ONLINE CIRCUIT BREAKER MONITORING SYSTEM

A Thesis

by

ZARKO DJEKIC

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2007

Major Subject: Electrical Engineering

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ABSTRACT

Online Circuit Breaker Monitoring System.

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Circuit breakers are used in a power system to break or make current flow through power system apparatus. Reliable operation of circuit breakers is very important to the well-being of the power system. Historically this is achieved by regular inspection and maintenance of the circuit breakers. An automated online circuit breaker monitoring system is proposed to monitor condition, operation and status of high and medium voltage circuit breakers. By tracking equipment condition, this system could be used to perform maintenance only when it is needed. This could decrease overall maintenance cost and increase equipment reliability. Using high accurate time synchronization, this system should enable development of system-wide applications that utilize the data recorded by the system. This makes possible tracking sequence of events and making conclusions about their effect on-line. This solution also enables reliable topology analysis, which can be used to improve power flow analysis, state estimation and alarm processing.

To my parents and Maja

ACKNOWLEDGMENTS

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1   INTRODUCTION

1. 1   Background

Circuit breakers are electromechanical devices used in the transmission and distribution power system to connect or disconnect the power flow at the generator, substation, or load location. The circuit breakers are capable of making, carrying and breaking currents under normal circuit conditions. This relates to making and then carrying currents for a specific time, as well as breaking currents under specified abnormal circuit conditions such as those of short circuit [1].

The breakers consist of current break/make contacts, opening/closing mechanism and control circuit. Breaker may have a lifetime of over 40 years. The majority of the time circuit breakers remain either open if the point in the network needs to be isolated or closed and simply act as connector between two sections of an electrical conductors. But, but in many occasions they do indeed perform their intended role in protective and switching functions.

They can be operated by power system protection relays, which detect fault on the system and identify the appropriate breakers needed to be open in order to isolate the fault and enable the rest of the system to function normally. During one event, circuit breaker can operate several times. Reclosing is used to clear temporary faults on the line usually caused by lighting. This is usually done by reclosing relay, which force breaker to close back the transmission line shortly after the opening [2].

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This thesis follows the style of *IEEE Transactions on Power Delivery.*

If the fault still exists after reclosing, relay opens breaker immediately. Breaker will open and close several times before it eventually locks out. Typical clearing time sequence for distribution breaker is given in Figure 1 (TA – trip applied; O – opened breaker; C – closed breaker). On extra high voltage circuit breakers single-shot reclosing (one reclose attempt) is employed because of stability concerns [3].
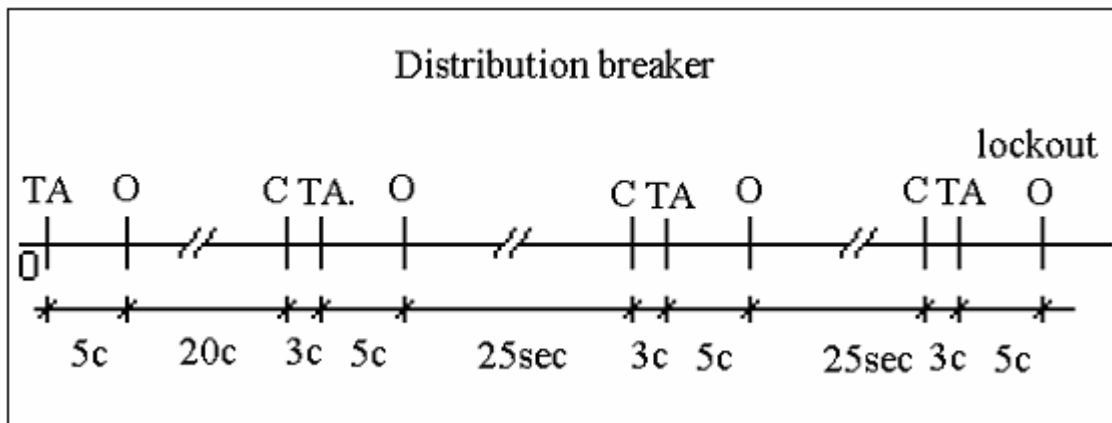
Figure 1. Typical permanent fault reclosing sequence– distribution breakers

When a fault, manifested as a short circuit current, occurs in an electrical system, it usually becomes necessary to operate a current interrupting device. In that case, interruption of the current in a circuit frequently takes place during a transient condition when very high currents are present. The interruption itself may produce an additional transient that is superimposed upon the instantaneous conditions of the system. Thus, it is recognized that interrupting devices must cope with transients in the currents caused by an event generated elsewhere in the system, plus the transients that have been initiated by the interrupting device itself. The opening of the contacts should occur at a current zero when interrupting short circuit currents to reduce transient effects in the grid. In some

cases breaker cannot interrupt current during firs zero crossing interval so it makes several attempts before interrupt current. This creates very harsh working condition for circuit breakers. It is very important that circuit breakers are in good condition to be able to interrupt currents and prevent further damage on power system equipment.

In addition, a breaker may be operated through a manual command issued by power system operators. Sometimes the breaker may not open or close on command, allowing the fault to exist for a longer duration than the system can sustain while functioning normally. Unless a breaker failure initiate action is taken, misoperation of breakers can lead to undesired changes in system functioning that may result in the system going in an abnormal state, potentially causing major system-wide power outage.

The circuit breaker forms a critical part of the protection system used to isolate power system faults, as well as the Supervisory Control and Data Acquisition system (SCADA) used for power system switching. Opening or closing the contacts of a circuit breaker is normally done in a very random fashion driven by environmental conditions leading to a fault or power system operating conditions leading to an isolation of certain parts of the system. Consequently, transient current and voltage disturbances may appear in the electrical system. In many cases, it is possible to control these transients by operating the circuit breaker in synchronism with either the AC current or voltage, depending upon the type of switching operation at hand. The synchronization may be based on magnitude and phase difference at two pints of connection or on the zero crossing conditions of the alternating current or voltage. For example, the opening of the contacts should occur at a current zero crossing when interrupting short circuit currents and the closing of the

contacts should take place at voltage zero when energizing capacitor banks. Operations that may require synchronized switching are those involving the switching of unloaded transformers, capacitor banks, and reactors. Energizing transmission lines and opening the circuit breaker to interrupt short circuit currents are also good candidates for performing the synchronous switching [4]. Additionally, the success of a synchronized operation will depend upon the proper matching of the operating characteristics of the circuit breaker with the response of the system. Since circuit breaker operating characteristics may be changing, it is very important to monitor circuit breaker characteristics over its lifetime to be able to match those characteristics to the operating needs.

Through the SCADA, system circuit breakers' contacts are used to determine power system topology. By monitoring open/closed status of all circuit breakers, it is possible to create bus/branch topology configuration of the power system. This information is essential for several power system applications used to improve reliability of the power system, such as power flow, state estimation and alarm processing.

In order to ensure operation that is more reliable and status information of circuit breakers all over the system, efficient and adequate circuit breaker monitoring is required.

1. 2   Problem Definition

In order to stay competitive in today's market, electric utilities are being pressured to reduce their overhaul and maintenance costs and improve power system operation. Maintenance clearly affects component and system reliability: if too little is done, this may result in an excessive number of costly failures and poor system performance and, therefore, reliability is degraded; done too often, reliability may improve but the cost of maintenance will sharply increase. One way to accomplish the goal is to perform maintenance based on equipment condition rather than elapsed time. To sustain the confidence level about the operating state of circuit breakers (CBs) different maintenance programs have been established. These programs follow established standards, guidelines and the recommendations of the manufacturer [5]. In the past, maintenance routines consisted mostly of predefined activities carried out at regular intervals (scheduled maintenance). However, such a maintenance policy may be quite inefficient: it may be too costly (in the long run), and may not extend component lifetime as much as possible.

The most common maintenance plan is to adopt a rigid inspection and maintenance schedule where predefined activities are carried out at fixed time intervals. Whenever the component fails, it is repaired or replaced. The maintenance intervals are selected based on long-time experience. The intervals and durations for scheduled inspection and maintenance show considerable spread. Intervals range from several months to over a year and maintenance duration could last up to few weeks [6]. Usually all maintenance recommendations are based on experience with particular CB types being used in a given system. Performing the same maintenance approach on all breakers can be inefficient

especially in the cases when utility company owns large number of diverse units. This may also be very costly because of the down time required to perform these procedures. A more logical approach may be to continually evaluate the condition of CBs that through experience have been identified as being the most likely to fail and provoke a severe damage that would disrupt the power delivery service.

Most of the high and medium voltage circuit breaker failures that have been observed in the field can be attributed to the mechanical problems and difficulties related to the auxiliary control circuits. A report by CIGRE shows that approximately 25% of the major and minor failures of circuit breakers in service are caused by the control circuit failures [7]. By observing control circuit signals, it is possible to make conclusions about CB health. Besides this conclusion, circuit control signals can be used to make conclusions about some other parts of circuit breaker internal parts such as mechanical contacts and moving mechanism [8]. The above-mentioned statistics can be used as a guideline for the selection of the components that should be monitored. The most desirable option would be to develop a system that constantly monitors critical components and detects any deterioration that may occur over time and to predict, in a proactive way, impending failures.

To improve system operation, the information obtained by the monitoring system should not be limited exclusively to evaluating the condition of the circuit breaker. It may be used to control sequence of circuit breaker operation and changes in system topology. Further, it can be used to enhance the accuracy of the controls for synchronous operation. More precise and reliable assessment of system topology may be achieved by

integrating redundant data from SCADA system and CB monitoring system. It may also be possible to adjust the initiation of the closing or opening operation to compensate for variations in the breaker making or breaking times that are influenced by the parameters that are being monitored.

The benefits offered by such monitoring should not be restricted to providing information for future use or to developing condition trends about the well being of the circuit breaker that will be applicable to future maintenance actions. Additional monitored parameters may not directly reflect as an improvement in the breaker operation but taken as a whole will serve to increase the reliability assessment of the equipment and power system.

Data collected from circuit breakers in a substation or all over the system should be combined to make conclusions about the system topology and operation performance that could help in increasing system reliability [9]. Such applications may require that the collected data should be synchronized in time. While the circuit breaker monitor (CBM) data can provide information about the operation and status of individual circuit breaker, substation and system-wide applications can help increase reliability by providing information about the sequence of events and topology changes of the power system. Some of this information is also obtained by SCADA. The redundant and more detailed information from circuit breaker monitors can be used to verify the consistency and increase redundancy of the measurements thereby increasing robustness of data and reducing operation errors.

1. 3   Existing Approaches

Different monitoring systems have been designed and proposed to monitor the condition of different breaker elements, detect CB health and predict the time intervals for maintenance. All those devices monitor different physical properties such us: the mechanism velocity, phase currents, gas pressure, temperature or circuit breaker vibration [10],[11] etc.

A number of condition monitoring systems have been proposed, including the use of acoustic signatures [12] but as of now most of these systems have not yet been translated into a massively applied product and still remain mostly in a demonstration environment. Furthermore, the reliability of such systems has to be proven primarily because of its complexity and its high measurement sensitivity, which makes it vulnerable to noise and to influence of extraneous sources.

Some of the data acquisition systems currently available to cater specifically to measuring quantities from the control circuit [13],[14],[15],[16],[17],[18] are not suitable for on-line monitoring applications of breaker performance in a switching sequence that involves multiple breakers. Table 1 shows devices available on the market and their characteristics.

Table 1. Data acquisition systems available in market. Source: Ref. [13]– [18]

Product Name	Company Name	No. of channels	Bits per sample	GPS	Sampling Rate	Online	Wireless Transfer
BCM 200	Qualitrol corp	10	10	No	2kHz	Yes	No
CBT 400	Qualitrol corp	10	12	No	10kHz	No	No
SICAM AI16	Siemens	16	12	No	1kHz	Yes	No
Optimizer+	INCON	-	-	No	1.9kHz	Yes	No
TDR9000	Doble	3-24	-	No	10kHz	-	No
CBWatch-2	Areva	10	-	No	5kHz	Yes	No

They have limitation that they do not record enough information to make accurate diagnosis of control circuit faults that may occur on multiple breakers performing common switching sequence. Most of them do not have sufficient number of channels, online monitoring and time synchronization capabilities to enable the artificial intelligence tools to make good decisions about the status of the breaker and/or system. Most of the existing monitoring systems do not have any option for time synchronization of recorded data. This limits application of data only to the usage for maintenance purposes.

Available monitoring devices do not have time synchronization capabilities and cannot be used to track status information of the breakers that could be used to determine system topology.

1. 4   Objectives

The objective of this thesis is to investigate feasibility, specify requirements and propose implementation architecture of an automated circuit breaker monitoring device that enables continuous and reliable system monitoring of condition and at the same time status and operation of high and medium voltage circuit breakers. Online system implementation is essential for efficient circuit breaker monitoring because of infrequent and in many cases, unpredictable time of breaker operation. These design requirements should not rely on a specific analysis purpose but should provide various data for different user needs. Investment in online circuit breaker monitoring system should not be limited only to improving maintenance but should also be used for improving existing system control applications, which may need breaker operational or status data. Circuit breaker monitoring data should enable development of different maintenance and system-wide switching operation applications. Some of the useful usages require implementation of time synchronization between the data acquisition units. Monitoring systems should be simple, low cost and user-friendly and require a minimum of engineering time to retrofit into the design of new and existing facilities. In addition, installation should be as simple as possible to minimize installation time and cost. System needs to be noninvasive to enable installation without breaker isolation and inexpensive to enable system-wide installation.

2   CIRCUIT BREAKER MONITORING

2. 1   Introduction

Circuit breakers, as critical components of the power system, should be able to satisfy all required specification reliably. Electric power transmission system breakups and equipment damage may occur if a circuit breaker fails to operate due to a lack of preventive maintenance. The need for proper maintenance of circuit breakers is very important, as circuit breakers status may remain idle, either open or closed, for long periods. Circuit breakers are also often located in remote areas, which make their inspection and maintenance more difficult and expensive.

To improve reliability of the power system through various system analysis functions it may be necessary to know power system topology configuration. Real time and on-line monitoring seems to be perfect solution for circuit breaker condition and status monitoring. First on-line monitoring of circuit breakers was introduced through Supervisory Control and Data Acquisition (SCADA) system. This system is used for CB status monitoring and remote breaker operation. This system monitors status of CB mechanical contacts and transfers it in real time to a central place. Condition monitoring is a relatively newer concept that has come about primarily because of recent developments of electronic sensors and data acquisition equipment that have made this idea not only technically feasible but also economically attractive.

Condition monitoring is also an essential component for synchronous switching simply because this depends on how accurately the operating characteristics of the circuit

breaker can be controlled. It is know that the breaker health, status and operating characteristics can be affected by extreme ambient temperatures, and by other prevailing conditions such as mechanism operating energy levels, control voltages, operating frequency of the equipment, its age, and its maintenance history among others. Collecting real time information about these variations, breaker operation performance and status would provide a good data source to improve breaker maintenance, synchronous operation, topology analysis and other system-wide analysis that rely on circuit breaker status or condition data.

2. 2   Circuit Breaker Status Monitoring

As the demands for reliable electric power became greater and as the labor shortage and expertise became a more significant part of the cost of providing electric power, technologies known as "supervisory control and data acquisition," or SCADA, were developed to allow remote monitoring and even control of most important system conditions. Due to low processing and communication capabilities at the beginning, SCADA was limited to monitoring and control of only critical parameters in a substation. Even with introduction of new microprocessor and wide-band communication technologies, the industry was slow to accept these technologies in critical real-time applications. Today SCADA remains limited to simple monitoring and control task such as CB status assessment; voltage, current, active and reactive power monitoring; and CB remote switching and power flow operation as shown in Figure 2.
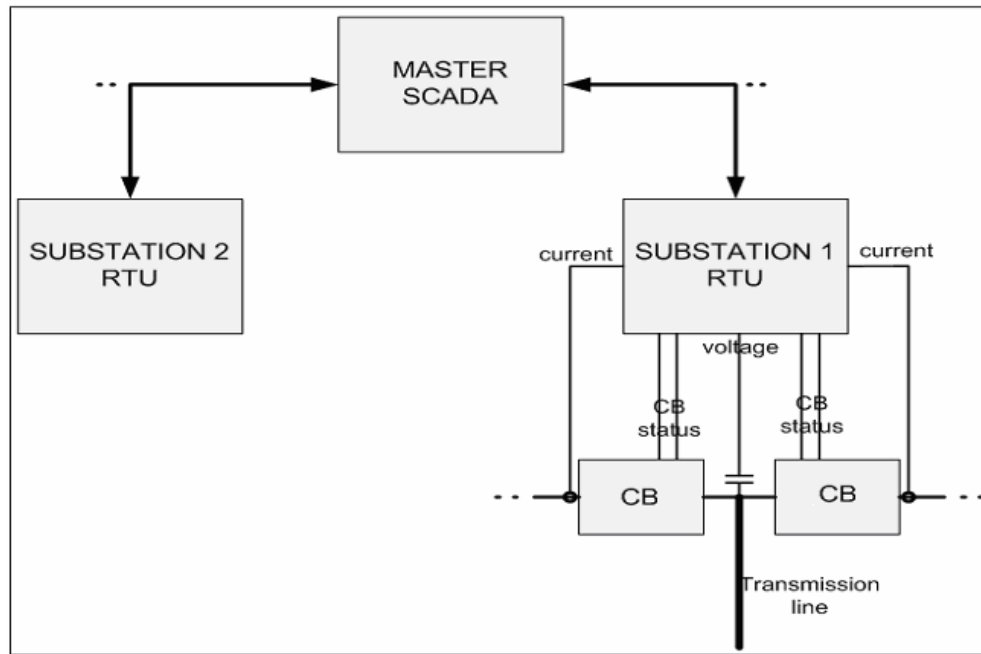
Figure 2. Traditional SCADA topology

Substation RTU is wired to CB auxiliary contacts (52a and/or 52b), which are used to track circuit breaker status. They operate when the breaker mechanism changes state. The 52a and 52b contact signals represent the voltage across auxiliary switches that specify the open or close status of the circuit breaker - Figure 3. Contact 52a opens when the breaker opens and closes when the breaker closes. It is also called "a contact". Contact 52b has opposite logic: it opens when the breaker closes and closes when the breaker opens. It is also called "b contact"[2].
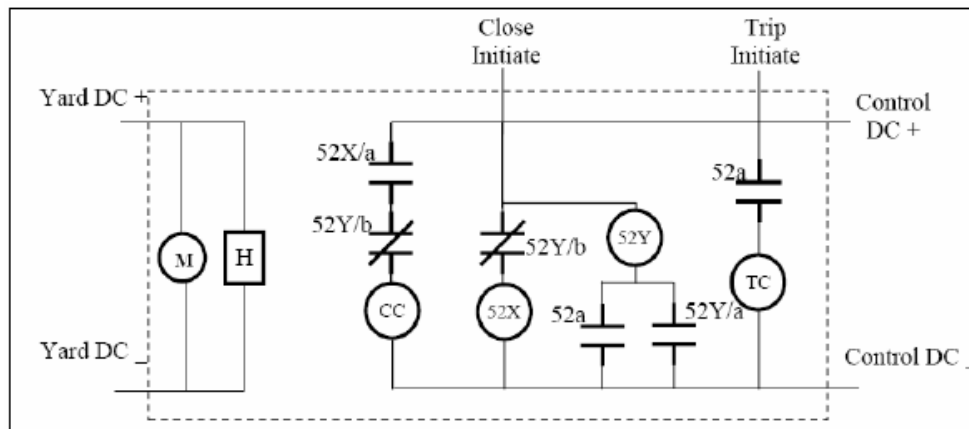
Figure 3. CB control circuit

SCADA system samples input signals at a very low sapling rate and transfers status data to the central place - SCADA master. Information available from such a system is statuses from all circuit breakers connected to Remote terminal Units (RTUs), which is used by the operator and system analysis applications. In some cases, auxiliary contact doesn't show actual breaker status due to mechanical, electrical and/or wiring problem. In many cases, wrong status information cannot be detected easily. It could create significant errors in a state estimator and alarm processor that can lead to unwanted and unexpected operator actions regarding power system operation. Redundant circuit breaker status monitoring through a dedicated CB monitor should decrease breaker status error probability and increase power system reliability.

2. 3   Circuit Breaker Condition Monitoring

To keep circuit breaker in good performance condition different maintenance programs have been established. These programs follow standard guidelines and the recommendations of the manufacturer. Maintenance programs are generally based on

manufacturers and users operating experience. This practice could be often inefficient and costly because of the down time required to perform maintenance procedures. In many cases, these procedures develop problems caused by maintenance of otherwise satisfactorily performing equipment. The need for circuit breaker maintenance is increasing as one has more impacts of aging equipment, more aggressive system expansion and more stringent customer reliability requirements. A new approach is to continually evaluate the condition of those components that through experience have been identified as being the most likely to fail and those whose failure could provoke a severe damage that would disrupt the electric power service. Condition monitoring is a relatively new concept that has come about primarily because of recent developments of electronic sensors, data acquisition equipment, and affordable communications that have made this idea not only technically feasible but also economically attractive.

Circuit breaker monitoring can be used to improve or develop flowing functions [19]:

- Determine the condition of a specific circuit breaker

- Asses the condition of the circuit breaker support and control functions

- Optimize maintenance activity

- Understand the condition of a larger population of circuit breakers acting in similar circumstances by examining a representative sample of the population

- Facilitate circuit breaker utilization

- Reduce circuit breaker failure rates

- Expand knowledge available to determine the cause of failures after the fact

- Improve economics of equipment operation

There are several experimental and commercial applications of circuit breaker monitors. Some of them are more focused on breaker health condition; the others are more related to breaker operation. The information that is gathered by the monitoring system does not have to be limited exclusively to evaluating the condition of the circuit breaker. It may also be used to enhance other power system functions and applications. It is entirely possible to use the CB monitoring data to adjust the initiation of the closing or opening operation to compensate for variations in the closing and breaking times of the circuit breaker. Data could be also used to improve power system topology analysis, alarm processor function and other system analysis applications. The benefits offered by condition monitoring are also not restricted to providing information about current breaker condition. In addition, the solution may be use to improve circuit breaker design and performance.

2. 4   Conclusion

This section presents problems and current solutions for circuit breaker status and condition monitoring. It describes the importance of circuit breaker condition monitoring. It also explains circuit breaker status monitoring and related requirements as well as circuit breaker maintenance needs for online condition monitoring. An assessment of the benefits that could be realized from such a monitoring system is also given.

3   SYSTEM REQUIREMENTS

3. 1   Introduction

First step in the process of developing a system for circuit breaker monitoring is to define data acquisition. Data needs to be acquired and stored to enable extraction of any information. It is very important to acquire sufficient data to enable high quality analysis and yet the data acquisition solution has to be low cost. Based on desired circuit breaker operation that we wish to analyze, we need to choose an appropriate set of signals to be monitored. The signals have to carry enough information about breaker condition. Those signals need to be converted to digital form to enable simple and efficient data storage, transfer and processing. Data sampling on all the signals used to monitor circuit breaker operation needs to be synchronized to enable system wide applications.

3. 2   Parameter and Signal Selection

There are a large number of parameters and signals that could be used for circuit breaker monitoring purposes. There are also many methods to measure or calculate those parameters [20],[21]. The parameter candidates for monitoring should be chosen in such a way that keeps system complexity and price low but at the same time gives enough information to make reliable conclusions about breaker condition and operations. The complete set of parameters/signals needed to perform quality analysis and give reliable breaker status information has to be carefully selected. Our approach is to avoid direct measurements of mechanical parameters and instead we acquire electrical signals necessary to estimate non-electric parameters. Using this approach, we should be able to

perform analysis of mechanical and other non-electric parameters measuring only electrical signals available in CB control circuitry. This can eliminate all complicated and expensive transducers necessary for acquisition of mechanical parameters. We can also decrease the cost and increase reliability of the monitoring system.

Circuit breaker parameters could be grouped as follows [20]:

- Components at high voltage

- Control Circuit and Auxiliary Contacts

- Operating Mechanism

3. 2. 1   Components at High Voltage

Components at high (operating) voltage include insulation bushings, tank medium, and main contacts. Several parameters could be monitored on every part. Dielectric failures and interrupter failures represent a high percentage of the reasons for circuit breaker problems. Many of these failures would take place without any prior warning, but by monitoring high levels of corona, high leakage currents, high moisture content and low insulating gas density, one could predict the failure. Few parameters can be monitored in a relatively simple way, but there are many others, which are difficult to monitor while the circuit breaker is energized and in service. For SF6 circuit breakers, a gas density measurement is the only insulation system parameter that could be measured in a live tank mode. Gas pressure and temperature measurements could be used to estimate gas density information [8]. It is very hard to develop universal device, which could monitor gas pressure on all kinds of breakers because different CB vendors install different pressure sensors with variety of output interfaces. Installations of additional

sensors require complicated and expensive maintenance procedures. Gas pressure monitoring is accomplished manually by reading values on preinstalled sensors on the breakers during regular inspection.

Monitoring contact erosion and interrupter wear has a direct influence on the required maintenance frequency [21],[22]. It is not only desirable but also beneficial to accurately evaluate the condition of the interrupters rather than to rely only on the presently used method of simply adding the interrupted currents until the estimated accumulated duty that is given by the manufacturers' recommendations is reached.
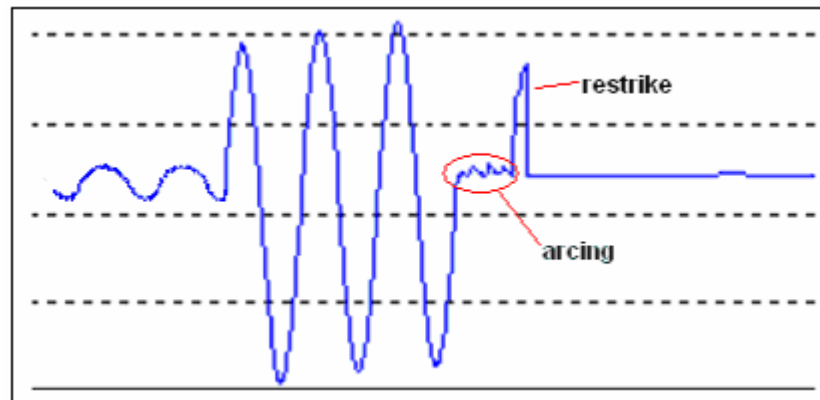
Figure 4. Main contact arcing and restrike

Measurements of contact erosion or interrupter wear cannot be made directly, but can be done by capturing phase current waveforms and measuring arcing time. These waveforms can be non-intrusively obtained via the secondary currents of the available CTs. The waveforms could be analyzed to assess cumulative contact erosion and restrike. Figure 4 shows typical current signal waveform during arcing and restrike on the main contact. Arcing time can also be obtained from a measurement of the arc voltage, but the arc voltage measurements are not available on all types of breakers. It can also be

calculated by estimating the point of contact separation and duration of the current flow from that time until it goes to zero. Monitoring the number of operations, arcing times, and cumulative magnitudes of the interrupted current can allow estimating the condition of the interrupters based on an actual duty the circuit breaker has been subjected to [8].

Monitoring of the contact or tank temperatures can indicate: high resistance contacts, as well as the broken or missing parts in the contacts, and/or current carrying circuit. Contact temperature cannot be measured easily but it can be approximated by measuring the temperature of the surrounding gas or ambient temperature and the continuous current that is being carried.

3. 2. 2   Control Circuit and Auxiliary Contacts

Monitoring of the control circuit and auxiliary signals together provides a lot of timing information. Many conclusions about condition of the mechanical part of the breaker can be obtained by analyzing signals from the control circuit and auxiliary contacts. Monitoring of Trip and Close Coil currents is relatively simple task. Monitoring the current drawn by the coils as they are energized and subsequently comparing the current signatures can provide useful information.
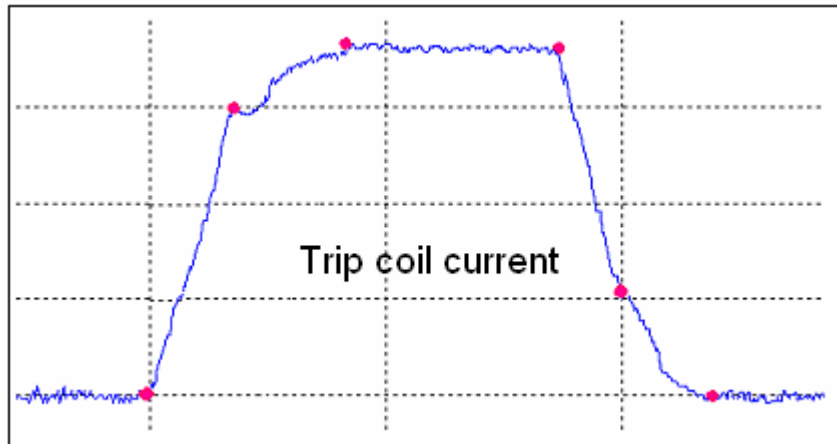
Figure 5. Trip coil current with characteristic points (characteristic times)

Changes that may occur in the timing of these points would indicate possible problems with the mechanical drive system such as condition of the latches, linkage failure, need for lubrication etc. For example, if the latches are not properly greased, the coil will draw more current and the shape shown in Figure 5 will change. By comparing these signals at specific times of circuit breaker over its lifetime, one could detect possible condition problems[23]. It is also very important that all the trip and close currents for the three pole breakers are monitors. These currents could be compared to each other to make more detailed circuit breaker condition analysis. Auxiliary contacts provide important information about mechanical operation of the breaker. Together with coil currents, they provide trip/close timing information and information about incorrect sequence of operation. They could also be used for estimation of travel time and velocity. X and Y auxiliary contact could be used to determine timings of the closing sequence.

AC and DC supply voltages should also be monitored at the circuit breaker to verify adequate voltage supply to the mechanism and control circuits. In some cases, inadequate

supply for mechanism and/or control circuit could lead to slow breaker operation or even to breaker failure.

3. 2. 3   Operating Mechanism

The most likely parameters to be monitored because of their significance and the simplicity of the monitoring are: contact travel and velocity, number of operations, space heater condition and ambient temperature. Some user guides suggest that charging motor current should be also monitored [20]. The motion characteristic, travel time, and velocity will provide main contact performance information. From the measured or estimated contact travel time and speed, it should be possible to track condition of deterioration of linkages, increased friction that could mean lack of proper lubrication and/or deterioration of bearings. For example, the time difference between the transitions of the two auxiliary contacts is inversely proportional to the velocity of the operating mechanism. A deformation of these signals may indicate a dirty contact, a binding mechanism or a slow breaker operation. Example of correlation between control circuit signals and mechanical characteristics of the breaker is shown in Figure 6.
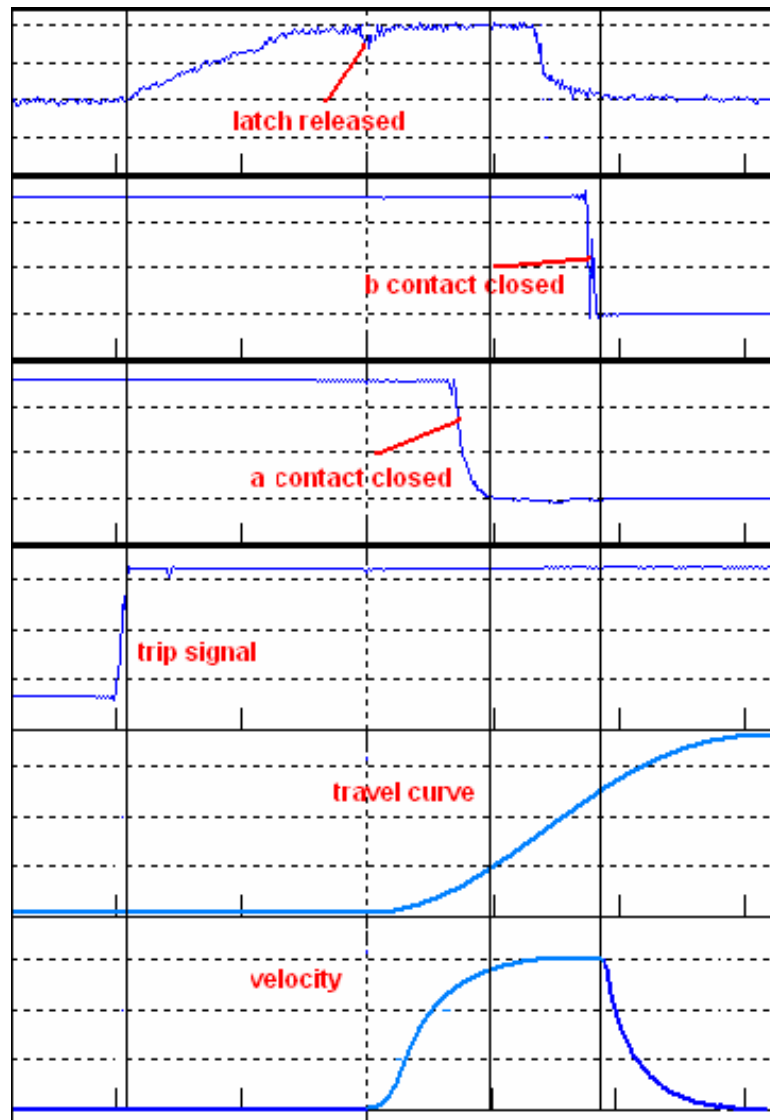
Figure 6. Correlation between control circuit signals and mechanical parameters

It is not always feasible to install a motion transducer to an in-service circuit breaker. Motion transducers are generally applied in the CB control cabinet and require a unique transfer function if they are to represent the actual movement of the main contacts. In many cases, motion monitoring may not be recommended for in-service breakers [20]. In

that case, some considerable information and travel speed estimate can be derived by online monitoring of auxiliary contacts, coil currents and protection inputs [19].

The CB heaters are simple but their failure may cause significant problems [8]. Monitoring of the heater elements is a trivial task that can be done by simply continuously measuring control cabinet temperature. One disadvantage of this method is that heaters are not energized all the time but only when the ambient temperature drops below a certain level. Consequently, a logic circuit that relates the ambient temperature to heater temperature should be provided but it still does not provide continuous monitoring of the continuity of the heater element itself during high ambient temperature. This is usually not a problem because during high ambient temperatures heater failure cannot cause a significant problem. The monitoring of the ambient temperature could not only be used to check heater condition but also to detect deviations from the historical operating characteristics of the circuit breaker under similar conditions. This measurement can also be useful to compensate for variations in the operating time during synchronous switching

Table 2 sums up the most important circuit breaker condition, operation and status parameters and electrical signals need for quality parameter extraction. Additions to the electrical signals from control cabinet are temperature measurements. By choosing these signals, we should be able to extract enough information about circuit breaker condition, status and operation and at the same time keep the solution as simple as possible. All signals could be monitored online and we should be able to install the monitoring system by just wiring the data acquisition unit to the breaker control circuitry.

Table 2. Circuit breaker parameter and signal selection

Component	Parameters	Signal Measured
Control Circuit	Trip timings (slow/fast)	Trip Coils (all poles)
	Close timings (slow/fast)	Close Coils (all poles)
	Sequence of operation	Backup Trip/Close Coils
	Auxiliary switch condition	Auxiliary contacts (52a, 52b)
	Maladjustment of coils	X, Y coil status
	Battery status	Supply voltages
	Battery charger status	
Operating Mechanism	Contact travel curve	Trip Coils (all poles)
	Contact velocity	Close Coils (all poles)
	Deterioration of linkages	Auxiliary contacts (52a, 52b)
	Friction and binding	Heater (Cabinet) Temperature
	Heater status	Ambient Temperature
Main Contacts	Contact erosion	Phase currents (a, b, c)
	Interrupter wear	Auxiliary contacts (52a, 52b)
	Arcing time	Tank temperature
	Cumulative interrupted current	Number of operations
	High contact resistance	
Other	Circuit breaker status	Phase currents (a, b, c)
	Circuit breaker interruption time	Auxiliary contacts (52a, 52b)

3. 3   AD Conversion Requirements

Before any signal analysis is attempted, all signals need to be converted to a digital form using Analog to Digital (AD) converters. Quality AD conversion requires that several important design parameters be chosen such that original signals could be

reconstructed from the digital stream without significant deformation. Two parameters that have largest impacts on AD conversion quality are sampling rate and quantization resolution.

3. 3. 1   Sampling Rate

The sampling frequency or sampling rate f_s is defined as the number of samples obtained in one cycle, or $f_s = 1 / T$. The sampling rate is measured in hertz [Hz] or in samples per cycle. Based on the Sampling Theorem, the sampling frequency should be higher that twice the maximum frequency of the signal component that we are trying to recover. In our case, it is very difficult to characterize signals that need to be monitored. Higher frequency components of the control circuit and phase currents signals are usually generated by fault transients, arcing or contact bouncing. Since we do not need highly accurate measurements of these phenomena, it is only important that we are able to detect changes in those signal features.

Power system fault currents are also hard to characterize. They could have large DC and/or high harmonic content. In most of cases, components over 32nd harmonic are very small and can be neglected. Converting that into sampling frequency means that sampling frequency over 3840 Hz (60 Hz system) should be satisfactory for the phase current measurements.

Contact signals from circuit breaker control circuit are even harder to characterize. Determination of appropriate sampling rate for these signals requires an analysis specifically performed for this purposes. If the circuit breaker conditioning applications are aimed at analyzing high frequency contact features, providing high sampling rate is

required to capture small oscillations and signal shape during contact transition shown in Figure 7-a. At least few samples are required during transition to be able to capture these specific features. Speed of contact transition is defined by mechanism velocity and contact shape. In most cases, this transition is slower than 0.3ms which sets required sampling rate to 10kHz. Most analysis applications do not analyze very high frequency components because of high noise level. They only require that contact bouncing could be captured from the signal (see Figure 7 b). In those cases, sampling rate of few (3-5) kHz should be satisfactory.
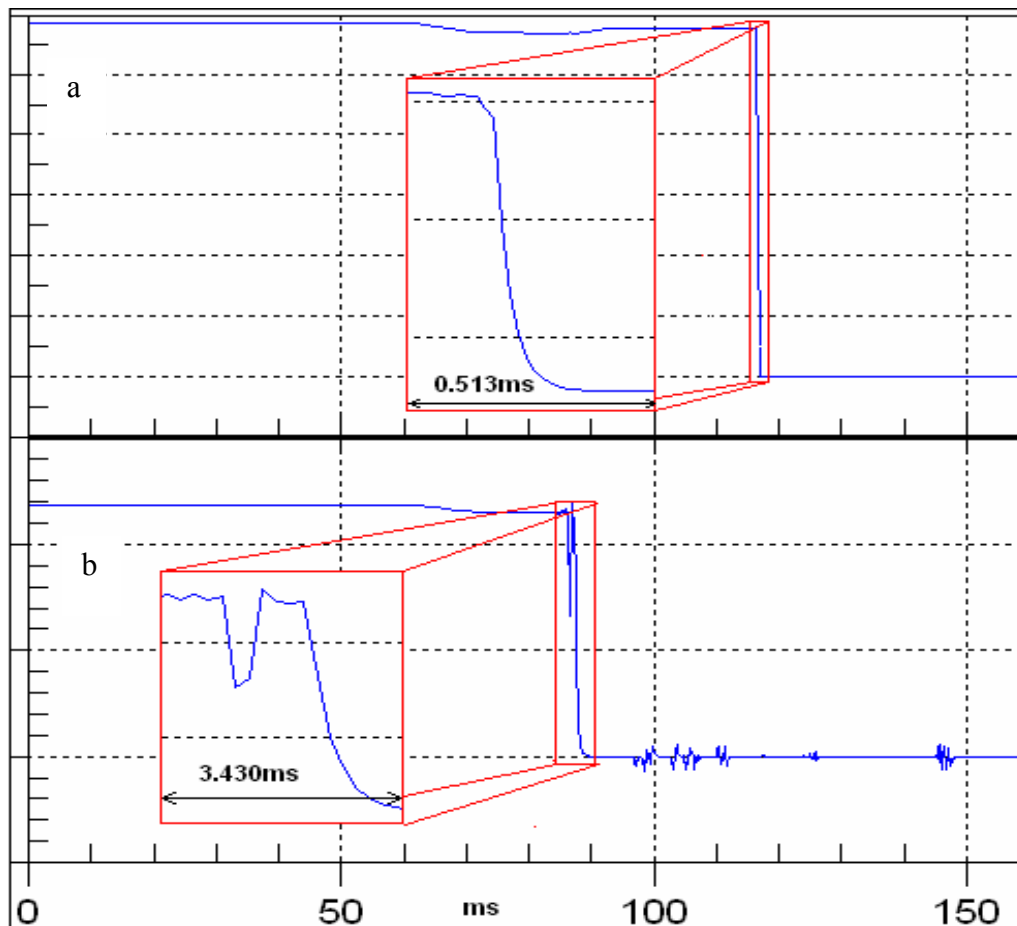
Figure 7. Contact transitions - zoom a) details b) bouncing

All other signals, Trip and Close coil currents and supply voltages, have low harmonic components and require lower sampling rate. Temperature measurements are very slow changing signals and require very low sampling rate (less that 1 Hz).

It should be noted that some signal processing algorithms require that sampling rates satisfy special requirements, or perform faster if that is the case. Some of the wavelet transformations require the number of samples in one cycle of the signal to be the power of two. In addition, for specific sampling rate signal processing could be made to perform much faster. Suitable sampling rates should be 32, 64, 96 or 128 samples per cycle, which converted is 1.92, 3.84, 5.76 or 7.68, kHz for 60-Hertz systems and 1.6, 3.2, 4.8 or 6.4 kHz for 50-Hertz systems.

Besides the sampling rate, very important consideration is how multiple channels are sampled. There are two ways of sampling multiple channels: synchronous sampling and scanning. AD conversion in both cases may be realized with one AD converter using multiplexer. During synchronous sampling process, all channels are sampled at the same time using multiple sample and hold circuits and than converted one by one as shown in Figure 8.
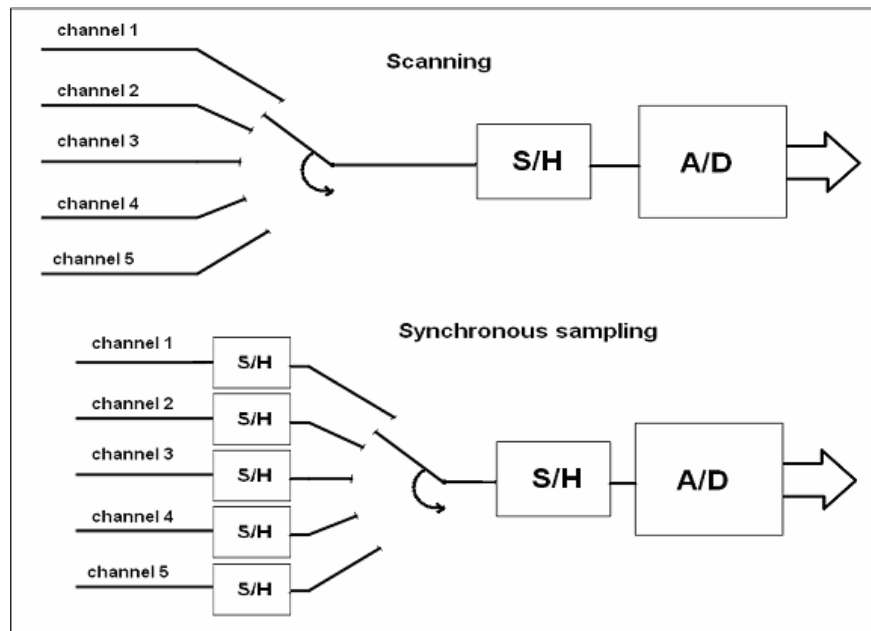
Figure 8. Scanning and synchronous sampling realization using multiplexer

During the scanning, channels are sampled and converted one by one using only one sample and hold circuit. For CB monitoring purposes sampling should be done synchronously because signal processing needs to extract timing differences between signals on different channels. In addition, majority of data formats for signal processing require synchronous sampling. In some cases when sampling and conversion times are much smaller than the sampling period, scanning may be satisfactory solution because error would be small.

3. 3. 2   AD Resolution

The AD resolution is also a very important requirement. The resolution requirement is directly related to dynamic range of the signals that have to be sampled. Dynamic range is ratio between the smallest and largest possible values of in a varying signal and

it is usually expressed in dB. From all the monitored signals, only phase currents have large dynamic range. To determine dynamic range of the phase currents is difficult to determine because it varies with fault type and location. It also depends on the transmission line and substation where breaker is installed.

During the process of conversion, noise is introduced into the digital signal. Quantization noise is a noise error introduced by quantization in the analogue to digital conversion process. It is a rounding error between the analogue input voltage to the AD converter and the output-digitized value. The noise is non-linear and signal-dependent. It can be modeled in several different ways [24]. Level of noise introduced by AD converter can be found using:

$$SNR_{ADC}=(1.761+6.02Q) \text{ dB}$$

Where Q is the bit resolution of the converter (the number of bits of the converter)

Quantization noise should be much less than value of the smallest signal of interest. In other words, SNR ratio of quantization noise should be much higher than the dynamic range of the signal. Analog signals used for the circuit breaker monitoring should have high SNR. Dynamic range of the phase current is very hard to determine. There are few ways to roughly estimate that value. Usually fault current is 5-20 times higher than the load current on the lines. In special cases during bus bar or transformer fault, it could go much higher than that value. In most cases, even the largest possible fault current is not much higher than 50 times nominal load current. Most of the medium and high voltage breakers have currents ratings less or equal to 63kA and nominal currents 1kA [25].

At the same time, analysis applications usually do not require high precision measurements of normal load current. They are more focused on the shape and timing of the interrupting currents during breaker operation. Current magnitudes could only be used for cumulative breaking current calculation, which is not significantly affected by error at low current measurements. The Table 3 shows quantization error at the lowest expected current.

Table 3. Quantization error for different ADC resolutions

Phase Current Dynamic range		Quantization error on the lowest expected current magnitude [%]		
Signal Ratio	dB	10-bit	12-bit	16-bit
20	26.02	0.975	0.24	0.015
30	29.50	1.45	0.37	0.023
50	33.98	2.4	0.6	0.038
100	40.00	4.8	1.2	0.075

From the table we can see that 16-bit resolution is satisfactory even for cases much worst than expected. It can also be concluded that 12-bit resolution could be used for purposes of circuit breaker monitoring in most of the cases. Error in the case when fault current exceed load current for one hundred times is around 1.2% for 12-bit converter. This accuracy is comparable to accuracy of most CTs and signal conditioning boards, and it could not significantly decrease accuracy of the low current measurement. Quantization errors for high current signals that are more important for condition-

monitoring purposes are very low so they can be neglected. It can be seen that 16-bit AD converter satisfy quantization accuracy in all cases, even for the extremes when fault current exceed load current much more than 100 times. In most of cases, 12-bit resolution satisfies accuracy requirements and it could be used for circuit breaker monitoring purposes. Converter with 10-bit resolution should not be used because it makes large quantization error even for relatively small dynamic range signals [26].

3. 4   Data Processing Requirements

Circuit breakers are located in substation switchyards all over the system. In some cases, switchyards could be large and located in remote areas. The system design requires that circuit breaker monitors be located very close to the breakers or in the breaker control cabinet. We need to transfer data from field units to substation control house and finally to a central location such as control center or corporate office. Wireless communication between field monitors and computer in the control house seems to be the best solution for data transfer especially in existing substation where installation of any additional wires or cables is very expensive may require disruption of the substation operation for longer period of time. Large amount of data may be recorded during autoreclosing involving system fault condition or complex switching operation involving breaker failure. This data should be saved and than transferred to the PC concentrator in the substation control house. Important requirements that have to be satisfied are data storage and communication network requirements.

3. 4. 1   Data Storage

Nonvolatile data storage size should be considered a very important requirement for monitoring device design. This decision is affected by requirements for monitoring different aspects of breaker operation such as event length, frequency of operations, signal selection and related signal sampling rate and resolution. Size of a single event file depends on many factors and it could be estimated for specific case. Typical event file size file size should be around 300kB. See Appendix A for details related to the data size and transfer capabilities. Even if we use very high sampling rate (10Khz), an event file would be less than 500kB. The data storage and transfer capability for online function of the monitoring system is very important. System should be capable of keeping relatively small number of event records if data transfer became busy or if it even fails. Sometimes, under some special conditions it is possible that large number of events happen in a substation. Field units should be able to keep all recorded events until transfer to the PC concentrator in the control house is completed. If we want to make sure that the files will not be lost during network failure, data storage size on the field units should be able to keep few dozens of records. Size of data storage should also be flexible to enable adjustment to a particular case. In some cases data transfer could be large due to a large number of breakers. In those cases, the memory should be large enough to enable slower transfer to the PC concentrator.

Data storage should have fast data transfer capability to support large data volume due to large number of sampling channels and high sampling rate. There are new technologies, which offer large, low cost nonvolatile memory with simple, fast and

standardized data transfer. Different kinds of flash memory devices are available and should be consider for this purposes. Secure Digital Card memory provides up to 4GB of low cost memory with fast three-wire SPI communication protocol.

Data storage capacity on the concentrator side in the substation control house should enable storage of large amount of data generated over long period. Some breakers operate rarely - few times a year, but there are circuit breakers (for example, breakers on capacitor banks), which could operate few times a day. The concentrator PC should be able to keep tens of thousands of record in the file repository, which converted to memory size is few GBs. The data should be protected from loss using some kind of a redundant data storage located on site and remotely.

3. 4. 2   Data Transfer and Communication

Data transfer from field units installed at circuit breakers in a switchyard, even though we need to transfer relatively small amount of data over relatively short distance (Appendix A), may encounter some difficulties: need for GPS signal distribution from substation control house to the switchyard, multipoint communication with dozen of distributed data acquisition points, time constrained installation need. Data transfer to a central place should be very flexible to enable easy implementation in all possible communication configurations. There in the worst case, several dozens of data acquisition units may be located in the switchyard. In those cases, we also need fast data transfer to enable data transfer from all the devices in real time. Communication networks, which require cooper or optic fiber cable installation between switchyard and

control house require expensive labor and long installation time, as well as a possible interruption of the substation operation for a period of time.

Wireless data transfer from substation switchyard to control house seems to be the best choice because it does not require the mentioned installation costs and long installation times as the wire installations do. Data transfer speed is not critical because data are not used in real-time control applications. As it is shown in Appendix A, data rate of 256 kbps should enable sufficiently fast data transfer. Using the suggested data rate, data transfer from one unit may last a few seconds, which meets requirements of even for on-line applications such is alarm processor. There are several technologies, which can be used for this purpose: Frequency Hopping Spread Spectrum (FHSS), ZigBee, and Wireless LAN etc. Some of them are more suitable for harsh environment and short distances. In addition, several configurations could be used for this network. Multipoint and mesh network configurations shown in Figure 9 are most suitable for circuit breaker monitoring communication.
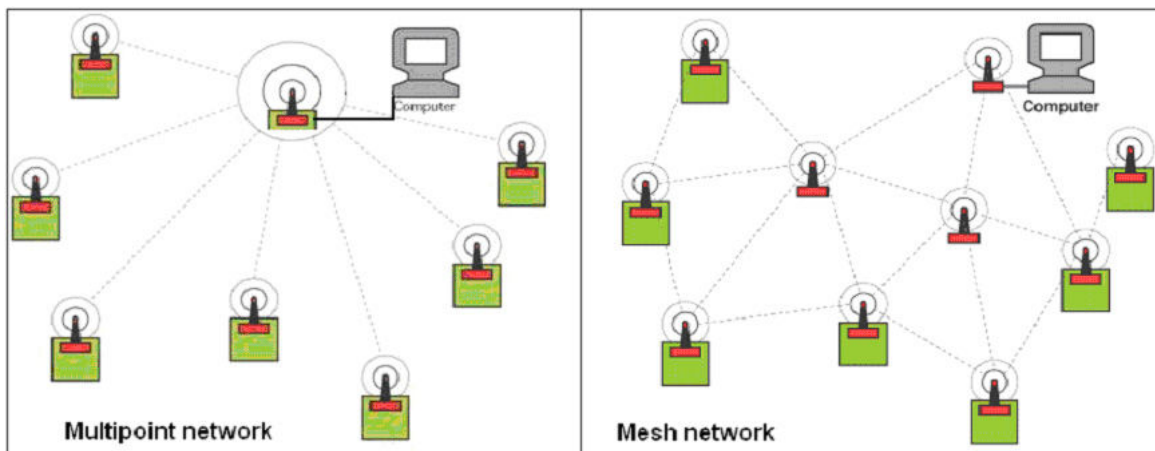

Figure 9. Multipoint and mesh network configuration

Because of the noisy environment, output power of transmitters should be higher than power required for normal outdoor application. Transmitter's Equivalent Isotropically Radiated Power (EIRP) in multipoint network configuration should be around 60mW (18dBm) for 2.4GHz frequency range [27]. In some countries maximum allowed power is limited to 10dBm or 12dBm so gain antennas and repeaters could be used if longer distance communication is needed. Mesh network configuration requires larger number of low power transmitter, which makes it very reliable because of multiple transfer paths through the network. Mesh network transmitters are relatively cheap and easy to use which makes them good solution for circuit breaker monitoring purposes. Network should also have implemented error detection and error handling mechanism.

Data security is becoming a major issue in critical infrastructure such is power system grid. Even though circuit breaker monitor data cannot be used to attack power system operation directly, real time event data could be used to gain advantage in deregulated power grid market. They contain information about current grid connection and information about grid congestions that could be used on the market. Some kind of data encryption should be implemented but it should not overburden microprocessor of the field unit. There are several encryption algorithms described in Appendix B that do not require very intensive processor work but could provide adequate information protection. Even though some of proposed algorithms are not completely secure, time required for breaking the code is long enough to age data and makes information about power grid topology useless on the market. Sometimes encryption algorithms are implemented in wireless transceivers and could be used without burden of the processor in the field unit.

Wireless manufacturers usually implement DES 64, Triple DES or AES 128, 256 encryption ciphers.

3. 4. 3   Data Format

Recorded signals should be organized in suitable standardized data format, which enables transfer of all available information. The format should be supported by third parties that could create different analysis applications based on circuit breaker monitor recordings. The choice for the data format should be one of the available open standard data exchange formats introduced by IEEE or IEC. There are several standardized data exchange formats available for transient power system data exchange. The most appropriate formats are "C37.111-1999 IEEE COMTRADE Standard (Common Format for Transient Data Exchange) for Power Systems" (1999) [28] and XML based "IEC 60255-24 Common Format for Transient Data Exchange (COMTRADE) for Power Systems" [29] (2001). There are two versions of COMTRADE 1999 file format: ASCII and BINARY data format. Binary data format is more suitable because of higher level of data entropy rate. For example, using universal lossless data compression LZW algorithm [30], ASCII file can be compressed to the average level of 10% but the same BINARY file to 55%. All of this makes binary COMTRADE format the most suitable file format for circuit breaker monitoring data transfer and storage.

3. 5   Signal Processing Requirements

To be able to perform multiple breaker operation analysis data from all circuit breaker monitor devices must be synchronized in time. To enable signal processing and

analysis that will incorporate multiple circuit breaker monitors, the solution has to be designed as distributed signal processing system shown in Figure 10.

In distributed signal processing systems, every node samples analog signals by its own AD converter. Sampling is controlled by autonomous clocks, which are generally not synchronized. In order to ensure synchronized operation among the different processing nodes of the distributed system, both the drift of these clocks, and the jitter of the sampling must be properly handled. In this kind of system configuration the time stamping should provide method for signal alignment in cases when data transfer is not continuous and when the data transfer delay couldn't be controlled. Almost no standard wireless network technologies today have these capabilities.
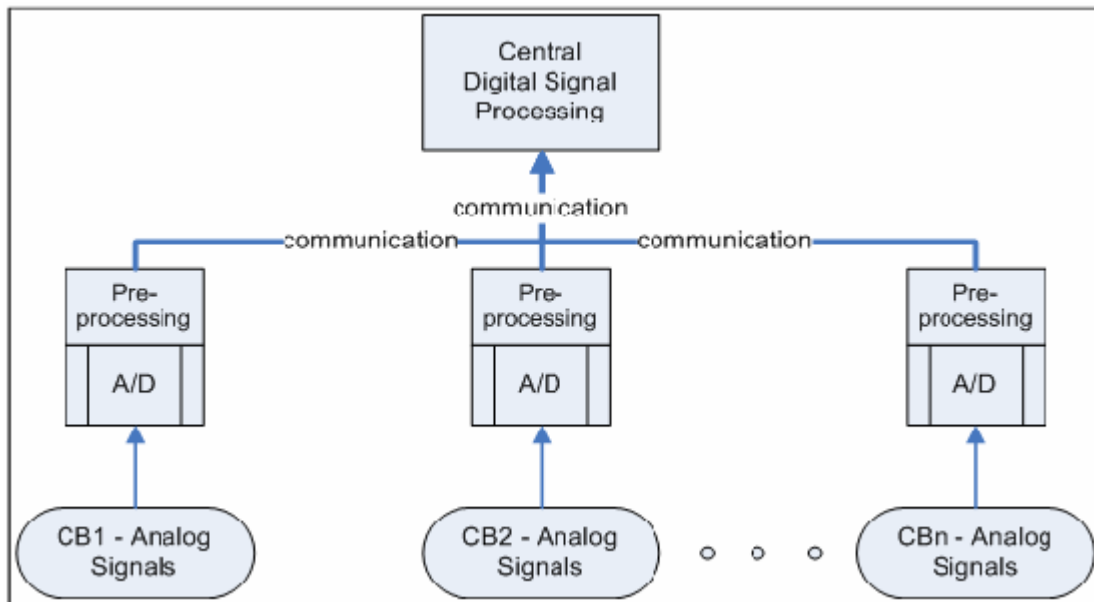
Figure 10. Multiple CBM solution as distributed signal processing system

For analysis of multiple breaker operations and system-wide applications, online circuit breaker monitoring solution should be designed as distributed signal processing

system, which comprises numerous acquisition nodes which are interacting with the central processor to perform data acquisition and signal processing. The nodes should perform online data acquisition and signal pre-processing. The input data for this system are digital samples of a discrete signal, usually sampled at the same clock rate.

Central processors and data acquisition units have separate clocks, which may violate data consistency constraints, due to their jitter and drift. This system should have event based data transferring and pre-processing so all samples should be time-stamped to enable signal alignment before processing in a central place [31]. This problem does not exist in centralized, one-processor, one-data acquisition systems, as generally these have only one master sampling clock that schedules and controls the sampling processes.

The field of distributed signal processing is not a well-explored area, so after the examination of this complex problem, the most cost-effective solution is proposed. This system uses GPS clock signal to synchronize all the processing nodes in the system. Every sample taken around the system needs to be sampled at the same time and stamped with common time stamp.

At the central processor, which performs overall signal processing and analysis, all signals can be aligned using the time stamp. Using this approach, we could avoid expensive real time data transfer networks. Nature of the monitoring task is that the response time is not a major constraint and hence this application does not require data transmission in real time. Instead, the event based recording process requires the time synchronization. Using signal alignment technique, we are able to meet these requirements and allow for a quality time analysis. Preprocessing at the remote data

acquisition nodes is necessary to perform event recognition and time stamping. Event recognition is used to capture all the events of interest. For circuit breaker monitoring purposes, event recognition implies determination of either the breaker trip or close signal change because all the breaker operations are initiated by sending one of those two signals. It is also necessary for the analysis to record signal status before breaker operation as shown in Figure 11.

This part of the captured waveforms is called pre-event recording and it is used to determine circuit breaker status and specific control circuit condition before operation. Pre-event recording is usually done using circular data buffer.
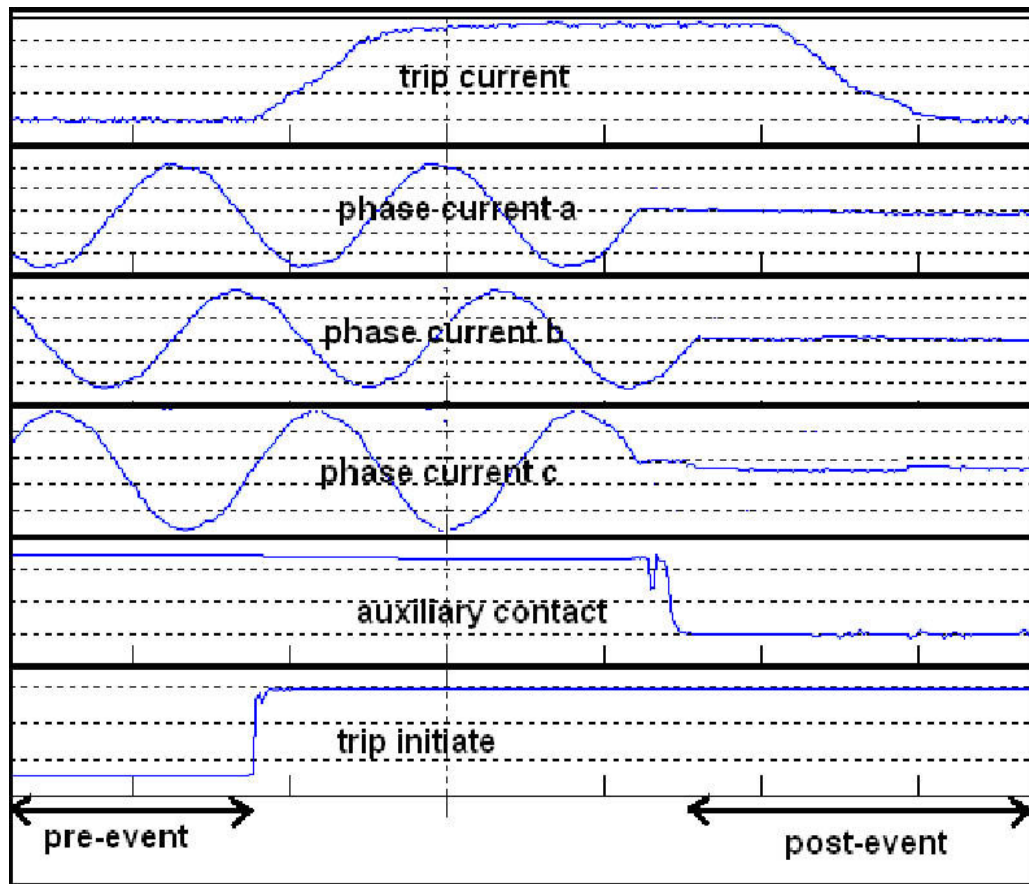
Figure 11. Pre and post event recordings

All samples are temporarily stored in a circular data buffer, which overwrites the oldest samples when it reaches the end of the free space. When event happens all data from the buffer as well as new samples captured during event are being stored to a memory. Length of this period is usually fixed to a few fundamental frequency cycles. Total recording length should be large enough to capture all the necessary information but at the same time as small as possible to avoid the long data transfer and storage congestion. Circuit breakers in the high voltage transmission system usually need 2 to 3 cycles to operate breaker. Medium and low voltage breakers could take up to 10 cycles to interrupt current. In all cases, the total length of recordings does not need to be bigger than 20 cycles. During reclosing operation of the breaker, event signals will be reinitiated and monitoring device will capture that event as a new recording.

3. 6   Time Synchronization

To perform multiple breaker or system wide analysis, signals collected in remote data acquisition places should be processed simultaneously. In distributed signal processing systems, a problem arises when two or more acquisition nodes have asynchronous clocks. All corresponding samples should be captured at the same time to be able to analyze or track simultaneous events. This can be achieved in such a way that all samples in form of real-time discrete signals should arrive to the digital signal processor at the same time. This solution requires fast and wide bandwidth communication between the processing nodes and central processor, which makes it not suitable for our application.

Circuit breaker analysis requires data recorded only during CB opening or closing events. This means that continuous data (samples) are not required and instead, sequence of samples can be recorded and stamped with corresponding absolute time and than transferred to central place for further processing and analysis. This kind of data transfer relaxes requirements for communication channel and decreases cost of device. However, it requires that local and central clocks work synchronously and have the same absolute time. Crystal oscillators usually control the sampling and time stamping at all nodes. Frequency deviation of such clocks is typically 20-50 ppm, which in relatively short period can create loss of synchronization problems.

First problem is that the signals at two different locations would be sampled at different times, which makes it impossible to perform some of the necessary signal processing operations. Second, after some time these sampling frequencies are not exactly the same at the all nodes since the clock crystals are not identical. The data recorded at the nodes is not consistent since after a certain period one node device produces different number of samples than the number of samples expected or produced at another. This means that all the clocks in the system should be synchronized to one common clock source through communication network as shown in Figure 12.
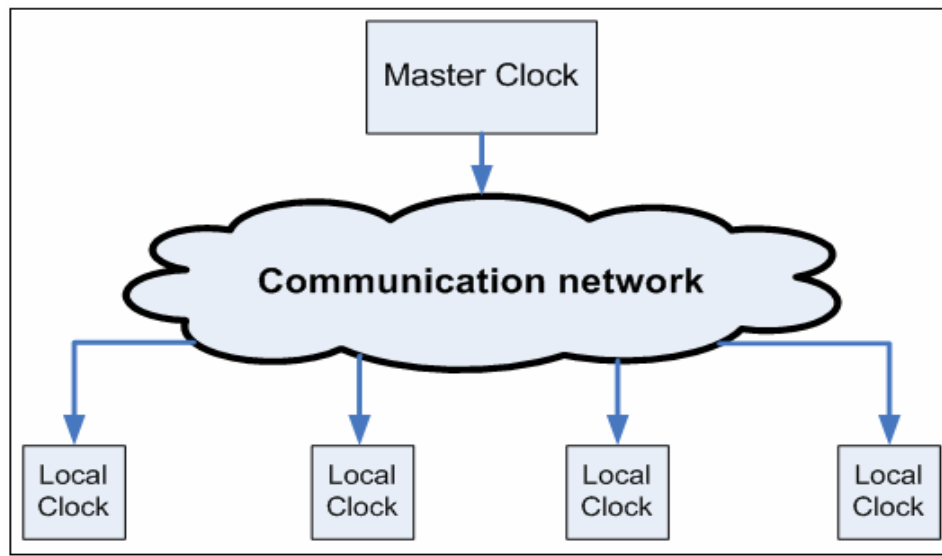
Figure 12. Time distribution architecture

Synchronization parameters that affect quality of time synchronization are:

- Latency (responsiveness) – affects sampling time by introducing different latency in clock signal distribution

- Resolution (steadiness) – makes sampling frequency at various nodes different to a fluctuation in the clock

- Update rate (smoothness) – relates to both of the previous problems causing mismatch in the period between time updates

To be able to perform adequate processing and analysis all three parameters should be in the range of tolerance, which satisfies requirements imposed by the signal processing algorithms. Since it is hard to specify general requirements due to the large number of existing signal processing algorithms, we will give estimates, which will guarantee requirements for most of algorithms. First, we should consider signal parameters that could be affected by the synchronization requirement.

Time synchronization is widely used in several power system applications. Some of them require precise time synchronization (stability, fault location, relaying) and some are not so sensitive to time drift. Table 4 shows some power system time synchronization requirements [32]

Table 4. Power system synchronization requirements

System Function	Measurements	Optimum Accuracy
Fault Locator	300 meters	1 microsecond
Relaying	1000 meters	3 microseconds
Stability Angle Control	±0.1-1 degree	4.6- 46 microseconds*
State Estimation	±0.1-1 degree	4.6- 46 microseconds*

* calculated for 60 Hz system

Specific requirements for breaker monitoring are not simple to determine because there is no widely agreed measurement error requirement related to circuit breaker monitoring. However, there is a way to estimate these values. Most important information extracted from the signals from circuit breaker control circuit are timings of the changes and signal shapes designating specific breaker mechanical and electrical operations. These timings could be used to create breaker signature, which should be compared with the referent values or the previous recordings to determine breaker condition. There is no need for precise extraction of current phasors from the recorded signals because the current measurements from the circuit breaker monitoring system are not intended for use in power system analysis applications. Those measurements are usually taken during power system transients from non-precise transducers in a very

noisy environment. Determination of the current transition timings, magnitude and waveform shape is sufficient for the condition and operation analysis purposes. There is no need for high synchronization requirements related to the signal phase error but specific timings calculated from recorded waveforms should be precise. Maximum timing accuracy that is possible to extract from the contact or coil current signals is equal to duration of the sampling period. It is not possible to detect anything between two samples because of an unknown shape of the signal. Similar analysis could be applied for all other circuit breaker control signals. Higher accuracy of measuring the phase signals is not required since the analysis uses such signal transition timings in addition to other timings from the control circuit.

Based on the analysis, we can conclude that time synchronization latency should be less than half of sampling period; translated to time this is 50 - 250 microseconds depending on the used sampling rate. Fifty microseconds requirement should be enough to satisfy the need of most of the monitoring devices.

We also need to specify the steadiness and update rate requirements. Both of those requirements are related to frequency deviation of the local clocks. Standard quality quartz clocks are usually warranted to have a long-term accuracy of about 10 ppm at 31 °C. Considering temperature variation in a substation, quartz oscillators used in electronic applications usually have a frequency stability of 20-30 ppm and an aging rate of 1-2 ppm per year [33]. Based on this we can conclude that in most cases stability is better than 40 ppm. From this we could see that the combined time synchronization

accuracy and update rate multiplied by the stability should not go over the time synchronization requirement:

$$\frac{1}{2f_s} > time\_sync\_accuracy + update\_rate \times oscilator\_stability$$

For example, if we use update rate of 1PPS (one pulse per second) and an oscillator with stability of 40 ppm we need a time source with accuracy of at least 10 microseconds to achieve synchronous sampling on 10kHz. If we use sampling rate of 7.68 kHz we need time synchronization source with accuracy better than 25 microseconds. Time source accuracy of 20 microseconds will satisfy most of requirements for high sampling rates used in our application.

There are several referent time sources of the time synchronization signal available for industrial purposes. From Table 5, which shows most common time sources, we can see that only few of them could provide the required accuracy [34].

Table 5. Sources of synchronizing signals

Time	Transmit freq.	Time Code	Susceptibility	Primary Use	Resolution	Location
AM						
WWV	2.5-20Mhz	BCD/1PPS/ IRIG	Fading, Propagation	Time	5ms	US
WWVB	60kHz - c shift	BCD/IRIG	Atm. Noise	Freq. Time	2ms	US/Canada
OMEGA	10-14kHz	IRIG/BCD/ 1PPS	Noise	Navigation	1-10ms	Worldwide
MSFDCF	60kHz - c shift	IRIG-B/TTL	Noise	Time	1-10ms	W. Europe
Loran-C	100kHz	1PPS	PLC, Noise	Navigation	20µs	N. Hemis
Spread Spectrum						
IS-95 (CDMA)	869-894 MHz	ASCII, 1PPS	Network vicinity	Phone, Time	10µs	America, Asia, Australia
Satellite						
GOES	468 MHz	IRIG/TTL	Loss of satellite	Weather, Time	100µs	W. Hemis.
GPS	1575.42 MHz	IRIG,1PPS, RS232	Lock on few satellites	Time, Position	0.2-0.5µs	Worldwide

Considering our requirement two of the choices shown in Figure 4 will be discussed: GPS (Global Positioning System) and IS-95 CDMA (Code division multiple access).

3. 6. 1 The Global Positioning System (GPS)

The Global Positioning System (GPS) is currently the only fully functional Global Navigation Satellite System. Utilizing a constellation of at least 24 medium Earth orbit satellites that transmit precise microwave signals, the system enables a GPS receiver to determine accurate and precise time, its location, speed and direction. It uses very precise time references to enable positioning. That time reference could be used for time synchronization between remote devices on the earth. Developed by the United States

Department of Defense it is managed by the United States Air Force 50th Space Wing. Despite this fact, GPS is free for civilian use as a public good. GPS provides a precise time reference with accuracy of 0.2 – 0.5 microseconds to UTC atomic clock [35],[36].
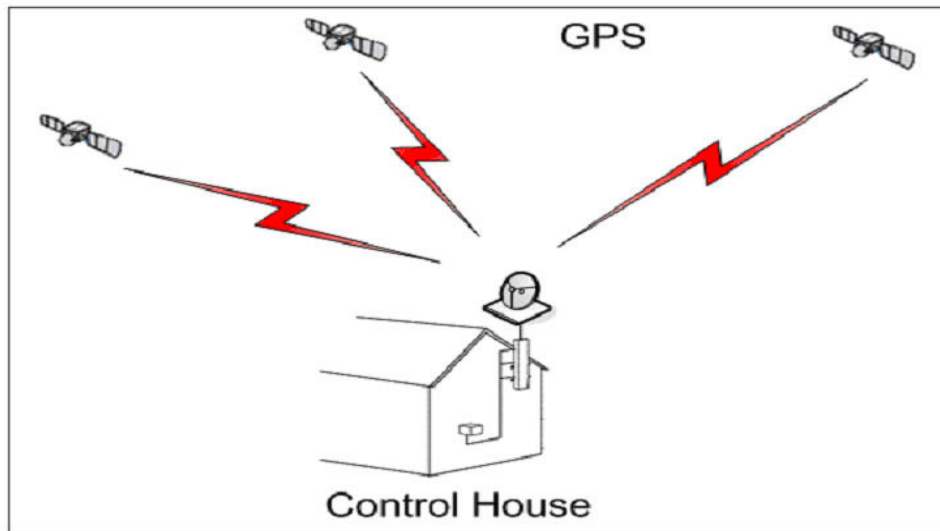
Figure 13. GPS time synchronization

GPS time synchronization is used in many applications including scientific study of earthquakes, synchronization of telecommunications networks and other industrial purposes. Signal is available worldwide but requires open sky access for antenna as shown in Figure 13. In some urban areas, that could be a problem because some substations are located indoor to reduce the noise from the transformers, and for other reasons of appearance and environmental impact.

Since GPS signals at terrestrial receivers are relatively weak, it is easy for other sources of electromagnetic radiation to disrupt the receiver, making acquiring and tracking the satellite signals difficult and sometimes impossible. Solar flares are one such

naturally occurring emission with the potential to degrade GPS reception. Man-made interference can also disrupt, or jam, GPS signals. Even intentional jamming is possible.

Outputs interfaces from GPS clock receivers are many and vary with the vendor but there are two required outputs. The fist is a precise digital output (1PPS) with 50-nanosecond rise time that occurs once per second. The second is an ASCII message transmitted at 9600 baud that identifies the year, day, hour, minute and second of the digital output. The output pulse is non-standard between manufacturers of these devices, and the timing edge can be the rising or the falling one, depending on the manufacturer. The time code could be unique to the manufacturer or one of the standardized codes. Inter-range instrumentation group time codes, commonly known as "IRIG" time codes [37], were created by the TeleCommunications Working Group of the Inter-Range Instrumentation Group, the standards body of the Range Commanders Council. The different time codes defined in the Standard have alphabetic designations. A, B, D, E, G, and H are the standards currently defined. The main difference between the codes is their transmission rate, which varies from 1 pulse per second to 10,000 pulses per second. Most common is one pulse every 100 seconds synchronized on the hour, IRIG-B. The time code transmitted in ASCII format in the following sequence: Year, day of year, hour (24 hour day), minute and second.

GPS system is free for use and rather reliable which makes it very suitable for time synchronization in power system applications at places with open sky visibility.

3. 6. 2   IS-95 CDMA

In some indoor urban substations, roof access may not allow antenna installation or it could be very expensive. In that case, other time synchronization systems should be used instead of direct GPS. All CDMA receivers receive transmissions from the base stations. This system requires the means of synchronizing the base stations throughout the network so that neighboring cells do not interfere with each other. The base stations are synchronized using Global Positioning System (GPS), which is itself a CDMA-based system. The base station time synchronization must remain within 10 microseconds of GPS time over periods as long as twenty-four hours during which GPS satellite signals might not be available. CDMA synchronization scheme receives the same initialization signals transmitted by the base stations that are used by the mobile telephones to establish their synchronization to system time [38],[39]. This means that during normal operation, the quality of the timing information being transmitted from each of the base stations is virtually a repeat of that directly obtainable from the GPS. Due to the nature of the IS-95 spread spectrum CDMA modulation scheme, this timing information may be extracted by a well-designed receiver with a precision of hundred nanoseconds. The big difference between GPS and this system is that the received signal strength from the base stations are a minimum of 30 dB larger than those from the GPS satellites, which makes it possible to receive the signals indoor.
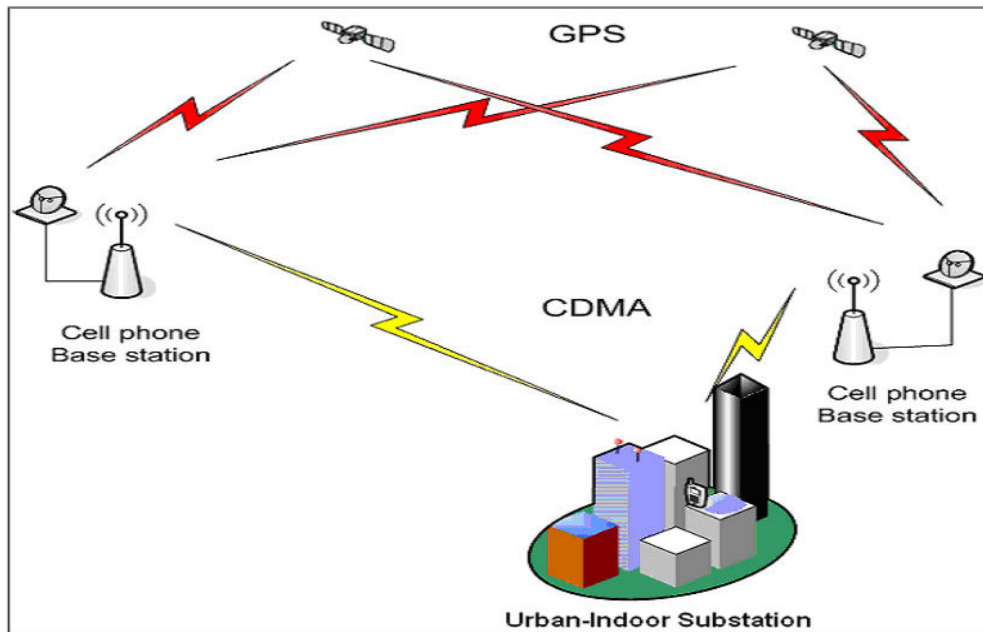
Figure 14. CDMA time synchronization

This feature makes this system very suitable for application in urban areas where GPS signal is not available or reliable but usually it is covered with good CDMA signal availability. CDMA time synchronization architecture is shown in Figure 14.

3. 6. 3   Substation Time Distribution

To decrease monitoring system cost and avoid multiple antenna installation in the switchyard we should use one time receiver per substation and than distribute time reference using existing communication network. The same time reference signal should be transmitted to all monitoring units in the switchyard. Communication network and protocol used for data transfer between field units and the concentrator PC can be easily used for time code distribution. Time reference distribution could be achieved using wireless network or using existing DC supply wires between control house and circuit

breakers. Some transmitter vendors already support 1PPS signal distribution feature with accuracy of 10-20 microseconds [40]. This means that using existing equipment necessary for data transfer we are able to reduce the number of time receivers to one per substation.

3. 7   Conclusion

This section gives overview of all the requirements that our system needs to meet to enable all signal processing and analysis tasks. It suggests solution, which could be the most suitable. It gives detailed signal recording criteria selection procedure. It also investigates data acquisition requirements such as sampling rate and resolution, and gives optimal parameter selection. Data processing requirements such as data storage and transfer are considered and some choices are suggested. Distributed signal processing and time synchronization are investigated in details, requirements are estimated and few solutions are proposed.

4   SYSTEM ARCHITECTURE AND IMPLEMENTATION

4. 1   Introduction

Architecture of the online circuit breaker monitoring system should enable realization of all proposed requirements, as well as fast, easy and inexpensive implementation of future requirements. It is very important that the system is modular so those users have value of installation of only one unit to a substation as well of several dozens of circuit breakers in one substation as needed. This feature should enable gradual installation of circuit breaker monitors over the longer period. With installation of additional units, benefits from the system will increase. It is also important that cost of the solution and its installation remains very low to impel system wide installation. That will gain benefits to the system wide applications such as topology processor or state estimator.

Detailed architectural and operational description of developed CBM system is given in Appendix C.

4. 2   Hardware

To enable low-cost production and installation and gradual deployment, the circuit breaker monitoring system needs to be divided into: field acquisition unit, located near the breaker, computer located in control house, which serves as data concentrator and communication network between them. System architecture is illustrated in Figure 15. This architecture does not require complicated and expensive installation and additional wiring in existing substations. Time synchronization should be also achieved using these

system modules. Additionally this architecture should enable data access from remote places such as control center or corporate office.
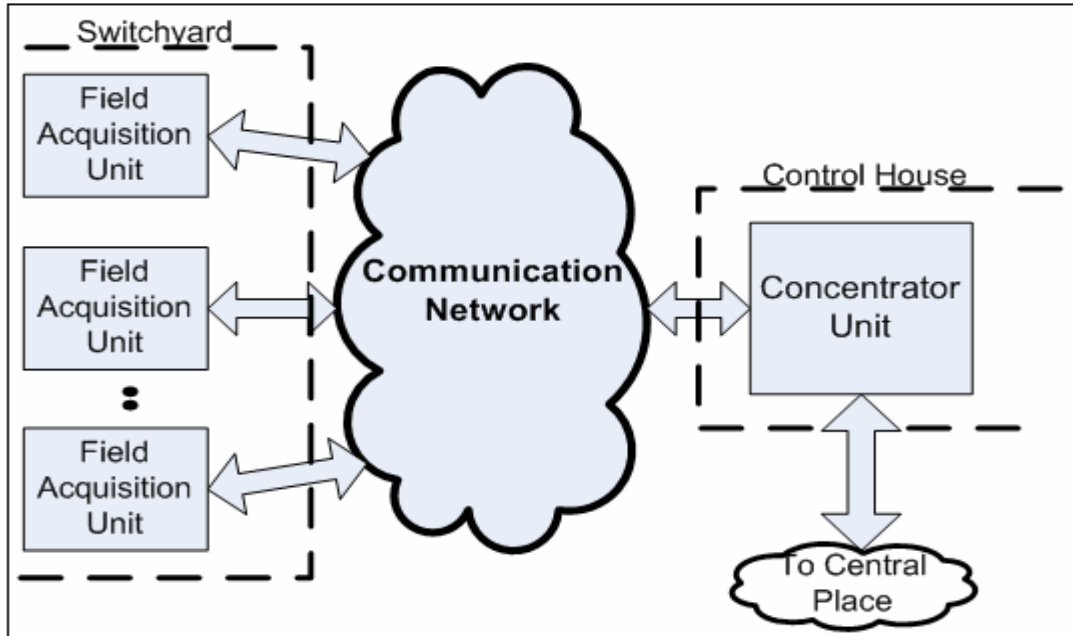
Figure 15. CBM system architecture

Technology used for CBM realization should be proven and such that remains available over longer period. Technology has to be reliable and able to work in very harsh environment such as substations characterized with extreme temperatures and high level of electromagnetic interference (EMI).

4. 2. 1   Field Acquisition Unit

To enable easy upgrade and to simplify designing problem we accepted modular approach. Modular approach allows us to create separate modules of field unit. Each of them should be independently designed, while integration of all modules implements

requirements given in previous section. Considering nature of the input signals and suggested requirements, there should be three separate modules as shown in Figure 16:

- Module for signal conditioning and overvoltage protection

- Module for data acquisition, signal preprocessing, storage and synchronization

- Communication module
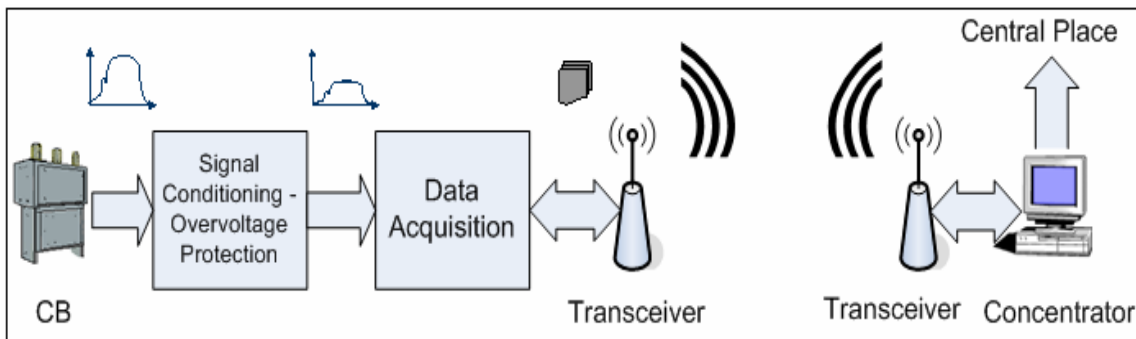
Figure 16. Modular structure of the field unit

Signal conditioning and overvoltage protection module has to provide appropriate voltage levels for data acquisition. Voltage levels of signals at circuit breaker could be as high as 130VDC or low as 10 mV with transients over 1000V. Since voltage range of the signals at the input of the analog to digital converter is always standard value (±1, ±5 or ±10)V, this module should scale all input signals to required value. Table 6 shows a list of control circuit signals and their electrical characteristics.

Table 6. Circuit breaker control signals

Signal Name	Channel	Type	Nominal Range
Control Voltage	Voltage	Contact	$125V \pm 15V$
Light Wire	Voltage	Contact	$125V \pm 15V$
Aux. Contact B	Voltage	Contact	$125V \pm 15V$
Yard DC	Voltage	Contact	$125V \pm 15V$
Aux. Contact A	Voltage	Contact	$125V \pm 15V$
Close Coil Current (3 phases)	Current	Shunt	<10A (1V)
Trip 1 Coil Current (3 phases)	Current	Shunt	<10A (1V)
Trip 2 Coil Current (3 phases)	Current	Shunt	<10A (1V)
Phase A Current	Current	Shunt	~5A (1V)
Phase B Current	Current	Shunt	~5A (1V)
Phase C Current	Current	Shunt	~5A (1V)
Close Initiate	Status	Contact	$125V \pm 15V$
Trip Initiate	Status	Contact	$125V \pm 15V$
'X' Coil	Status	Coil	$125V \pm 15V$
'Y' Coil	Status	Coil	$125V \pm 15V$

Second module is data acquisition module, which consists of analog to digital converter and microprocessor board for data acquisition, preprocessing, storage and time synchronization. This module performs and controls data sampling, monitoring and when the event occurs, recording and storage of all input signals. System has to continuously sample all input signals and keep specified number of samples in temporary memory.

There are several technologies, which enables low cost and simple implementation of these tasks. Digital Signal Controllers (DSC) provide integrated AD converters, programmable timers, relatively large program and data memory with DMA support and variety of communication modules which makes them suitable for implementation. This module needs to be also connected to the wireless communication module. It should communicate with concentrator computer using custom higher-level data protocol. It also

receives GPS synchronization signals and data from the master unit and synchronizes the local clock and recording accordingly.

Communication module needs to enable reliable communication between field units and concentrator. If we look into cost and requirements for data transfer speed and distance, frequency hopping spread spectrum (FHSS) [41] and ZiggBee [42] technologies look like good choice. This module has to enable relatively fast data transfer and transfer of time synchronization signals and data. Transceivers should be immune to high level of interference in a substation switchyard.

4. 2. 2   Concentrator Unit

As we can see from proposed architecture only one concentrator unit is needed per substation. This unit gathers data from all field units through wireless communication, stores data, performs data pre-processing and enables remote access of the data. This part of system consists of several modules. First and most important is computer module. This module needs to process incoming data and control the functioning of the complete system. This computer executes signal and data pre-processing software which analyses and stores data received from field units. The processor is connected to two devices. One device is a wireless transceiver, which allows it to communicate with the field units to acquire the data. Another device is a time receiver, which provides accurate time signals. The processor should also be connected to a network, like Internet, to allow information and data transfer to central place. Personal computer (PC) looks as an ideal solution for concentrator implementation.

4. 3   Software Architecture

    Software architecture should follow similar structure as hardware. It has to be modular and hardware independent. Software architecture should be based on data flow in the system as it is shown in Figure 17. Generally, system could be divided into two parts: data acquisition software running on field unit and applications running on concentrator. Important part of the software solution is wireless communication protocol between field units and concentrator computer. It has to implement all necessary functions without overburdening communication network. Communication from contractor to central place or other substation device has to be implemented using Internet communication protocols to enable fast data transfer from substation.
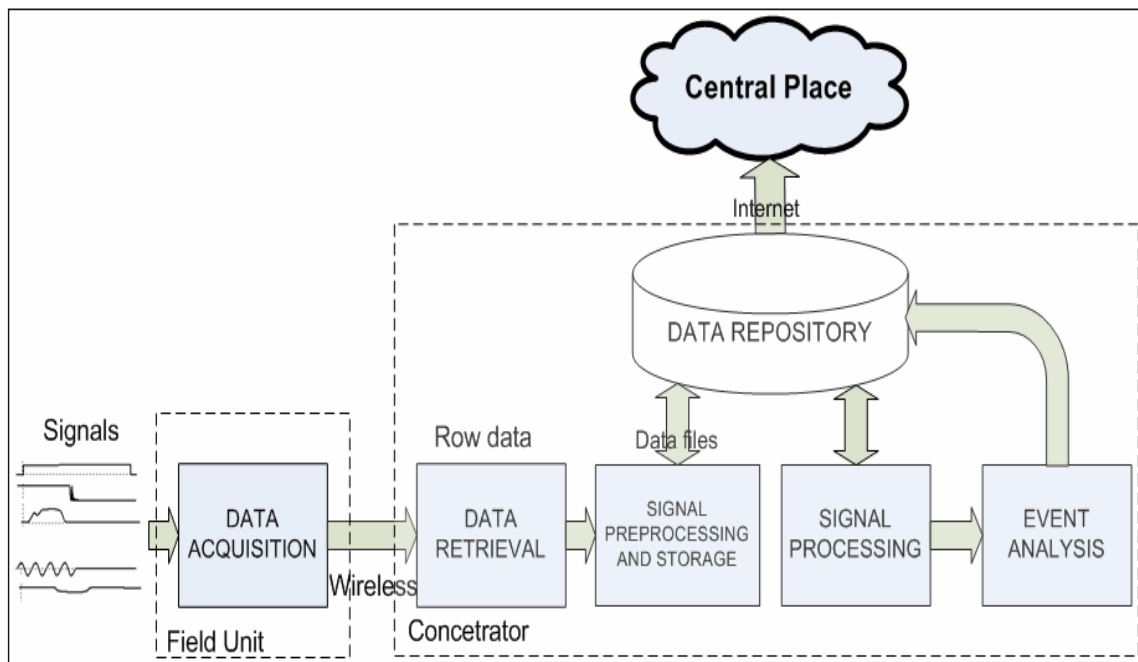

Figure 17. System data flow

Platform independence requirement could be completely implemented on concentrator side using middleware or platforms.

4. 3. 1   Data Acquisition Software

Data acquisition software should run in real-time environment because of the nature of tasks. It needs to continuously sample input signals and check for new events. Field units need to record pre-event part of the recording. This could be done using software circular buffer. This feature enables capturing of pre-event input signals, which are necessary for signal processing and operation analyses. Samples are stored in buffer as they are taken from AD converter. Pointer is used to point to next available space in the buffer. That pointer is incremented after every data transfer from AD converter to buffer. When pointer reaches last position in buffer, instead of going to next position (which doesn't exist) it goes to first position again. If buffer size is large enough, providing that the application takes data from buffer before they are overwritten, this is very efficient way of temporarily storing data. While nothing interesting happens, samples are being stored in buffers and overwritten after certain period. It is very important that application notices event and transfer samples to nonvolatile memory prior to overwriting.

Data acquisition software also needs to perform time synchronization in real time environment. It also needs to control all acquisition parameters and data transfer to concentrator.

Central part of the data acquisition software is module, which prioritizes the tasks that software must perform. Since, there are several real-time processes running on the same processor. The module is responsible for controlling the flow of the system

algorithm. It must detect events when they happen and activate the appropriate routine to perform required action. Direct Memory Access (DMA) module available in the core of the controller helps to relax number of real-time tasks running on the processor. Communication protocol between field unit and concentrator should enable data transfer, time code transfer and remote setting control of the field unit. It should also enable device setting setup through local communication port. In most cases, number of field units will be less than a dozen. However, protocol needs to enable communication between several dozens field units and concentrator.

4. 3. 2   Concentrator Software

The data retrieval software performs the following functions:

- Receive data from all field units and create data file

- Allow configuration of the field unit

- Perform time synchronization between clock connected to it and all field units

- Provides an easily accessible data interface for other applications

   This software is also event driven. It handles three types of events: those generated by the user, GPS clock, and by the field unit. User events include configuration of the field unit and field unit events include data transfer request. Concentrator controls field units by sending commands to specific unit. It also responds to data transfer requests form field units and creates files in specified format from data received from the field. Data files generated by data retrieval software are later provided to higher-level software applications.

Rest of the software running on the concentrator side should be independent of circuit breaker monitor system. It could be part of substation data integration application or even specialized third-party software. That application should enable data validity checking and efficient storage. It should perform file renaming following IEEE file renaming convention [43]. This enables efficient file storage and database indexing, sorting and searching. It should also perform data analysis to find and eliminate invalid data. That application also needs to enable easy data transfer between local substation and central place. Analyses applications, which perform circuit breaker condition analysis or breaker operation and status analysis, could be installed locally, in a substation, or centrally in control center or corporate office.

4. 4   Conclusion

This section describes the architecture of the online circuit breaker monitoring system. It outlines generic system architecture, which enables modular implementation of the requirements specified in previous section. This architecture is proposed to keep the cost of the system at minimum. The different components of the field and concentrator unit hardware are discussed. The software requirements for the system are defined and functionalities of their modules are presented. Implementation details are purposely avoided because they are related to currently available technologies.

5   APPLICATIONS AND BENEFITS

5. 1   Introduction

The importance of maintaining power system equipment, especially transmission and medium voltage distribution circuit breakers, has increased due to the aging assets problem. Proposed circuit breaker monitor system will improve CB condition monitoring performing online monitoring of all available signals in the breaker control circuit. This system should provide data for continuous condition assessment, identification of problems, and in some cases prediction of failures and operating problems before they become critical. Knowing the condition of the circuit breaker can facilitate planned maintenance of the equipment. This would allow decrease in down time and increase in reliability and availability of the circuit breaker.

While the monitoring data from single circuit breaker can provide only information about the operation and status of the individual breaker, data from multiple breakers located across substations can enable implementation of substation and system-wide monitoring and control applications [44],[45]. It is very important that additional applications can be implemented by using data from multiple circuit breaker monitors without making changes on existing data acquisition units as shown in Figure 18.

Based on data availability three levels of analysis applications are possible. Firstly, single breaker operation and condition analysis, which can be performed, based on current and historical data available only from single circuit breaker monitoring device. Secondly, analysis of a switching sequence that involves multiple breakers uses time-

correlated data from multiple circuit breakers form single substation or two adjacent substations. Finally, system wide applications are using data from multiple circuit breakers across the system.
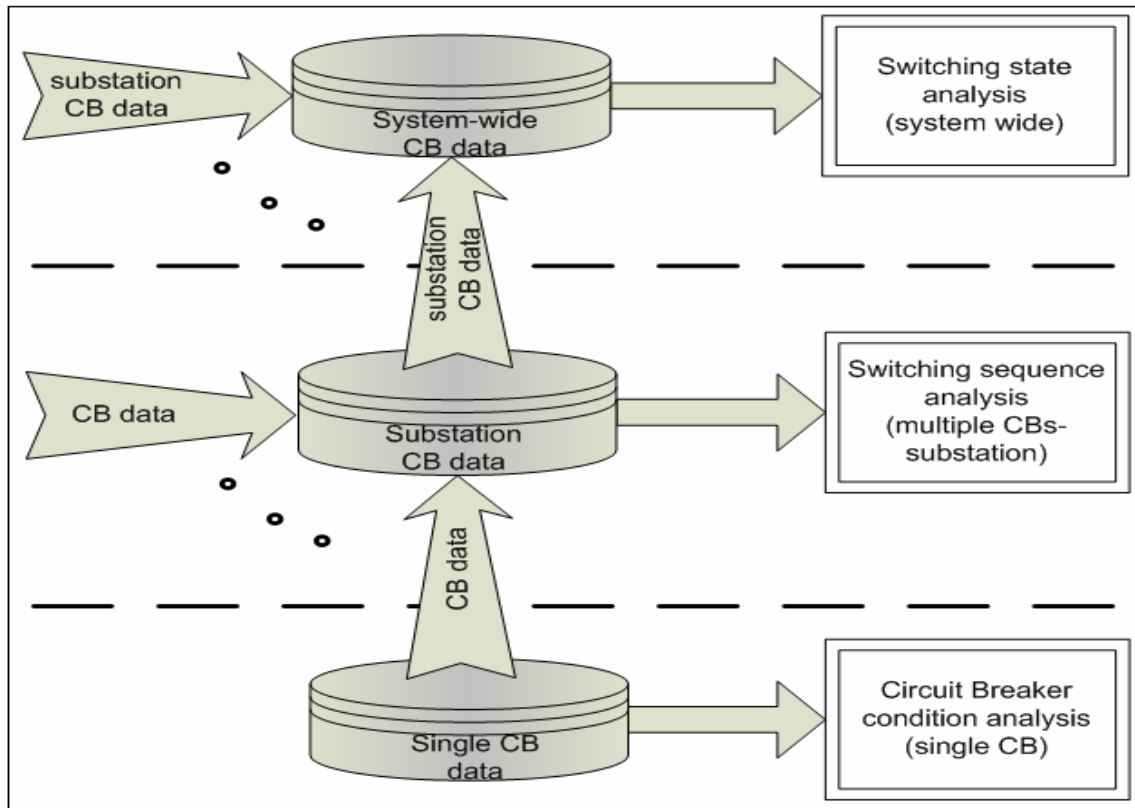
Figure 18. CBM data flow and application levels

First two application levels could be installed on a substation PC or circuit breaker monitoring concentrator. System wide applications require system wide data so they have to be located in the control center.

5. 2   Circuit Breaker Condition Analysis

In the past, circuit breakers were maintained using a time-based schedule. During maintenance, a number of problems could be discovered and solved. This method could

be costly and inefficient. In between maintenance intervals it was never clear if the breaker functioned exactly as desired. The reasons to propose a continuous monitoring of a circuit breaker is to assess if the breaker functions as desired and to track trends in the breaker behavior. Following is a list and brief overview of expected benefits from the utilization of online circuit breaker condition monitoring, which could be achieved using the proposed system:

Increase System Reliability

Most additions and improvements to power systems are made to increase system reliability. Used effectively, circuit breaker monitoring can increase the reliability and availability of equipment to meet these demands. Circuit breaker monitoring can help by providing information on the condition of the circuit breaker. Knowing the condition of the circuit breaker one can facilitate planned maintenance of the equipment. This information may be used to reduce down time and increase the reliability and availability of the circuit breaker.

Optimize Maintenance Activities

With accurate information on the condition of circuit breakers, utilities can better schedule maintenance activities. This will allow implementation of condition-based maintenance instead of the traditional time-based maintenance, and will provide a basis for optimizing the priority of the equipment to be maintained.

Reduce Maintenance Costs

Monitoring which provides the right information can be used to initiate condition based maintenance, allowing utilities to optimize the activities of maintenance personnel.

It could also provide information about equipment problem and suggest when to perform maintenance without performing costly on-site visit.

Extend Equipment Life

The circuit breaker monitor can identify some problems before they escalate into a major failure. Being able to identify problems early and allow for timely repairs will extend the equipment life and allow the utility to receive greater benefit for their investment.

Better Failure Analysis

Circuit breaker monitoring can provide adequate post-mortem information that can help a utility to determine if the failure was an isolated incident or if the problem is generic to a range of similar breakers. This information can be used to initiate action to prevent similar failures on other breakers. This information could also help the circuit breaker manufacturer to improve future circuit breaker designs.

Expert system based application which uses the control circuit signals to track breaker condition and suggest maintenance action is developed at Texas A&M University few years ago [46]. It compares information recorded during breaker operation with settings based on manufacturer's breaker manuals and breaker operational history.

Information obtained from online circuit breaker monitoring system can also be used to perform substation and system-wide reliability studies. It could give necessary equipment reliability parameters, which are very important for an accurate reliability study.

5. 3   Switching Sequence Analysis

In modern control centers, system operators should keep track of equipment operation. During switching in substation, many events could happen in a very short period. From data currently available to operator, it is very hard to track those events and make conclusions about performance of the switching operation. Automatically processing of the switching events could help to identify whether sequences of operation were as expected [47]. Necessary requirement for this kind of analysis is the time synchronization between signals from different breakers, which the proposed system provides. For example, in the case of a single breaker, analysis should give precise information whether breaker failure logic worked out properly and finally disconnected minimal substation section. This kind of monitoring and analysis enables us to track all events that happen on CBs, so later on we can precisely reconstruct sequences of events. In order to open all the circuits that supply fault current more than one circuit breaker typically reacts. It is very important that a minimal number of circuits is opened in such case. By tracking sequence of events in a substation, it is possible to predict some events that are anticipated in the near future. The most important feature is the ability to provide an operator with an explanation why certain events happened. If such the information were available, system operators could use it to make system restoration decisions after an interruption, or possibly prevent an interruption by switching breakers in a tightly controlled manner. Data collected from all circuit breakers in a substation can be analyzed to make deductions about the status of system switching state and performance of switching operation that will help increase system reliability. Switching sequence

analysis can be used to improve synchronous switching operations such as: switching of unloaded transformers, capacitor banks, and reactors [8]. It is very important that breakers, which need to operate simultaneously to disconnect faulted part of the system, have similar operation timings. If this is not a case, slower breaker will always take over complete fault current for a short period before opening. This means that slower breaker will be more stressed and perhaps have shorter lifetime as a result. Switching operation analysis could be used to readjust breaker mechanism, to make the operation synchronous.

5. 4   System Wide Applications

Data obtained from CBs from all over the system can improve several system wide applications. Accurate and reliable CB status data are used in the topology processor application aimed at maintaining accurate assessment of the current electric network topology.

Topology Processor

An automatic topology processor is widely used in many power system analysis programs, such as state estimator, security analysis, on-line load flow and optimal power flow computation, dispatchers training simulators, graphical power system representation programs, real-time power system fault diagnosis and restoration programs. Among them, some operate continuously on a periodic basis while others run on demand.

Network topology defines the connectivity of power system devices. A power system network is configured to satisfy reliable and secure system operation. Power system network connectivity does not remain static because the breakers change their status

(ON/OFF) from time to time due to various reasons. System disturbances like fault, sudden line overload, etc. may lead to tripping of transmission line(s) stopping propagation of the disturbance to the healthy portion of the network.

A topology processor examines the connectivity among the nodes (buses) of a power system and based on this analysis, determines topology of the system network. The most common way of determining power system topology is through monitoring of the circuit breaker status. This monitoring is typically done through a Supervisory Control and Data Acquisition (SCADA) system as show in Figure 18. The Remote Terminal Units (RTUs) are hardwired to the CB contacts. SCADA system detects changes in the CB status and sends information about the status to control center through a SCADA interface. Figure 19 illustrates the traditional way of circuit breaker status acquiring for topology processing.   RTUs usually monitor the control circuit contacts "a" and "b". Those contacts are designed to be in a complementing position so that an opening or closing of the CB can be easily determined by verifying the opposite status of the "a" and "b" contact positions. While this approach has been used for some time, the reliability of the contacts indication has always been a concern due to relatively frequent errors in the auxiliary contacts, that may malfunction, or the errors in the SCADA communications, that may fail.
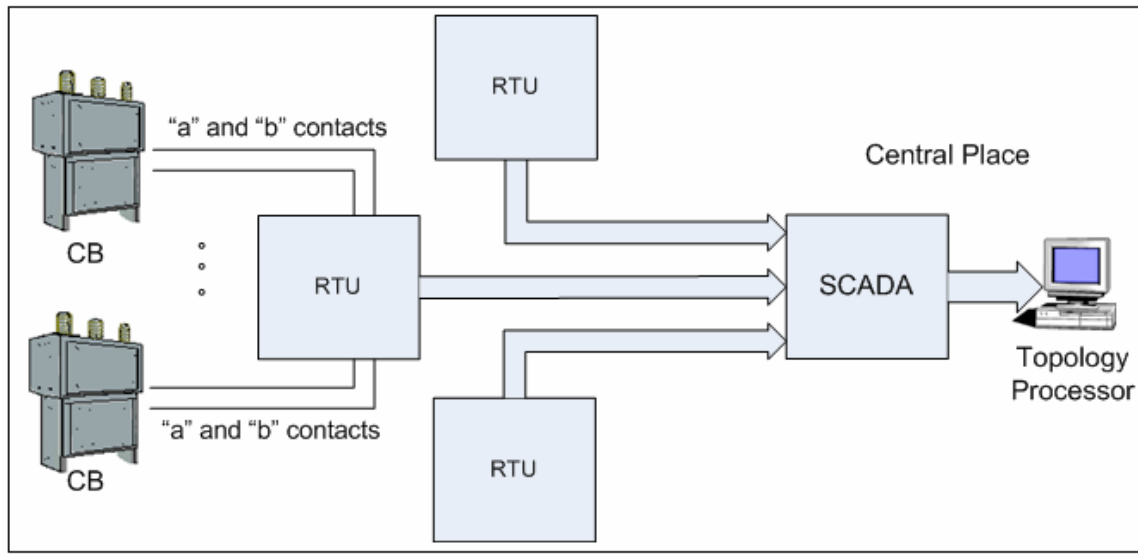
Figure 19. Traditional topology processor based on SCADA

There are many algorithms to validate CB status information based on other measurements form the substations [48],[49]. However, a status change does not necessarily result in a change in the bus/branch-oriented model, which is usually used to check the breaker status. A status change may not affect the bus connectivity but may change generation or load at a bus. This type of error as well as bus/branch model error can lead to the security analysis giving wrong results.

In a control center the topology processor program is usually used in several applications. Firstly, state estimator program uses system topology as an input to the real time security analysis. Power flow analysis also uses the topology processor as an input. In the training simulator programs, topology processor feeds the power flow program. Alarm processor uses network topology from topology processor as well as raw CB status data from SCADA system. Finally, some fault analyses application uses system configuration to be able to simulate system behavior during fault [50]. Some of the

applications, which use topology data, operate in automated (periodical) way, but some are initiated by the operator.

Topology processor could be improved in different ways by using circuit breaker monitoring data [51],[52]. In [51] author points that if the topology changes quickly due to a series of switching events, it may happen that the refresh rate of the analog measurements does not capture correctly the dynamic changes in the network topology. Besides, due to a switching event, the observability for the system may be violated since some of the measurements may be lost as certain circuit breaker monitor system could provide data with more accurate timings. This means that the CB monitor data should have higher time resolution than data taken through SCADA. They suggest implementation of two-stage estimator. This approach requires a reformulation of the state estimator for the case when the estimator indicates an error at a suspect substation. Since it is not easy to determine if the error is caused by a wrong topology or measurement, this approach allows expansion of the system model to include a precise topology of the substation. Using CBM data, it is a possible to eliminate cause of error associated with the topology and focus on measurement errors in further analysis. This data could be used for stability analysis and it could enable online validation of the protection system operation.
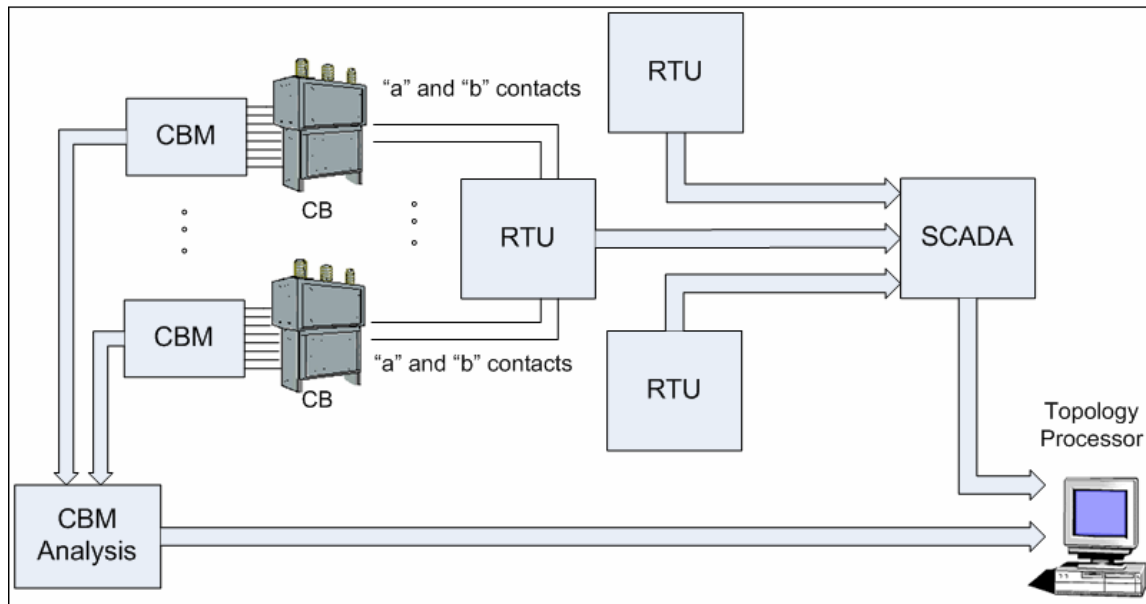
Figure 20. Topology processor improved with circuit breaker monitoring data

Data from online circuit breaker monitoring system could also be used to improve reliability of the topology processor and system control by introducing redundant and more accurate data [53],[54]. In [53], authors present how data integration from various substation IEDs can be used to improve system topology tracking. Circuit breaker monitor data is very important for this kind of analysis. They suggest that all available measurements from CBMs, Digital Fault Recorders (DFR) and Digital protective Relays (DPR) can be combined to gat more robust topology determination.

All this is possible because proposed CBM system provides accurate breaker status information based not only on CB auxiliary contacts but also on other signals available at the circuit breaker. As it is shown in Figure 20, it provides an additional path for circuit breaker status monitoring which increases reliability of the topology processor.

State Estimator

The main goal of the system operator is to maintain system in normal and secure state as the operating conditions vary with daily operation. To accomplish this goal identification of current operating state of the system is necessary. System state is represented by complete set of voltage phasors sufficient to describe system. State estimator is a program which process all row data collected from the system and provides optimal estimate of the system state [55]. This is later used for all Energy Management System (EMS) applications: contingency analysis, automatic generation control, load forecasting, optimal power flow etc. State estimator consists of different modules such as topology processing, observability analysis, state estimation (SE), and bad data processing. Network topology is usually determined directly from the switch/breaker status measurements through SCADA system. Any error in determining circuit breaker status measurement may result in wrong configuration of the network topology, significantly affecting the state estimation results. There are many methods suggested for topology error detection and identification but they usually increase the computational time [56]. As a result, identification of the topology errors using conventional topology processor is not always effective.

Circuit breaker monitoring data could be used to verify topology derived from SCADA/EMS system or to rely on those data in cases when SCADA data are not available. Using redundant data from the circuit breaker monitor system, we could avoid state estimation errors caused by the bad topology model.
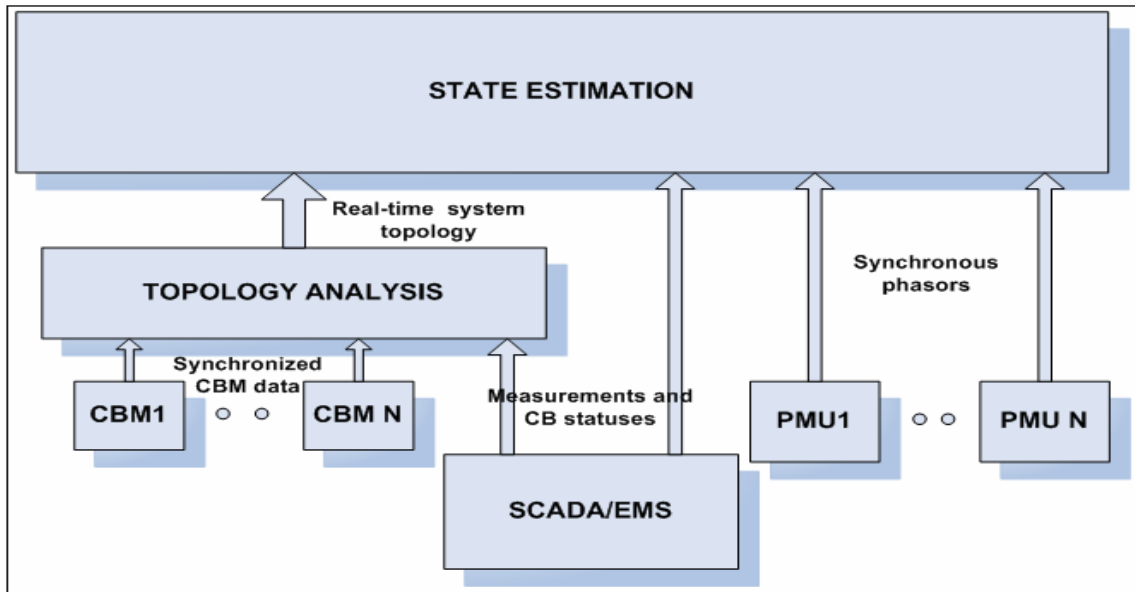
Figure 21. Improved state estimator

Data from circuit breaker monitors placed all over the system should be processed before used as an input to the state estimator. Processing in the substation computer could increase data transfer speed and make circuit breaker status data available in real time. Utilization of redundant data could improve the topology error detection, which will speed up state estimation computations and give solution that could be used more effective. Figure 21 illustrates how the CBM data may be used to improve the topology processor of a state estimator.

Alarm Processor

Alarm processor is used to interpret various alarms generated during power system operation. Alarms are events, which are triggered when a set of predefined conditions is satisfied. Generally, the conditions to generate an alarm are related to malfunctions, anomalous conditions or potentially hazardous situations. Alarms can thus be used to start some automatic safety procedure and to alert the human operators [57]. Accurate

system topology and circuit breaker condition information are also essential for good operation of Alarm Processor. Proposed CB monitor provides real-time CB status and topology information necessary for alarm processor [58]. This paper emphasizes the idea of utilizing data recorded by individual IEDs (including proposed CBM) to help analyzing transmission line faults and CB switching events. They suggest implementation of two-stage alarm processor. In first stage called EMS Level Alarm Processor (EAP), processor have task to find those alarms that are important and need to be analyzed. The following alarms are considered important: Changes of status alarms associated with a CB and Over-current alarms. Second stage called SAS-level Alarm Processor (SAP) draws conclusions about what happened solely based on raw data from a single substation. The aim of the SAP is to dig out more information from the detailed measurement data. Enhanced alarm processor could be used to improve operator's decisions following alarms. Accurate topology is necessary to enable operators to properly isolate power outages in emergency state. The alarms related to problematical substation bus configurations can help operator restore system after interruptions.

Our solution also provides information about condition of the critical breakers in the system. That information could be used directly to alarm operator about condition of circuit breakers, which may fail or their proper operation is unlikely. The improvements in the alarm processor are shown in Figure 22. In suggested example circuit breaker monitor data can be used by system operators to make system restoration decisions, or possibly to prevent an interruption by removing a suspicious breaker in a controlled manner.
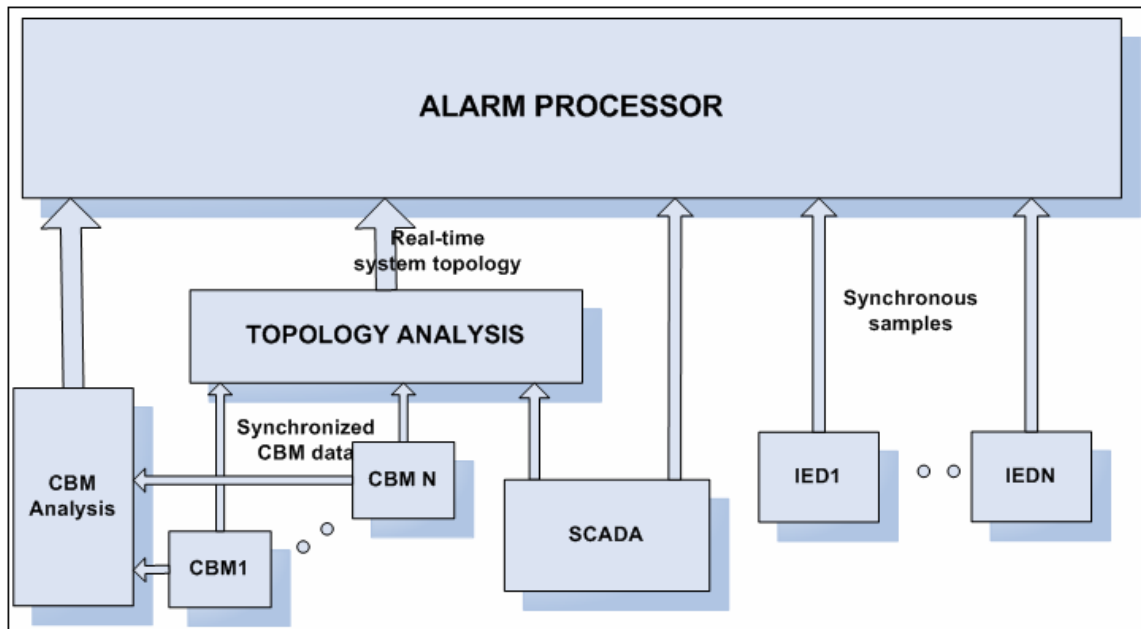
Figure 22. Improved alarm processor

5. 5   Conclusion

This section presents applications that could benefit from information extracted from the circuit breaker monitoring data. Circuit breaker condition-based monitoring could improve and decrees cost of equipment maintenance. The solution provides synchronized data that could be used in the switching sequence analysis and in system analysis applications such topology processor, state estimation and alarm processor. All these applications should increase reliability by using additional and more reliable information about the power system switching status. Additional information from CBM monitors could be used to verify the consistency and increase redundancy of the overall measurements, thereby increasing robustness of data and reducing monitoring errors.

6 CONCLUSION

6. 1 Summary

The circuit breaker forms a critical part of the protection system, as well as the Supervisory Control and Data Acquisition (SCADA) system used for power system switching. To sustain the confidence level in this critical piece of equipment comprehensive maintenance programs have been established. It was shown through the years that these methods are not very efficient and they are expensive. Condition monitoring is a relatively new concept that has come about primarily because of recent developments of electronic sensors and data acquisition equipment that have made this idea not only technically feasible but also economically attractive. Proposed online circuit breaker monitoring solution provides data, which can be used to estimate circuit breaker condition for maintenance purposes. It enables utility company to conduct maintenance only when it is needed due to breaker condition. By deploying this solution, it is possible to reduce maintenance and personnel cost.

As an addition to circuit breaker condition monitoring this system provides information that could be used to enhance circuit breaker status and operation monitoring.

This thesis gives functional requirements that should be followed to gain maximum value from the breaker monitoring solution. It also provides generic system architecture and implementation description that should be followed to keep the cost of the design at minimum and enable easy and noninvasive installation.

6. 2   Research Contribution

Before this research took place, circuit breaker monitoring has been limited only to monitoring of condition of the circuit breaker and status monitoring based on auxiliary contact positions. Because installation of proposed monitoring equipment in the substation could provide additional information and help solve some of the existing operational problems, contributions of the thesis can be divided into two categories. First, requirements and implementation descriptions of the new circuit breaker monitoring features and second, ideas how additional information obtained from these features could be used to help solving existing power system operational problems.

In the literature, no complete requirements are available that would explain which control circuit signals should be monitored and what data acquisition requirements that will enable quality analysis of recorded signals are needed.

Based on the analysis of the circuit breaker operation, presented in section 3.2, thesis provides selection of the circuit breaker (CB) control signals of interest and gives list of CB parameters that could be measured or estimated from these signals. Analysis of the signals characteristics, given in sections 3.3 and 3.4, results in data acquisition requirements for Circuit Breaker Monitor (CBM). This includes specific AD conversion parameters such sampling rate, AD resolution, and processing requirements such as data storage and communication parameters.

Time synchronization is an additional feature that will enable usage of CBM data in analyzing multiple breaker operation, estimating CB status more accurately, and developing and improving several system wide applications. These analyses require that

samples from multiple breakers be synchronized in time before processing. Based on this, section 3.5 provides specific requirements for time synchronization between CBM field units and gives suggestions for implementation.

CBM time synchronization feature has not been introduced before in the literature and it was not used in the kind of analysis proposed in this Thesis. This feature provides additional information that could be used to improve power system operation. Section 5 gives ideas how additional information from a CBM system could be used to develop and improve substation switching sequence analysis and enhance system wide applications such are topology processor, alarm processor and state estimator. It also shows some of the problems that could be solved and benefits that system operation could gain from better circuit breaker data.

6. 3   Future Work

Data collected by the CBM solution should be incorporated in the substation and control center databases to provide simple data access in the future. This could be done though data integration following some of the data modeling standards in this area. It is also suggested that some of the processed results should be available for different kind of system wide analysis. Future work should be focused on the problem how to integrate row data from CBMs, as well as how to process information from online circuit breaker monitoring system and make it available for different users. This could be done at both the substation and system wide levels. Availability of data in a suitable form such as the central database will provide improvement in the existing system analysis applications and development of new applications.

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APPENDIX A

DATA STORAGE AND DATA TRANSFER

Knowledge of the nature and duration of an event is of essence for the calculation of the parameters such as the transfer bit rate and memory capacity. Depending on the type of the circuit breaker and the nature of the fault, several different scenarios of the breaker behavior may occur. Generally, two types of faults may occur in the power system – temporary fault and permanent fault. Permanent faults define longer events and therefore, they will be examined since they represent the most demanding case. Abbreviations used in Figures 18-20 are: TA – trip applied; CA – close applied; O – opened breaker; C – closed breaker, 1 cycle = 1/60 sec.

If the fault has occurred and the circuit breaker was closed, chronological description of the circuit breaker operation is shown in Figure 18. Breaker will be reclosed three times trying to connect line back into system. In the case when the fault is still present after three attempts, it will open again. This time the lockout will occur and the breaker will remain opened until closed manually. The graphical representation of the above description is given in Figure A.1.
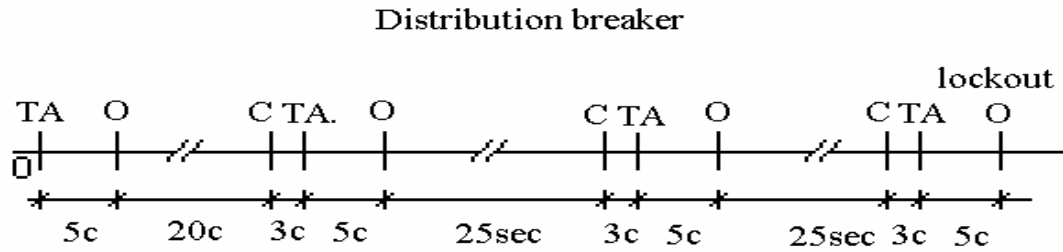
Distribution breaker

Figure A.1. Permanent fault – Distribution breakers

Similar sequence of event will be followed on transmission breakers. The chronological description of the transmission circuit breaker behavior is represented in Figure A.2.
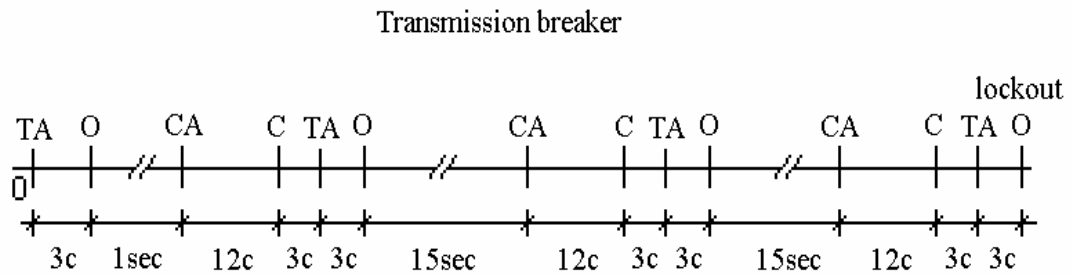
Transmission breaker

Figure A.2. Permanent fault – Transmission breakers

On extra high voltage circuit breakers only one reclose attempt will occur because of stability concerns.

It can be seen that most of the time between relosing events breaker do not operate so there is no need to record during these time intervals. We can also notice that events of

interest do not last more than 30 cycles for all cases. With addition of the pre event and post event there is no need for event recording to last over 1 sec. This time interval should be enough to catch all useful information even in case of slow breaker operation.

Calculation of the event file size and memory requirements

Assumptions are:

- High sampling rate is used for data acquisition: 7680Hz.

- Number of channels: 18

- Number of bits to represent each sample: 12 bits (minimum) or 16 bits (optimal value)

- Binary COMTRADE file format

Considering the duration of an event to be 1 (one) second (7680 samples), event file size will be as follows.

Minimum file size:

file size (min) = 7680 samples x (18 ch. x 12 bits/sample + 1 time stamp x 16 bits/sample)

= 223 KB (approx. 225 KB)

Optimum file size:

file size (opt) = 7680 samples x (18 ch. x 16 bits/sample + 1 time stamp x 16 bits/sample)

= 292 KB (approx. 300 KB)

In order to make the system flexible in such way that it can record and temporarily save few recordings in case when communication network is busy or even unavailable. This

concept requires local nonvolatile memory capable to store several dozens event recordings. 16 MB memory is able to keep up to 50 circuit breaker event recordings. Memory should be utilized on such way that always keep maximum number of recordings and overwrite the oldest recording when new is captured. Considering the frequency of the breaker operation in many cases this will be enough to keep breaker operation history for several years. This data could be also used as a backup if the data transferred to control house or control center is lost.

Data transmission requirements

Circuit breaker operation data should be available for system analyses in the relatively short period. Even though CBM data is not used in real time power system control applications, it should be available in several seconds after breaker operation. In the real system, several circuit breakers can operate at the same time in the case of the bus fault and therefore, the system should be able to transmit data from every operating breaker location to the concentrator in relatively short period.

bit rate (minimum) = 300KB / 10 seconds

= 240 kbits/second (approx. 256 kbits/sec)

Above defined bit rate is valid for the communication between a single breaker and the concentrator. In the case of simultaneous operation of several circuit breakers in the substation data transfer time for all data should be les than a minute. In the case of local

bus fault or breaker failure operation not more than 5 breakers will operate at the same time.

data transfer time (maximum) = 5 breakers x 300 KB / 256 kbits/sec

= 47 seconds

Using 256kbits/sec data transfer speed to transfer data from five breakers will enable that data from all breakers will be available in les that 50 seconds after event. Higher bit rate communication is desired but not necessary for applications that have been proposed.

APPENDIX B

CIRCUIT BREAKER MONITOR DATA SECURITY

Cyber security is becoming a major issue in the power system industry because attackers could compromise electric power system to alter or shut down the supervisory control and data acquisition (SCADA) systems, which run critical processes. Thus, a successful attack might shut down power and create huge loss for community. The North American Electric Reliability Council (NERC) has issued eight reliability standards on cyber security. These Cyber Security Standards, effective June 1, 2006, provide a cyber security framework for the identification and protection of critical cyber assets to support reliable operations of the bulk electric system. These eight new standards address different aspects of cyber security. Like several other security regulations, NERC Cyber Security Standards mandate the goals for information security without prescribing specific solutions.

Circuit breaker monitoring data cannot be classified as a critical data but still carry information that could be misused. Circuit breaker monitoring data provide power system topology information that could be used to gain advantage on deregulated market. Someone could use this data to acquire information about transmission system congestions and use that information to increase energy price. This makes necessary to protect data during wireless transfer between field units and concentrator in the control house. It should be mentioned that encryption should not overburden processor on the field unit side. Several ciphers could be used for secured communication between field

units and concentrator. Some of them are completely secured and some require long time to be broken. Circuit breaker monitoring data carry time critical information, which become useless after relatively short period. This allows usage of ciphers that could be broken but require relatively long time to be broken.

Many communication equipment vendors provide wireless transceivers that have implemented some kind of data encryption. Most common ciphers that are used in transceivers available on the market are Data Encryption Standard (DES), Triple DES and Advanced Encryption Standard (AES).

Data Encryption Standard (DES)

Data Encryption Standard (DES) is a widely used method of data encryption using a private (secret) key. The DES is a cipher selected as an official Federal Information Processing Standard (FIPS) for the United States in 1976, and which has subsequently enjoyed widespread use internationally. DES is now considered insecure for many applications but still widely in use. This is mainly because the 56-bit key size being too small. In several occasions, DES keys have been broken in less than 24 hours.

DES is the archetypal block cipher — an algorithm that takes a fixed-length string of plaintext bits and transforms it through a series of complicated operations into another ciphertext string of the same length. In the case of DES, the block size is 64 bits. DES also uses a key to customize the transformation, so that decryption can only be performed by those who know the particular key used to encrypt. The key ostensibly consists of 64 bits; however, only 56 of these are actually used by the algorithm. Eight bits are used

solely for checking parity, and are thereafter discarded. Hence, the effective key length is 56 bits, and it is usually quoted as such.

Although more information has been published on the cryptanalysis of DES than any other block cipher, the most practical attack to date is still a brute force approach. The brute force is process of trying every possible key in turn. The length of the key determines the number of possible keys, and hence the feasibility of this approach. For DES, questions were raised about the adequacy of its key size early on, even before it was adopted as a standard, and it was the small key size, rather than theoretical cryptanalysis, which dictated a need for a replacement algorithm.

In the past, many different variations of DES cipher were used for ATM transaction data encryption. In spite of all the criticism and weaknesses of DES, there is no known example of anyone actually suffering monetary losses because of DES security limitations. Many DES users use Triple DES algorithm, which is simple done by applying DES cipher three times on the same bit stream with three different keys. In recent years, the cipher has been superseded by the Advanced Encryption Standard (AES).

The Advanced Encryption Standard (AES)

The Advanced Encryption Standard (AES) is a Federal Information Processing Standard (FIPS), which specifies a cryptographic algorithm for use by U.S. Government organizations to protect sensitive, unclassified information. AES cipher algorithm is based on Rijndael algorithm, which is a symmetric block cipher with variable block and key length. For AES the block-length was fixed to 128-bit and three different key sizes

(128, 192 and 256-bits) were specified. Therefore, there are AES-128, AES-192 and AES-256 as three different versions of AES. The cipher is based on round operations. Each round has a round-key of 128-bit and the result of the previous round as input. The round-keys can be pre-computed or generated on-the-fly out of the input key. Due to it's regular structure it can be implemented very efficiently in hardware. Decryption is computed by application of the inverse functions of the round operations. The sequence of operations for the round function differs from encryption, which results often in separated encryption and decryption circuits. Computational performance of software implementations often differs between encryption and decryption because the inverse operations in the round function are more complex than the according operation for encryption.

Most of frequency hopping spread spectrum and ZigBee wireless modules have already implemented some of the mentioned ciphers. Most common is AES 128 algorithm, which is sufficient to protect classified information up to the SECRET level. This algorithm is recommended for sensitive and secret data encryption by US Government in June 2003.

APPENDIX C

CIRCUIT BREAKER MONITOR IMPLEMENTATION

Introduction

This Appendix describes the implementation of two working prototypes designed to meet the requirements described in section 3 of the Thesis. The development of the Circuit Breaker Monitoring System is an ongoing process at Texas A&M University. The implementation of two prototypes is completed and both units are being tested for longer period at the field setup in 345kV substation in south Houston area.

The implementation can be classified into two categories. One category is hardware, which describes hardware architecture and components used for development, and software, which describes the operation of the system. Several upgrades are developed during development of the second unit but they are also applied on the older prototype making it equally operational.

Hardware

The system hardware consists of two parts: field unit located in switchyard and concentrator PC located in substation control house. Field unit is hardwired to the circuit breaker control circuit and it samples signals from the breaker; recognize events and records samples on local memory. It also communicates with concentrator PC to perform data transfer and time synchronization. Concentrator PC gathers data from all field units in a substation and save them on the local.

Field unit

The field unit consists of four modules connected together: signal conditioning and overvoltage protection module, data acquisition processor module, wireless transceiver and power supply. Architecture of the field unit is shown in Figure C.1.
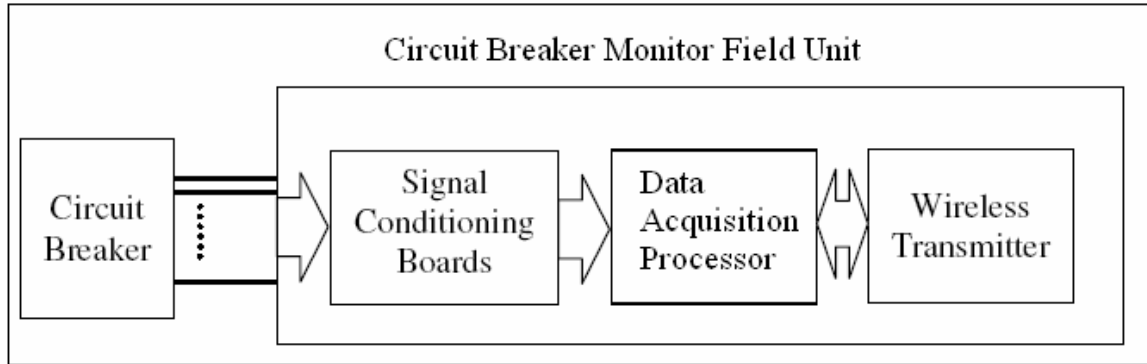

Figure C.1. Architecture of the CBM field unit

Signal conditioning and overvoltage protection module

This module is used to scale signals from control circuit of the circuit breaker to the input range of the data acquisition module. It also provides protection from high voltage transients generated in circuit breakers control circuit. This board also performs low pas antialiasing filtering. This module is implemented in discrete component technology mounted on a custom designed PCB. The circuit is replicated as many times on the PCB as the number of required channels - 15.

The circuit consists of three parts according to the function that performs. First part is overvoltage protection implemented using transient suppression Zener diodes and resistors used to limit surge current. Inductors, and capacitors on the input side are used to perform noise filtering. Second part is two stage amplifier used to scale signal to the

appropriate amplitude. Operational amplifiers are used to implement these amplifiers. Final stage is antialiasing filter implemented as 2-pole low-pass Chebyshev filters.

Data acquisition processor module

Diamond Systems' PC 104 architecture based computer with 32 MB of memory and 16 channels of 16 bits AD conversion board is used to perform sampling and acquisition of the signals. It uses RS 232 port for communication with wireless transceiver connected to it.

Wireless transceiver

A wireless transceiver is connected to the serial port of the processor. Module used in this system is FreeWave Technologies, Frequency Hopping Spread Spectrum transceiver that have 1 PPS distribution and DES encryption capabilities. The transceiver is set to operate as a slave unit in the point-to-multipoint network configuration.

Master unit hardware

The concentrator PC hardware consist of computer, a laptop or a PC is used as the processing and storage device, wireless transceiver, the same model of transceiver that is used in field unit, and GPS clock receiver. PC is connected to GPS clock receiver to receive time code and wireless transceiver configured as a master unit in point-to-multipoint network. GPS receiver is also connected to the 1PPS input pin of the wireless transceiver. This connection is used to transfer these synchronization pulses to the field units.

Software

Software can be also grouped into two developments: Field unit software and concentrator software. The slave unit software is implemented in C programming language. Field unit software performs following tasks:

- Signal sampling (through interrupt)

- Time synchronization (through interrupt)

- Event recognition

- Samples recording

- Data transfer

- Time code update

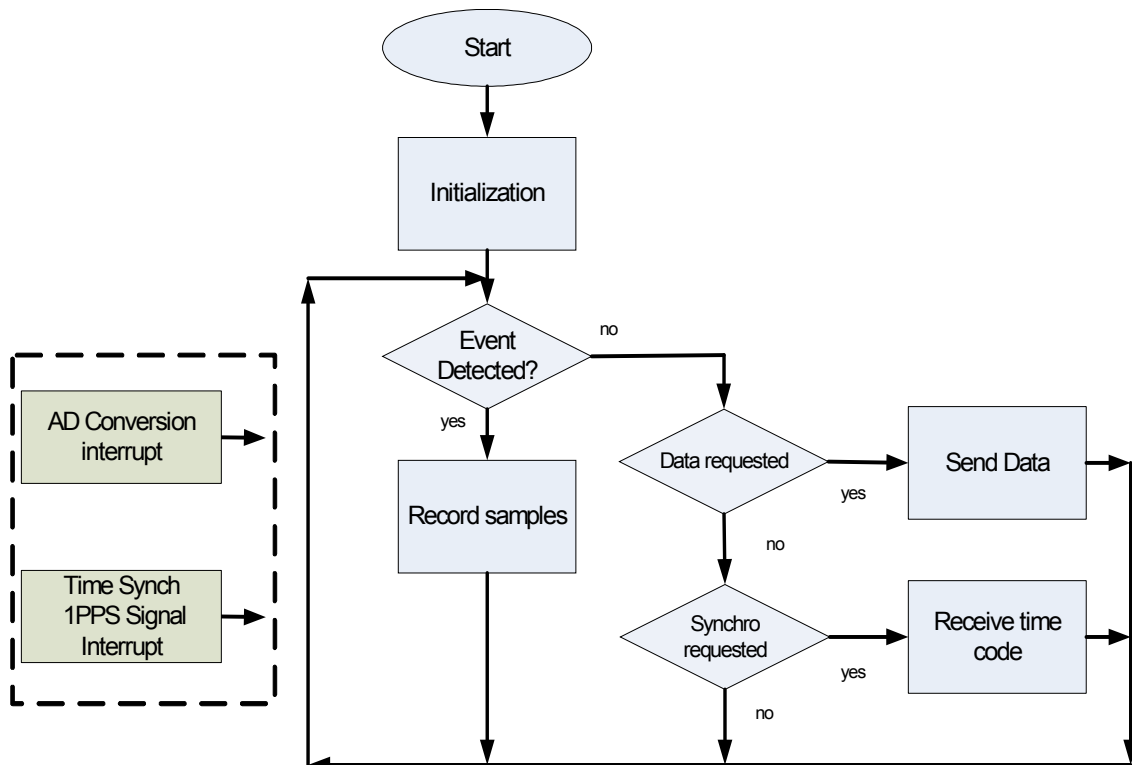Algorithm that shows field unit is showed in Figure C.2

Figure C.2. Field unit software algorithm

The wireless system designed works in a point-to-multipoint mode. In this mode, the master sends out the same message to all the slave units and the message is not acknowledged by the slaves. However, when slaves send a message to the master the message is acknowledged by the master. The communication protocol implemented in the software is designed to use previous logic. It uses commands that consist of unit ID and request commands. Data transfer from field unit to the concentrator goes through strong link so cannot be received by other slave units.

Concentrator unit software performs data gathering from field units by pooling every unit in equal time intervals. If unit has file to send data transfer will start and received file will be renamed stored on hard drive. Concentrator software also sends time code information to the field units. It gets code from GPS clock receiver and than distribute it to the all units. This code is used to stamp samples recorded by field units. Real time synchronization is done using 1PPS signal from GPS clock that marks beginning of the following seconds. By measuring time between two pulses and counting seconds, field unit is able to keep very precise time information. Time code is used just to get absolute time on the beginning. This process is repeating during the work to resynchronized field unit if unit gets unsynchronized.

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