be defeated causing a loss of signal. The consequences would be a line relaying or an inaccurate power measurement.

3.2 Birefringence

The speed of propagation of light in some specific media (crystals) is dependent on the direction of propagation and the polarization of the light. Please reference Figure 3. Consequently, the phase angle of the light is rotated due to the retardation of this light through this medium. This effect is called birefringence. An effect much like this can be induced by an external electric or magnetic field in certain materials.

From a power system point of view, current and voltage can be measured as the intensity of the light output is modulated by a sinusoidal external electric or magnetic field. The benefit is that this modulation takes place only in a specific direction. The net result is that electric or magnetic transients generated by faults or breakers opening present little interference on the output of these devices.

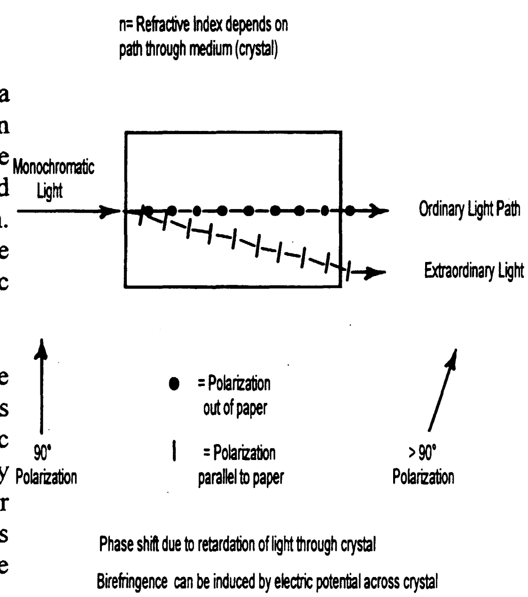

Figure 3

4. OPTICAL TRANSDUCERS

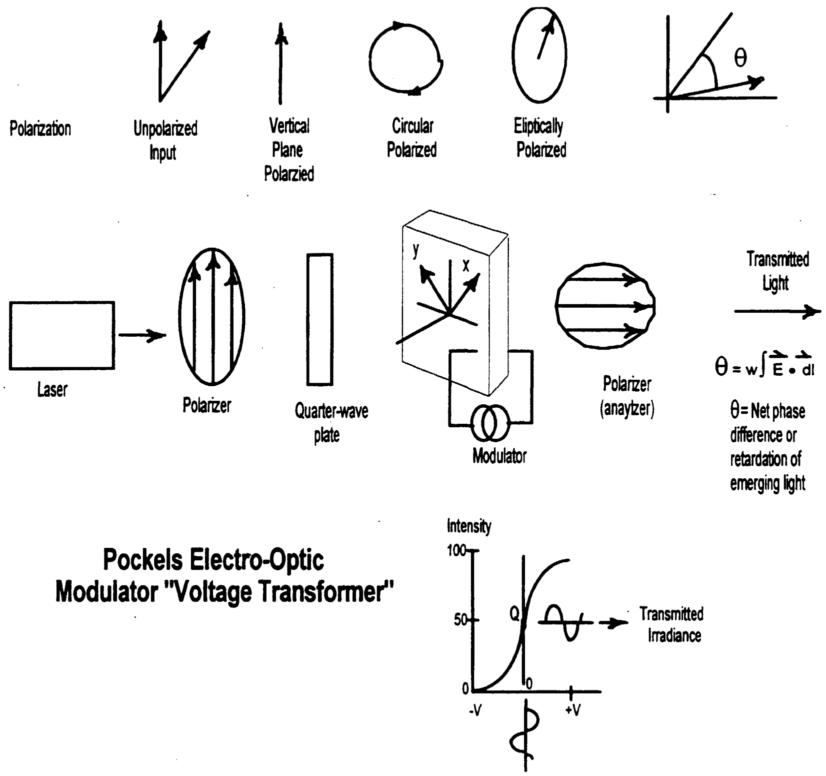

Figure 4

4.1 Pockels Electro-optic Modulator "Voltage Transformer"

When monochromatic (single frequency) light is transmitted via an optical fiber to an optical "PT" on a power line, the light is first polarized in one direction through a polarizer. Please reference Figure 4. Then, the light is passed through a quarter-wave plate which rotates the phasor of the light beam to result in circular polarization. Equal intensity exists on the x and y axis. Then, this plane polarized light passes through an electro-optic modulator which modulates the phasor of this light due to the applied electric field from the power line potential. The emerging light passes through another polarizer which will then be a replica of the applied line potential. For the application at Keeler Substation, 525 kV would be represented as 2.828 volts rms for metering potential and 1.414 volts rms for relaying. Accuracy is 0.3 and 3.0 percent, respectively, over a temperature range of -20 to 35 degrees Celsius.

Stated simply, the intensity of the light output is directly proportional to the voltage this device "sees" from the power line[2].

4.2 Faraday Magneto-optic Modulator "Current Transformer"

When monochromatic light is transmitted via an optical fiber to an optical "CT" on a power line, the light is first polarized in one direction through a polarizer. Please reference Figure 5. By design, the light is transmitted to a magneto-optic modulator subject to a time varying magnetic field. The plane polarized light is rotated by an amount proportional to the magnetic field component parallel to the direction of propagation. The emerging light then passes through another polarizer. The intensity of this light represents a replica of the applied line current. For the application at Keeler Substation, the nominal current is 2000 amps represented as 2.0 volts rms for metering current and 0.2 volts rms for relaying. Accuracy is 0.3 and 3.0 percent, respectively, over a temperature range of 20 to 35 degrees Celsius. The optical current transducers are rated to 100k amps.

Described in simple terms, the current in a power line creates a magnetic field that circles the conductor as power moves down a power line. The light intensity output is then a measure of this current as this magnetic field varies sinusoidally with the current in the conductor.

Faraday Magneto-Optic Modulator "Current Transformer"

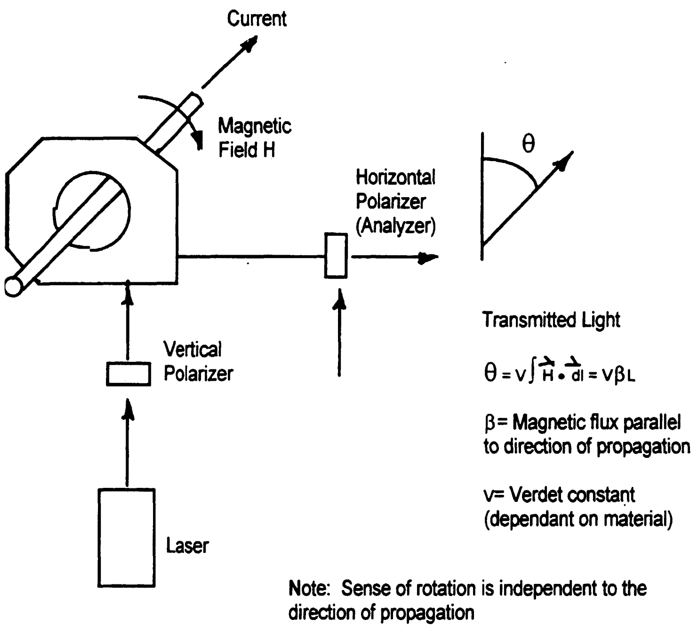

Figure 5

5. LOW POWER INPUT RELAY AND METER EVALUATION

5.1 Relaying

Two microprocessor base line protection relays were adapted to accept low power input signals for this project.

a. Schweitzer Engineering Laboratories (SEL) 321 line protection relay. The SEL 321 is a 16 sample/cycle relay used as a single pole trip three zone protection scheme without transfer trip with time delayed back up. Fault event reports and fault locations are available for analysis along with phase current, voltage and power flow monitored to determine the need for maintenance.

b. General Electric DLP line protection relay. The DLP is also a 16 sample/cycle relay used as a single pole trip three zone protection scheme without transfer trip with time delayed back up. Fault event reports, fault location and oscillography are available for analysis along with phase current, voltage and power flow monitored to determine the need for maintenance.

5.1.1 Relay Testing

The Schweitzer Engineering Laboratory's Relay Test System (RTS) prototype low power output test device was use to evaluate the performance of these relays.

Specifications

SEL 321 (two) Model #'s 93239011, 93239012

- Nominal voltage 303 kV = 1.414 V at PTR 4500/1
- Nominal current 2000 A = 0.2 mV at CTR 2000/5
- Input impedance 0.0001 VA
- Accuracy 3.0 percent

GE DLP (two) Model #'293239011, 93239012

- Nominal voltage 303 kV = 1.414 V at PTR 4374/1
- Nominal current 1750 A = 0.175 mV at CTR 1750/5
- Input impedance 0.15 VA
- Accuracy 3.0 percent

SEL-RTS Relay Test System, Model # 93344019

- Twelve analog output channels (+/-5 volts peak, scaled to values above)
- Accuracy 0.25% at 10-100 percent full scale at 60 Hz, 0.2 degree at 60 Hz
- Output THD 1.0 percent

Figure 6

Metering for Calibration of Relays and SEL-RTS
- Fluke 8840A, Calibration 1994, BPA# 160601

Discussion

The line relays were set for a conventional single pole trip three zone protection scheme (without transfer trip) with time delayed backup. Instantaneous power flow, input channel monitoring and trip event reporting are available from each relay via RS 232 serial port interfaces. Schweitzer Engineering Laboratory also provided the SEL-RTS low power output relay test system that provided a pseudo-transient relay test device to evaluate the trip performance of both DLP and SEL 321 relays. The SEL-RTS is a low power output multichannel source that accurately recreates low level output voltages representing 500 kV primary voltages and currents. The SEL-RTS creates a prefault, fault and postfault waveforms with the actual current and voltages phasors using data from the BPA fault study program (Aspen). Each relay was tested at zero, fifty and one hundred percent of the line for single phase, phase to phase and three faults. All relaying tripped as expected.

5.2 Metering

Several common revenue meters have been adapted to accept low power input signals for this test. The two meters that are being evaluated are:

a. JEM I 603 by Scientific Columbus. This meter measures watts in and out, vars in and out which will be monitored by the digital monitoring system. Pulses for kilowatt and kilovar hours will be totalized by a Sentry 100 recorder by Process Systems. Since the low power input JEM I's are new, they will be compared to a JEM I with conventional voltage and current inputs from PT's and CT's on site at Keeler Substation.

b. Iliaco 2200 by Asea Brown Boveri (ABB). This meter measures watts and vars in and out which will be monitored by the digital monitoring system. Pulses for kWh and kilovar hours are recorded internally by the 2200. This low power input meter has been in service by ABB for several years and was calibrated by ABB.

5.2.1 Meter Testing

Since no standard low power input metering test equipment was available, a system was created by the Laboratories adapting the standard meter test equipment used at BPA (please see figure 7).

Specifications

JEM I (three) Model # 94061190, 94061191, 94061192
- Nominal voltage 525 kV = 2.828 V at PTR 4500/1.
- Nominal current 2000 A = 2.0 V at CTR 2000/5.
- Input Impedance 0.0001 VA.
- Accuracy 0.3 percent.

Meter Test System
- MicroJoule standard, Model # 6353, BPA # 162287, Calibration 1/94.
- Fluke 8840A Multimeter (two) BPA # 163770, 160601, Calibration 6/94, 1/94.
- Voltage divider 120 V = 2.828 V calibrated 0.1 percent with Fluke 5100 meter calibrator, BPA # 160579, calibration date 6/94.

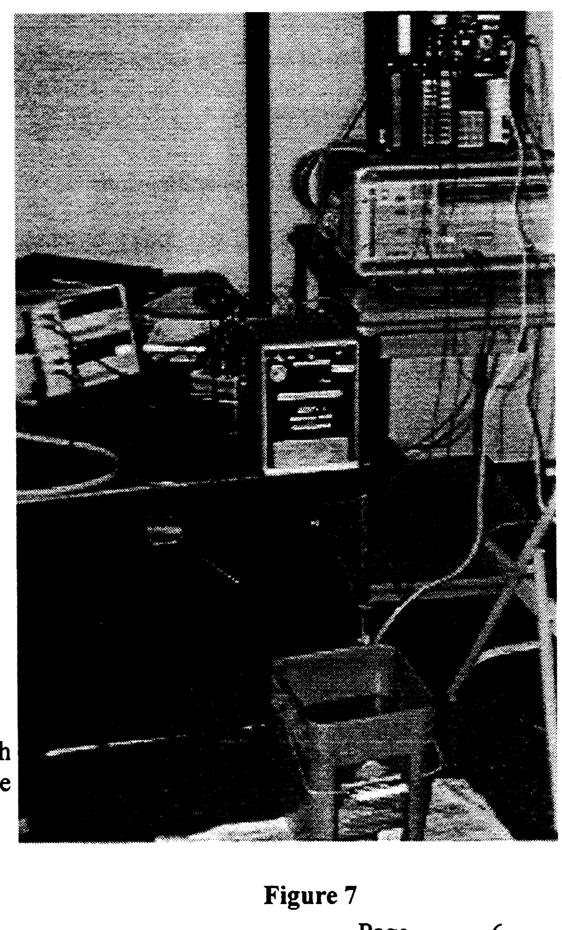

Figure 7

- Current shunt 5 A = 2.0 V, 0.40016 ohm calibrated with ESI Potentiometric Voltmeter Bridge Model # 300, BPA # 89631, calibration date 1/94, emersed in oil to maintain stability.
- MultiAmp Epoch 10 voltage/current source, BPA # 178680, Calibration 7/93.

Discussion

Three manufacturers provided low power input metering for this project. The first was Scientific Columbus who modified the JEM I, the BPA standard revenue meter, to accept low power input signals. A modified metering test system was developed to test the JEM I using the conventional MicroJoule standard. All JEM I metering tested to be within the 0.3 percent error tolerance for this project. Standard BPA RMS totalizers accept the pulse outputs of the JEM I meters and are accessed every 15 minutes from the data acquisition system on site at Keeler Substation. ABB provided the ABB 2200 revenue meter which was calibrated by ABB and accepted since no standard metering test equipment was available within BPA. Also, Square D provided the 2000 power flow meter which was calibrated by Square D since BPA had no standard meter test equipment to evaluate this meter as well. Both the ABB 2200 and the Square D are accessed via RS 232 communication interfaces and down loaded to the data acquisition system at Keeler Substation every 15 minutes.

6. DATA ACQUISITION SYSTEM

6.1 General Description

The data acquisition system (DAS) installed at Keeler Substation was primarily designed to record the long term steady state outputs of the optical and magnetic transducers under test. However, some transient information can be gathered in it's raw form. In it's normal operating mode every 15 minutes the DAS records the values currently at the outputs of the optical devices and inputs to the relaying and metering, performs some data analysis on the raw information, and then stores the resulting values in a database. The data can then be analyzed by BPA personnel connected to the BPA Wide Area Network (WAN).

The DAS is a VXIbus based test system[3]. VXIbus (VME eXtensions for Instrumentation bus) is an industry standard computer bus architecture primarily targeting the needs of data acquisition, test and measurement[4]. By using devices designed for VXIbus one gets excellent accuracy of analog readings, high data throughput, and a versatile test and measurement environment able to support devices from many different manufacturers. The computer in this system is a standard IBM compatible PC from RadiSys Corporation modified for use in a VXIbus enclosure. It is running under Microsoft's Windows For Workgroups operating system. The programming environment used to produce the DAS software was LabVIEW from National Instruments. LabVIEW is a graphical programming environment incorporating icons and other visual objects in Windows to produce a program. The user interface consists of graphical objects mimicking the buttons and displays of hardware front panels on the computer screen. A mouse or other pointing device is used to push buttons, move levers, etc. to direct the program. In addition to standard computer inputs and outputs such as serial and parallel, the DAS currently has a capacity of recording 48 channels of analog data at 16 bits resolution and sampled up to 10KHz. The analog digitization is accomplished with analog input boards from Kinetic Systems.

The DAS was designed in-house at BPA for primarily two reasons. First, some of the unique requirements of the DAS such as communicating with several different relaying and metering devices, and integration into the BPA network environment were unavailable off the shelf. Second, development of this type of system would provide a usable prototype VXIbus DAS that could be applied easily to other future projects.

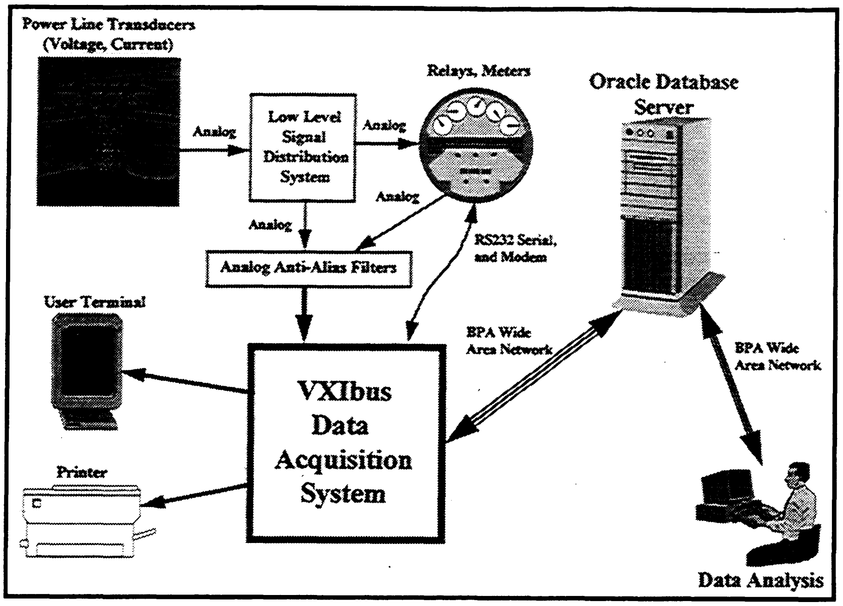

Figure 8

A general description of the DAS organization can be seen in Figure 8.

The optical and magnetic PT/CT devices produce analog outputs representative of the power line voltage and current. The analog signals are then passed through the Low Level Signal Distribution System (LLSDS) (please see figure 9) where they are adjusted to the correct voltage levels associated with each signal destination. The DAS monitors the PT/CT signals as well as the relaying and metering devices. The metering and relaying devices perform their analysis of the signals and the resulting values are collected by the DAS through RS232 serial, phone modem, and analog connections.

The data collected by the DAS every 15 minutes is then picked up from Keeler substation through the BPA Wide Area Network (WAN) by the Oracle database server located at the BPA Ross Complex in Vancouver Washington. Once the data is stored it can be analyzed with a variety of tools available for the Microsoft Windows Network environment through the BPA WAN. The user can also access current data values onsite from the DAS through a user terminal located at Keeler. Selected data results can be sent to a printer for later analysis.

6.2 Power Line Transducers

The power line transducers consist of two types of optical devices and a set of standard BPA magnetic devices. They produce a low level analog output representative of the power line current and voltage. The two optical devices under test in this project are being driven by a 500KV power line, and are manufactured by ABB (Asea Brown Boveri) and GEC (Balteau). The analog outputs are then routed to the LLSDS.

6.3 Low Level Signal Distribution System

The LLSDS is a collection of analog amplifiers designed in-house with an output signal accuracy specification of 0.1% of full scale input. The LLSDS routes signals to specified devices and provides isolation from the power line transducers. Please reference figure 9. Normally, power line transducers from magnetic devices provide a signal to the instrumentation at 120VAC and 5.0A, but the optical transducers provide a low level signal (usually within $\pm$ 10V) to the instrumentation. The LLSDS accomplishes it's task through a series of gain changes to convert the incoming voltage levels to their desired ranges and instrument amplifiers for isolation. All of the devices (relays, all but one of the meters, and the DAS) have specialized requirements for input voltage range at the low level and the LLSDS provides the correct ranges within defined accuracy, resolution, and phase specifications. Below is a single phase one line of the low power signal distribution system from the optical devices to the relaying and metering. This system simultaneously samples every 15 minutes (see circled test points) to monitor the fidelity and drift of the optical devices and low voltage distribution system over time.

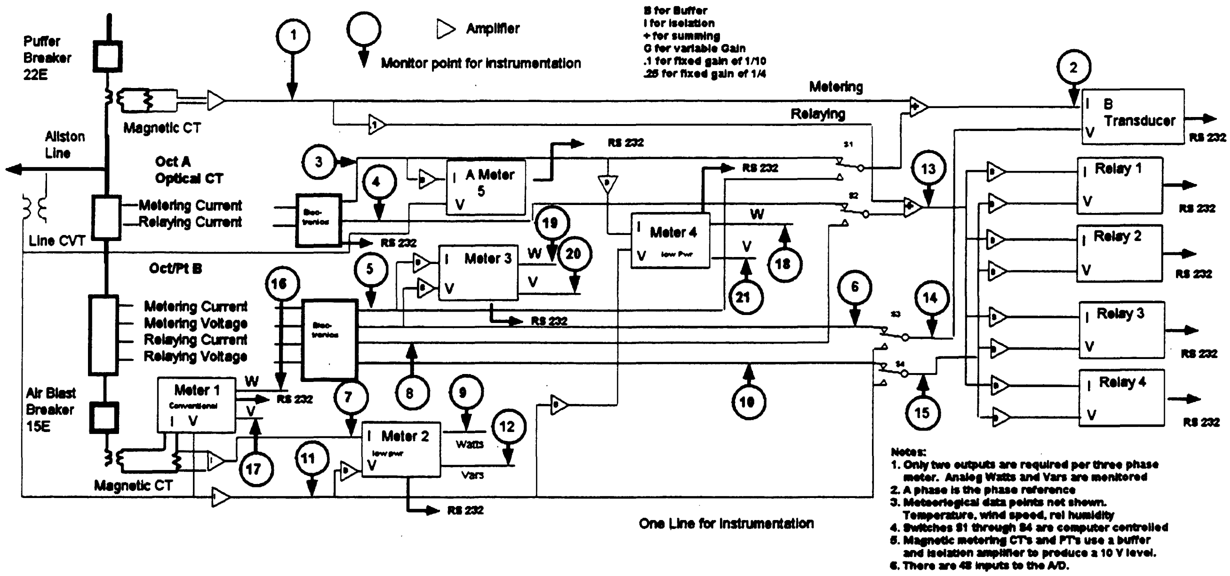

Figure 9

6.4 Relays and Meters

There are several different kinds of relays and meters installed at the site. After the power line transducer signals are collected and analyzed by these devices, assorted parameters are then retrieved by the DAS through three different avenues as follows:

- An **RS232 serial** connection is used by the DAS to collect information from two General Electric DLP and two Schweitzer Engineering Laboratories 321 relays, a Square D PowerLogic Circuit Monitor, and an ABB Iliaco 2200 meter. An RS232 1-8 multiplexer box was used to allow one computer serial port to communicate with all the devices.
- A **telephone modem** connection is used to query four Process Systems Sentry 100 solid state recorders for the energy pulse counts indicating total power flow detected by the Scientific Columbus JEM-1 meters. Due to their built in modem an RS232 connection could not be used for these devices. An external modem for the DAS and a phone line simulator were used to complete this connection.
- **Analog** signals were recorded by the DAS from the eight JEM-1 meter outputs indicating instantaneous real and reactive power flow.

6.5 Analog Anti-Alias Filters

All analog inputs to the DAS are first conditioned using 8 pole low pass anti-alias filters to remove unwanted high frequency signal components that could not be digitized properly by the DAS. The filters have a cutoff frequency of 900 Hz and are phase matched to at least 0.3 degrees phase difference between all channels.

6.6 VXIbus Data Acquisition System

The main computer screen control panel can be seen in Figure10. The user manipulates the objects on the screen to control the DAS.

There are additional front panels that appear when the user selects certain action buttons, but only the main panel will be discussed in this paper. It has several different areas of operation.

The *Process Control / Status* area on the main panel is used to control some main parameters of the program and indicate DAS status. Included in this section is the ability to select the trigger mode. The DAS can collect the predefined 15 minute periodic data or it can send just the raw analog samples to the hard disk for later review. The 15 minute data which is saved in the database server is primarily used in the steady state analysis, and the raw data is used most often for transient analysis. A combination of the 15 minute or raw can be selected or lastly the test mode can also be selected. Test mode is used for debugging and to look at the data onsite. When test mode is selected the DAS will be controlled in the *Test Mode* section of the front panel.

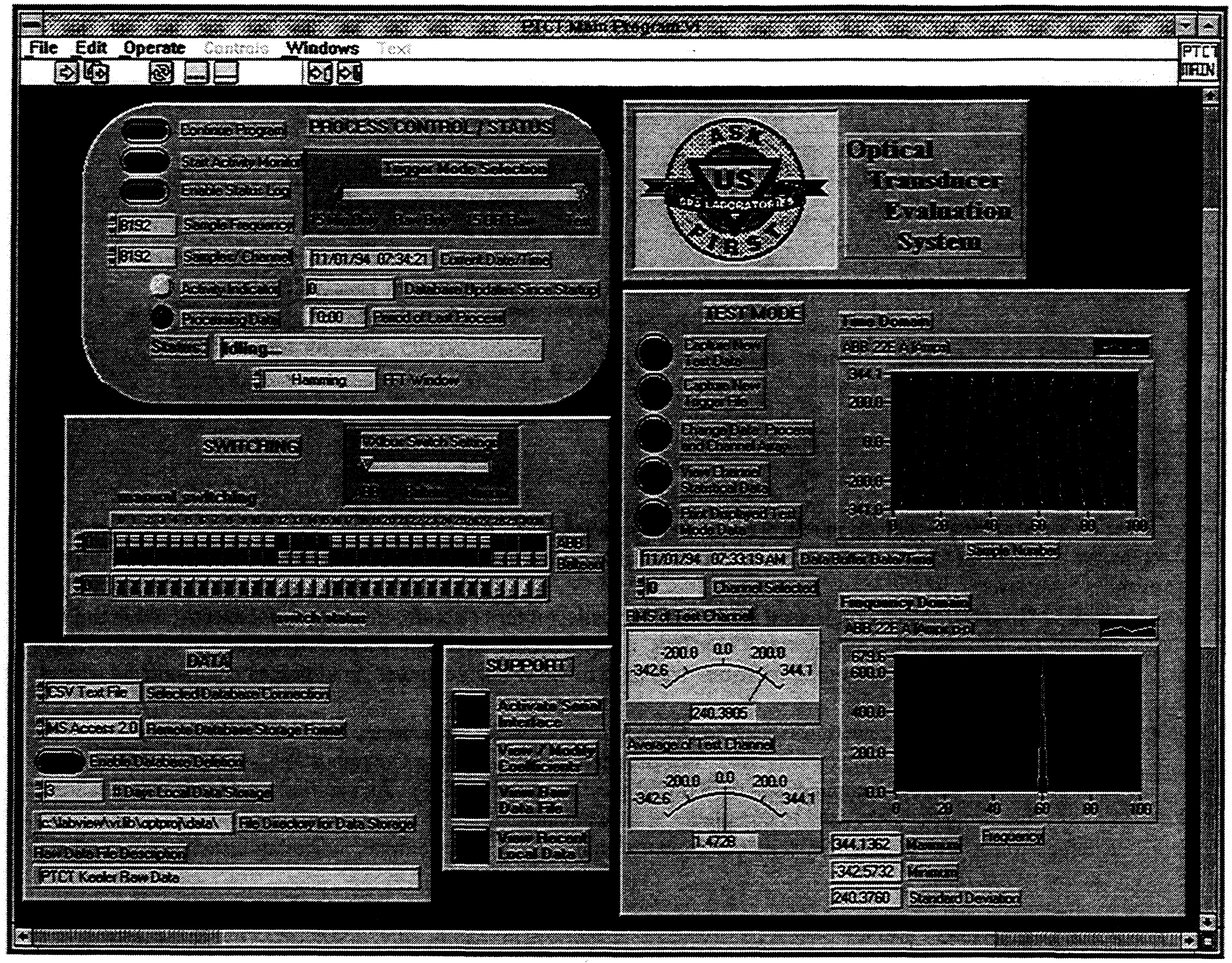

Figure 10

The sample rate for the 48 analog inputs can be set along with the number of samples acquired. During normal operation the 15 minute data sample rate is set at 8192 samples/second to accommodate the Fast Fourier Transform (FFT) analysis. The DAS can also log and display current system status and special events.

Test Mode is the area used for interfacing to the test mode of operation. *Test Mode* is used onsite to look in greater detail at data currently on the power line and to debug system signals. A series of simulated buttons is used to control the test.

First, a button is used to capture new analog test data for all channels specified by the settings found in the *Process Control / Status* section. Once the new data is captured, one channel of the data is displayed in the time and frequency domain in graphs to the right. The name of the channel along with the channel number are displayed for clarity. The user can select any one of the 48 analog input channels and the corresponding values from the previously sampled data are displayed. Additional statistical calculations are made on the data and these results are also displayed along with the date and time of the data collection from the PC clock. The statistical values including RMS, maximum, minimum, standard deviation, and average are also displayed for the data points. Through specialized hardware, the PC clock is synched with a GPS driven IRIG-B time source along with some of the relays and meters to provide an accurate reading of time.

Second, a button is used to initiate the acquisition of raw data to the hard disk as defined in the *Control / Status* section. However, the raw data mode must be selected in the *Process Control / Status* section for this button to be active. The raw data can then be analyzed onsite or offsite with a tool available from the *Support* section of the main screen.

Third, the user can view statistical data for all the channels at the same time in a different larger screen. This helps in side by side comparison of input signals.

Finally any of the *Test Mode* information can be sent to a printer for a hard copy. Currently use of the change data process and channel array button is under development.

The *Switching* section is used to control a signal switch card located in the VXIbus. The power line transducer signals routed into the relays and the Square D meter can be switched between the GEC or ABB optical devices. The user can switch each of the signals individually, or all signals can be preset to the ABB or GEC devices.

The *Data* section is used to configure the type of database utilized for information storage. In the process of software development an interface was developed for three different database formats consisting of ASCII, Microsoft Access, and Oracle 7.0. In the currently operating DAS configuration the data is stored onsite in the ASCII format and imported by the Oracle server at set intervals through a shared disk drive across the WAN.

The *Support* section is used to activate additional tools for working with the data. The tools are as follows:

- The **Serial Interface** is used to separately query any one of the serial or modem devices. The individual parameters collected are different for each device, but they include a combination of line voltage, line current, watts, VARs, device time, energy in and out, and line frequency.
- The **View/Modify Coefficients** tool is used to input a new multiplication coefficient and offset used in converting the raw voltage readings on the input signals to engineering units. The changed value is only good as long as the computer is turned on. At startup the DAS reads the initial values from a boot up file on the hard disk.
- The **View Raw Data File** tool is used to analyze a raw data file created by the trigger file button in *Test Mode*. The same analysis is performed as in the *Test Mode* section, except on data values stored in a file rather than in memory. This is useful in reviewing captured transients after a test.
- The **View Recent Local Data** tool is used to access the temporary onsite database information configured in the *Data* section.

6.7 Data Collection

The DAS in 15 minute mode collects harmonic information in addition to the line voltage, current, and power. For each signal originating at one of the power line transducers the amplitude of all 60Hz harmonics up to the 15th are stored along with other values such as weather and relay signal switch status. Before the analog signals are read by the DAS they pass through analog anti-alias (low pass) filters from Frequency Devices Inc. to remove higher frequency components that would not be recoverable after digitization.

After collection data can be viewed onsite through the user terminal or saved as a hardcopy from a printer. All 15 minute data is retrieved from Keeler Substation through the BPA WAN by an Oracle based data server at the Ross Complex.

6.8 Oracle Database Server

The data is stored and retrieved primarily with database management software from Oracle. The server is a high performance PC running under the Microsoft Windows NT Operating System. It is connected to the BPA WAN and is accessible to anyone on the BPA WAN with the correct access privileges.

6.9 Data Analysis

The data analysis can be performed by anyone connected to the BPA WAN. This includes users of any IBM compatible PC, Macintosh, or VAX based computers. Some of the software packages used for analysis are Oracle Browser, Microsoft Excel and Access.

7. LABORATORY EVALUATION OF OPTICAL TRANSDUCERS

A series of electrical tests were performed on a set of prototype optical CT/VTs, and one set each of commercially available optical CT/VTs and CTs. (The prototype and commercially available CT/VTs were manufactured by the same company). This testing took place over a two week period from August 1 through August 15, 1994. The equipment from both manufacturers had either been returned to each manufacturer to be upgraded or repaired, so, consequently, were not ready for evaluation until August 1, 1994. Since a short time period was available for the laboratory evaluation, the data presented here is considered preliminary and will be compared to the steady state performance over the two year evaluation period. The main focus of the tests was an evaluation of the metering ratio and phase angle stability. Other tests performed included vibration at high current, and lightning and switching impulse withstand. (Ambient temperature changes and vibration effects are thought to be the most likely cause of performance problems for optical instrument transformers.) All tests were performed at Bonneville Power Administration's Ross Complex in Vancouver, Washington, by BPA's Laboratory Services.

7.1 High Current Tests

High current tests were performed on the Company X prototype CT/VTs and Company Y CTs, to evaluate the performance of the optical CT circuits during and after application. A current of 40,000 amps was applied for approximately 10 cycles. Current metering and relaying outputs were monitored on a digitizing oscilloscope during the test. Output waveforms were evaluated for signs of vibration effects, such as electrical oscillations or waveform distortion.

No disturbances could be detected during the high current tests, for both the prototype CT/VTs and the CTs.

7.2 Impulse Tests

Impulse withstand tests were performed on Company X prototype CT/VTs and Company Y CTs, to test their electrical insulation design. The prototype CT/VTs were tested to 1550 kV lightning impulse and 1175 kV switching impulse. The CTs were tested to 1500 kV lightning impulse (maximum voltage capability of the facilities at that time). Time restrictions did not allow testing of the commercial CT/VTs, but they appeared to have an insulation system identical to the prototypes. All tests were performed according to standard IEEE test procedures.

Both the prototype CT/VTs and CTs withstood all impulse tests. No abnormalities were detected.

7.3 Metering Ratio and Phase Angle

Metering ratio and phase angle were evaluated using techniques designed especially for these optical transformers. Standard ratio and phase angle instrumentation will not work with optical instrument transformers, due to the low output voltage, and in the case of current transformers, the conversion of current to voltage. For both optical voltage and current transformers, the ratio and phase angle were evaluated by comparing the optical transformer output to the output of a reference standard. The output of the optical transformer and standard are measured using a GPIB controllable precision voltmeter. A computer program was written to query both almost simultaneously, and to calculate the optical transformer ratio. Several readings are taken and averaged to improve accuracy.

Phase angle was determined by evaluating the difference in zero crossing between the optical transformer and reference standard. Voltages were measured using a 12-bit resolution digitizing oscilloscope. Several readings were taken and averaged to improve accuracy. A resolution of 1 minute was achieved with this technique.

Reference voltage was measured using a precision capacitive voltage divider. The high voltage section of the divider consisted of a Micafil 1000 kV standard capacitor, traceable to NIST, with a tolerance of calibration of ±0.05% absolute. The actual capacitance was calculated before testing, based on the capacitor gauge pressure, barometric pressure and ambient temperature. The low voltage section capacitor was a Tettex 1 microfarad precision capacitor (normally used with a ratio bridge for instrument transformers).

Reference current was measured using a BPA "standard" 2000/5 amp current transformer, loaded with a one ohm shunt. This standard was checked at the NIST prior to this test. A calibration curve supplied by NIST was utilized for the test. Current was measured indirectly by measuring the voltage across the one ohm shunt.

Ratios were measured by comparing the instrument transformer output to the output of the reference standard using HP 34401A multimeters. These meters have a 90 day accuracy rating at 60 Hz of 0.06%. All instruments were controlled and data acquired using a LabVIEW program written for these measurements. For evaluation of ratio stability, the LabVIEW program collected data into a spreadsheet file for later analysis and graphing.

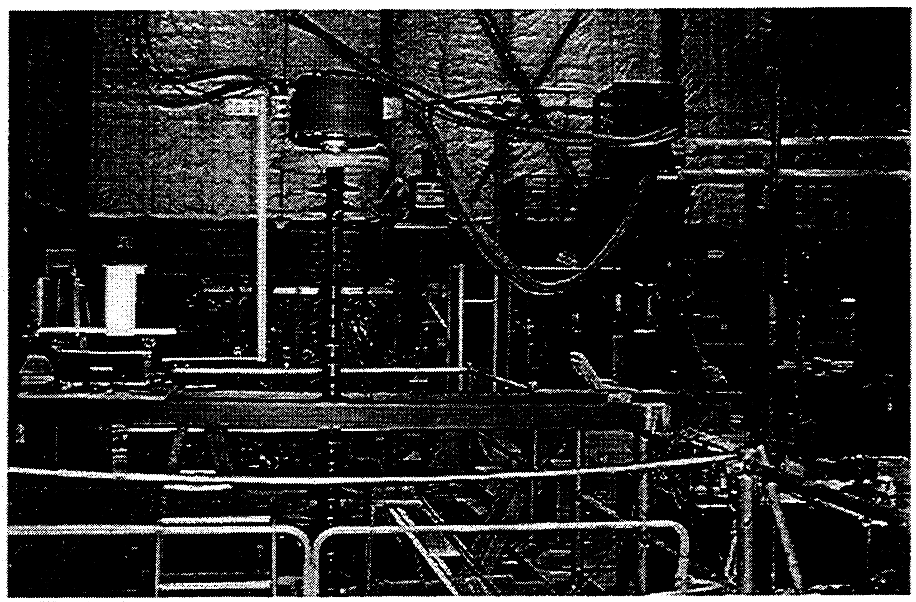

Figure 11

In some cases, a conventional magnetic VT or CT was also put in the circuit, for comparison to the optical transformer. This provided additional confidence in the data when the optical transformer appeared to be unstable with time.

7.4 Vibration Testing

An optical CT was connected to a current power supply with a steady state current of 600 amps. Vibration was increased from 5 Hz through 60 Hz in 5 Hz increments (please see figure 11). Current was measured with a 400/1 current transformer supplying a one ohm burden calibrated by NIST. All plots were taken with a Hewlett Packard 3561A Dynamic Signal Analyzer, BPA # 188727, calibration 2/94. A baseline measurement was taken with no mechanical shaking of the optical CT. The plots were compared to this "zero shake" plot to help identify "potentially significant" responses. The vibration test set-up introduced mechanical vibration in two degrees of freedom measured with a "north/south" accelerometer and an "east/west" accelerometer (please see figure 11 and 12). Several plots representing introduced voltage on the CT output are indicated in figures 13, 14 and 15. These particular frequencies were selected for significant introduction of secondary voltage and are only a small sample of the total vibration data collected. The vertical scale represents a per cent of introduced voltage over the 60 Hz fundamental. This will be discussed further at this conference as time and interest permit.

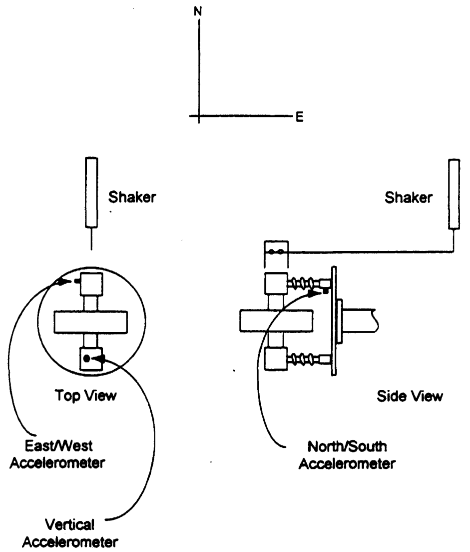

Figure 12

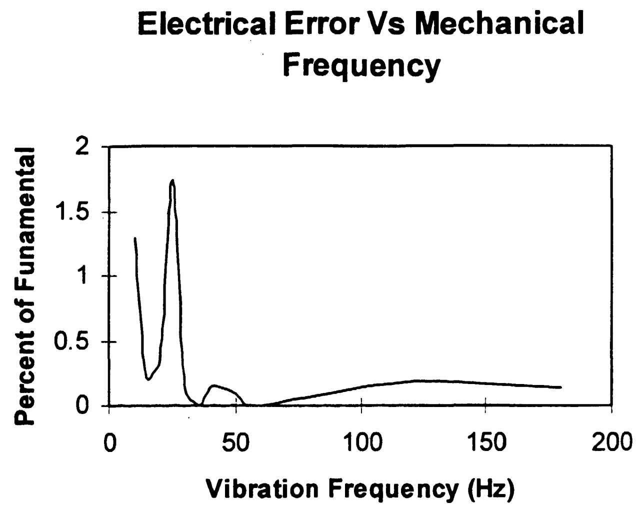

Figure 13

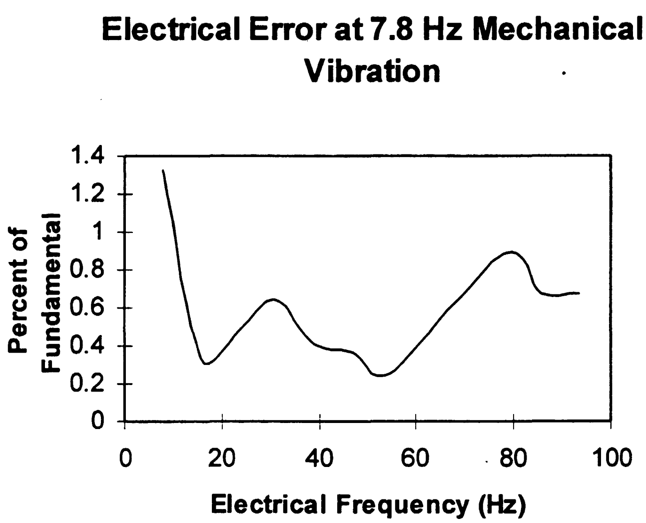

Figure 14

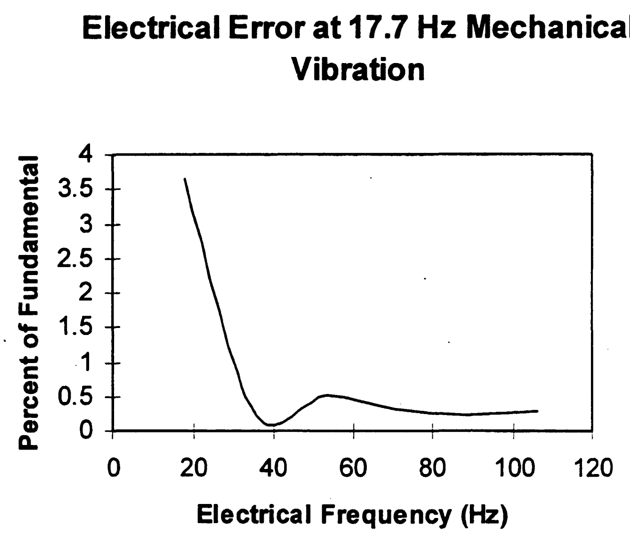

Figure 15

Discussion

These tests have shown that the optical transformer technology is close to if not already meeting industry standards. However, metering accuracy may only marginally meet industry standards on some of the units tested due to changes in metering ratio related to changes in ambient temperature. This will be compared to the steady state evaluation over the next two years.

8. TRANSIENT PERFORMANCE DURING STAGED FAULT TESTING

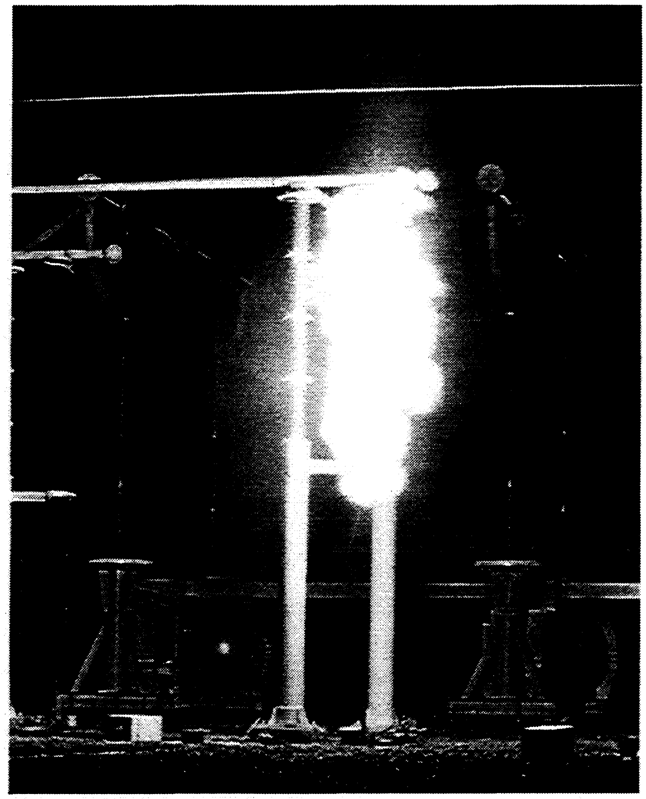

Figure 16

As part of the testing of the new static var installation at Keeler Substation, three faults at 525 kV were initiated by the Laboratories. One of the faults can be seen in Figure 16. These three faults occurred only 100 feet from the optical transducer installation. This provided a unique opportunity to do a transient evaluation of the optical transducers themselves as well as determine that the low level signal distribution system and relaying would operate properly under fault conditions.

Upon inspection of the fault waveforms, one can see the increased frequency bandwidth as compared to a standard CT used as a reference. Each relay operated successfully. This was the first relay operation using all low power voltage and current inputs occurring from an actual power line transient. The relay test results will be discussed in further detail at the conference.

9. STEADY STATE PERFORMANCE

Since March 15, 1995, a data base of steady state data has been collected. Since installation in late September, 1994, the low level signal distribution system, meters and relaying were observed for performance anomalies. After several rechecks of the optical transducers, relaying and metering along with two end to end calibrations of the low level distribution system, the steady state data was determined to be stable and within specifications since early March, 1995. Inputs to the low power input JEM I meters in comparison to a standard 120 volt 5 amp input JEM I at Keeler Substation were used to determine the stability of the optical transducers. The first plot is the JEM I watt error (please see figure 17); the second plot the JEM var error (please see figure 18); the third plot is the ABB metering current error (please see figure 18); and the fourth plot the GEC metering current error (please see figure 19). All traces indicate both optical current devices are within the 0.3 per cent error specification. This will be discussed further at this conference as time and interest permits.

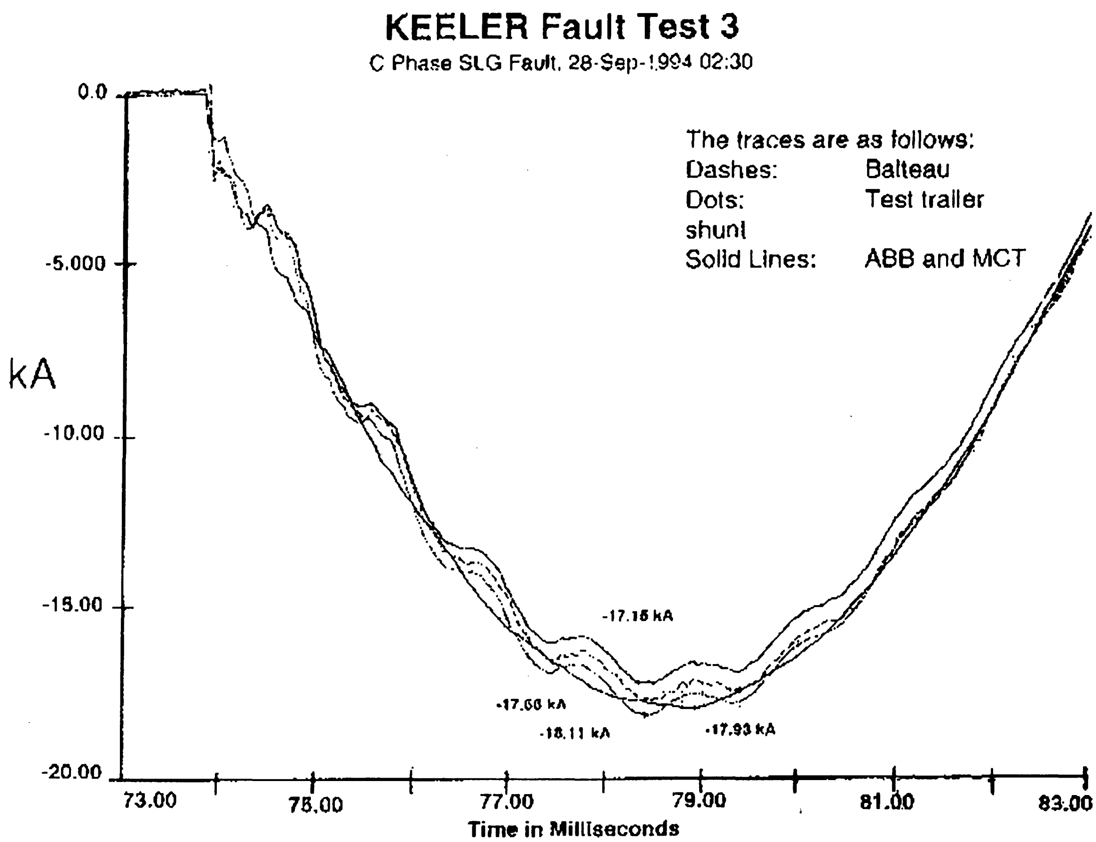

Figure 17

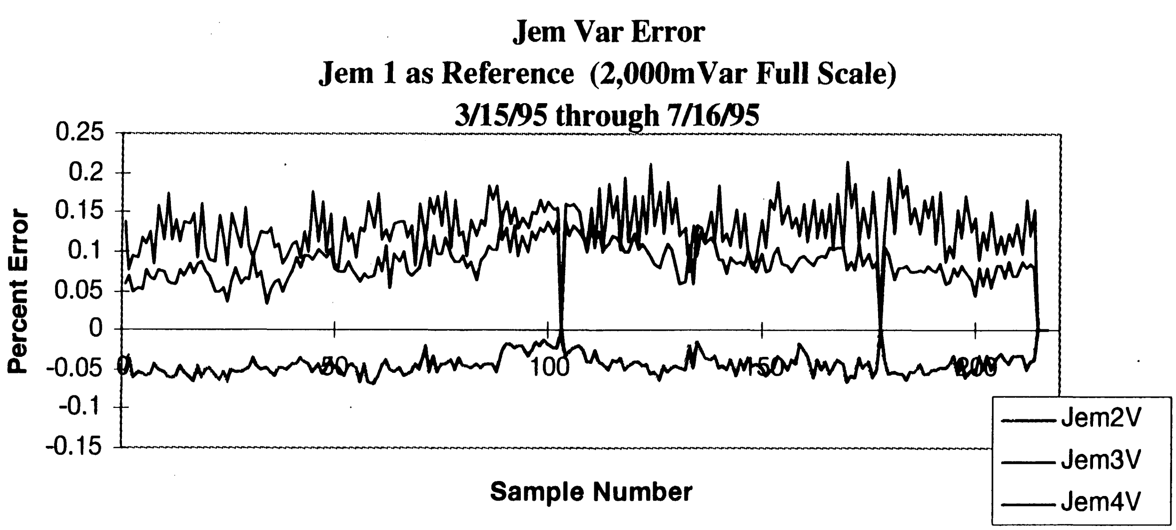

Figure 18

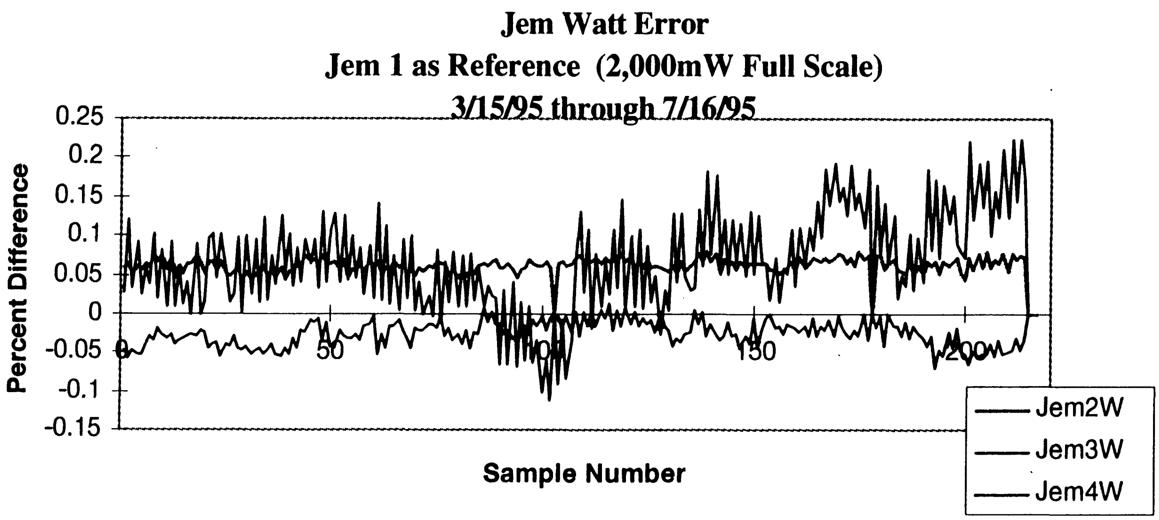

Figure 19

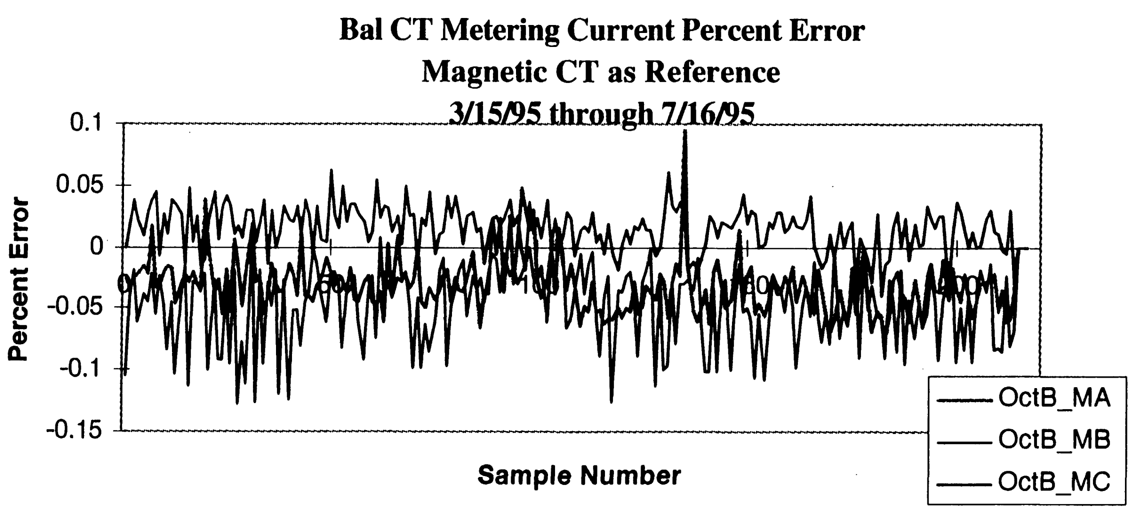

Figure 20

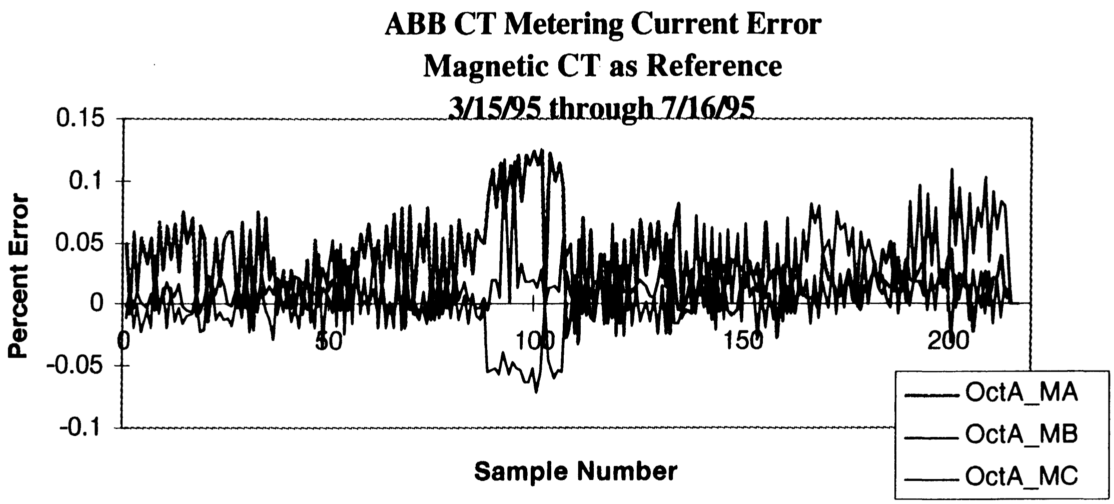

Figure 21

8. CONCLUSION

Increasing applications of optical devices in a modern substation environment is now a reality. Once in production, optical devices have the potential to reduce the cost of the design and installation of the substation of the future. All signals from the substation "PT's and CT's" will be brought in on one optical fiber that can carry a multitude of signals. New equipment can use the same optical communications bus without the need for new cabling. Substations will no longer require the electrical isolation from the secondary currents and voltages used today. The substation equipment will no longer need to transform these secondary signals to electronic voltage levels. Self diagnostics will indicate when repair is required leading to reduced maintenance costs and increased reliability. All equipment can be remotely accessed on one dedicated communication network reducing operational costs as well.

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