Real time generator monitoring system

M Kuzunovic*, I Rikalo*, D R Sevcik†, C W Fromen* and K W Tielke†

*Department of Electrical Engineering, Texas A&M University, College Station, TX 77843-7441, USA
†Houston Lighting & Power Company, USA

This paper describes a prototype of an intelligent generator monitoring system, developed jointly by Texas A&M University and Houston Lighting & Power company. The monitoring system is based on a high performance front-end data acquisition system and real-time processing of electrical signals from CTs and PTs, as well as contacts from related protective relays, circuit breakers, and switches. Based on this data, the system performs continuous monitoring of the electrical part of the generator and informs operators of any deviations from the normal operating conditions. As a result, performance of protection relays as well as related control and switching equipment can be evaluated. The system is implemented using a PC interfaced to a modified commercial digital fault recorder.

Keywords: Generator, Digital fault recorder, Control, Protective relaying, Real time systems

1. INTRODUCTION

Automated monitoring of large power plants is a well established practice in the industry. Several computer systems are employed today in a control room to monitor various parts of the power plant such as boiler controls, turning gear, as well as control and protection of the electrical part. Introduction of advanced data acquisition systems and intelligent techniques have prompted development of new monitoring systems that provide improved performance with a reduced overall cost [1 – 3]. Those developments have been primarily related to the specific applications such as monitoring of the electrical parts of the generator.

This paper describes a new design of an intelligent system for automated monitoring of the electrical part of a generator. The main advantage of this implementation over the existing ones is the improvement in the data acquisition and related processing of the data.

The idea for such a system came from development of a similar system aimed at automated monitoring and analysis of faults in the high voltage transmission systems [4]. This system is also based on the high performance data acquisition front-end using substation digital fault recorders and advanced data processing using an expert system [5]. The substation system has been installed in the field and its performance has been monitored for over two years.

The experiences and the basic application concept from this development have been incorporated in the generator monitoring system design described in this paper.

The first section of the paper presents a discussion of the requirements for the new monitoring system. The next section describes hardware and software modules of the monitoring system prototype built for Houston Lighting & Power Company. The application characteristics are outlined in the next section. Several examples of the data processing functions are given next. Future activities, conclusions and a list of references are given at the end.

The prototype has been installed since the beginning of 1996 and currently field tests are under way. Figure 1 depicts the control room in the power plant where the generator monitoring system is installed. The system monitors a 730 MW generator unit in one of the HL&P's fossil-fueled steam plants. The 21-inch monitor can be seen in the background. All system messages are displayed in real time for the operators. Additional information (e.g., event report files) can be retrieved manually by using a track-ball.
2. SYSTEM REQUIREMENTS

2.1 Data acquisition requirements

A close analysis of existing computerized monitoring systems [1 - 3] for the electrical part of the generator has revealed the following:

- The input data sensors and selected sampling rate can only provide periodic update of the system conditions. This is realized using averaged values of the analog inputs which may not be sufficient to account for some important transient and fast dynamic changes.
- The monitoring philosophy is to alarm all the individual deviations of the input quantities. This may produce a large number of alarms for a given event that may be difficult to interpret in the case of some unusual or complex operating conditions.
- The type and number of sensors and measuring instruments as well as related wiring and instrument transformers, are selected to fit individual measuring tasks. This does not provide for any intelligent comparison or redundant checks among all the measured quantities that are naturally correlated by the laws of the electrical circuits.
- There are digital fault recorders installed at generating plants at some utilities, but their function is only to record data once they are triggered and no intelligent processing or analysis is performed.
- The communication between the data acquisition equipment and monitoring computer is done via relatively slow RS232 serial port.

As a result of this analysis, it was realized that an advanced data acquisition and processing system consisting of a digital fault recorder and a PC can offer several major benefits if the following update of the requirements is provided:

- The input data is obtained by using synchronized sampling of currents, voltages, and contact states. This provides enhanced resolution and temporal relation for the input quantities that enables monitoring of fast transients and dynamic changes of the generator electrical system.
- An intelligent processing of alarms is performed. This may eliminate the need to report the individual alarms by automatically correlating the alarms and providing one comprehensive resulting statement about the prevailing generator operating condition.
- All the input data is gathered in a common data base that is updated in real time. This enables consistent processing of input quantities, where intelligent correlation may be established, thus providing additional redundancy and logic checks for improved monitoring.
- High speed processing and reporting of transient and fast dynamic changes is performed. This provides real-time reporting to the operator.

2.2 Application requirements

Based on the mentioned features, it was concluded that the new monitoring system should benefit different groups of personnel responsible for the various aspects of the generator system operation.

The following are the major application requirements identified regarding the specific groups of personnel:

- The operators need to have a dedicated high-performance system capable of making intelligent conclusions about the operating state based on a variety of system measurements and conditions. This may simplify the operator tasks while improving overall quality of the operations.
- The engineering and design staff need to have a system capable of recording system conditions and operations with increased accuracy and selectivity. This may provide useful information needed for the ongoing analysis of the generator operating performance and improvements in the engineering design practices.
- The protection engineers and maintenance technicians need to have access to the data, that have not been available earlier, describing abnormal operations and conditions on the generator. This may improve their capability to troubleshoot various operations of control and protective relaying systems and to better understand impact of these systems on the generator.
Figure 2 shows the breakdown of the application functions that are initially identified as the most important for all three groups. The list of functions is by no means final. It does include the functions that are related to the monitoring of the most important electrical quantities as well as some protection relays and breakers.

Two different generator modes of operation are supported by the monitoring system:

- normal operation of the generator,
- generator and bus synchronizing.

During normal operation of the generator, plant operators need to be alerted when generator operating parameters are not within prespecified limits.

During generator and bus synchronizing, a digital synchroscope needs to be displayed and the synchronizing procedure needs to be monitored. The system should help the operator to synchronize the unit with the least amount of stress to the unit itself by calculating and displaying the optimal closing time of the control switch.

The next section presents basic hardware/software modules that were designed for this monitoring system. The system was designed to allow easy reconfiguration for other power plants as well as functional extensions.

3. SYSTEM IMPLEMENTATION

Figure 3 shows the basic block diagram of the generator monitoring system. A digital fault recorder (DFR) serves as a data acquisition front-end, providing continuous data flow toward the monitoring system PC. At the same time, the DFR maintains its basic function of recording the events according to the internal triggers and storing those events on the local hard drive inside the recorder. These stored events are available remotely per request over a dial-up line, using master station software provided by the DFR manufacturer.

The DFR system consists of two recorders (i.e., master and slave unit) having a total of 64 analog and 48 digital channels [6]. These channels are completely isolated from each other and the control electronics. The DFR sampling frequency is fixed at 4.8 kHz. All analog and digital channels are sampled synchronously. The DFR Master unit is organized around an Intel 486 chip operating at 33 MHz with 256 kilobyte cache. It also has a local hard disk drive for storage of recorded events.

The communication between the DFR and monitoring system PC is done via a high speed parallel interface board. Data samples are transferred to the PC in 16 Kbyte data blocks. Each block contains 244 samples of every input channel (this corresponds to 3.05 cycles of data). Data blocks are queued and processed by the system software continuously. To facilitate continuous data transfer between DFR master unit and the PC, TAMU and the DFR vendor jointly specified and designed a special communication board. DFR master and slave units are interfaced using high speed fiber optic link. Additionally, adapter cards for the master unit are designed to accommodate the real-time external data transfer. The interface card for the PC plugs in a free ISA slot and is capable of buffering 16 Kbyte of data in a single interrupt.

The main software modules are given in Figure 5. The Data Transfer module is a stand-alone DOS program that is servicing interrupts coming from the interface board. Data blocks coming from the DFR are time tagged.
and queued at a prespecified memory location. Data Preprocessing and the rest of the modules are MS Windows 95-based applications. The Data Preprocessing module accesses blocks of data samples and calculates the measurements needed for every application function on a power cycle basis. These measurements include voltage phasors, frequency, current phasors, neutral voltage, MW, MVARs, third harmonic voltage at generator terminal and neutral, and rotor speed. Some of the digital signal processing algorithms used for these calculations are listed in the Appendix. The Recorder Configuration module provides information regarding the DFR channel connections such as channel type, PT or CT ratios. This information is utilized by the data preprocessing module to obtain scaled values for all analog signals. The Application Functions module is the core of the generator monitoring system. The application functions are described in greater detail in the following sections of the paper.

The GUI module represents the system's interface to the operator. Finally, File Archiving and Data Logging module is used to manage generated report and log files. In addition to the alarm messages displayed on the monitor, the monitoring system generates comprehensive reports for every generator event. These reports contain the following:

- plain English description of a generator event, pinpointing the problematic areas
- several cycles of historic data (e.g., voltages, currents, status of different relay contacts, status of auxiliary breaker contacts, etc.).

The reports are created for the benefit of protection and design engineers to help them in performing a post-mortem analysis of a given generator event.

4. APPLICATION FEATURES

Table 1 summarizes the functions related to the monitoring of the normal operation of the generator unit. In addition, there are several completely new functions, that are monitoring generator parameters presently not covered by any protection instrumentation.

Table 2 shows a summary of the types of signals that are monitored by the digital fault recorder (DFR) and the generator monitoring system (GMS) at a power plant. It contains the total number of analog and digital inputs for DFR and GMS, and the types of those inputs.

The one line diagram of the power plant given in Figure 6 outlines the physical location of the monitored instrumentation (e.g., current transformers, potential transformers, etc.). Table 3 summarizes the types of input signals used by the generator monitoring system.
5. EXAMPLES OF DATA PROCESSING

5.1 Generator synchronizing

Figure 7 shows the digital synchroscope and information presented to the operator during the generator synchronizing procedure. The GMS monitors the synchronizing procedure and helps the operators by providing 'optimal' closing angle. In this way, the operator will always synchronize the generator and the system with the minimal stress to the generator unit. The 'optimal' closing angle is calculated based on breaker closing time (fixed setting) and frequency difference between running and incoming voltages.

The analysis of synchronizing procedure is performed automatically after closing the control switch. The 'quality' of synchronizing is evaluated based on the maximum transient detected in the generator output current. The analysis report also contains time intervals between 'optimal' and actual control switch closing times, first appearance of the generator output current and breaker auxiliary contact change.

Table 3 Types of input signals

<table>
<thead>
<tr>
<th>Analog quantities</th>
<th>Signal Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>generator output currents</td>
<td>CT2</td>
</tr>
<tr>
<td>generator exciter field current and voltage from the main transformer secondary</td>
<td>CVT1</td>
</tr>
<tr>
<td>generator neutral current and voltage</td>
<td>CT1, Neut. Tran.</td>
</tr>
<tr>
<td>generator terminal voltages</td>
<td>PT1, PT2</td>
</tr>
<tr>
<td>voltages in the auxiliary busses</td>
<td>PT1, PT2</td>
</tr>
<tr>
<td>voltages from the system busses</td>
<td>CVT1, CVT2</td>
</tr>
<tr>
<td>turbine speed</td>
<td>Tachometer</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Digital quantities</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>relay contacts (e.g., generator locked relay, differential relay, etc.)</td>
<td>various</td>
</tr>
<tr>
<td>control switch (e.g., synchronizing switch, etc.)</td>
<td>various</td>
</tr>
<tr>
<td>circuit breaker (e.g., generator breaker, auxiliary transformer breaker, etc.)</td>
<td>CB1-CB10</td>
</tr>
<tr>
<td>phase transformer differential switch</td>
<td>DS1</td>
</tr>
</tbody>
</table>

5.2 Voltage unbalances

This function detects three different conditions:

- voltage unbalances between phases of the same potential transformer;
- voltage unbalances between same phases of two different potential transformers;
- under voltage condition.

Table 4 Monitoring of the voltage unbalances

<table>
<thead>
<tr>
<th>Voltage Unbalance Between Phases on the Same PT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event type</td>
</tr>
<tr>
<td>Phases involved</td>
</tr>
<tr>
<td>Events</td>
</tr>
<tr>
<td>Under Voltage</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Voltage Unbalance Between Phases on the Same PT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event type</td>
</tr>
<tr>
<td>Phases involved</td>
</tr>
<tr>
<td>Events</td>
</tr>
<tr>
<td>Under Voltage</td>
</tr>
</tbody>
</table>

Table 4 Monitoring of the voltage unbalances

<table>
<thead>
<tr>
<th>Voltage Unbalance Between Phases on the Same PT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event type</td>
</tr>
<tr>
<td>Phases involved</td>
</tr>
<tr>
<td>Events</td>
</tr>
<tr>
<td>Under Voltage</td>
</tr>
</tbody>
</table>
6. FIELD TESTING AND FUTURE EXTENSIONS

Initial field-testing is well underway. A generator shutdown and synchronizing have already been experienced. It has been recognized that for a given event, two or more functions may be triggered. This, in turn, produces a number of alarm messages that may be difficult to interpret in the case of some unusual or complex operating conditions. In order to address this issue, the authors envision additional software modules that will be designed to receive status messages from individual application functions and perform further inference action based on the available information.

7. CONCLUSIONS

Based on the research and development experiences gained...
so far, the following can be concluded:

- The existing generator monitoring systems can be enhanced if higher data sampling rate and improved processing are employed.
- The GMS design takes advantage of the high performance data acquisition front-end provided by the DFR, and the system software aimed at comprehensive assessment of the generator operating status.
- The monitoring capabilities of the GMS system may be useful for a variety of utility personnel including operators, as well as design and protection engineers.

ACKNOWLEDGEMENTS

The work described has been made possible due to the financial support from Houston Lighting & Power (HLP) Company. The authors appreciate the contributions made by Messiers, R. Comfort, D. Cloud, M. Janik, B. Slawinski, L. Slavinska, and O. Williams of HLP company as well as J. Sun and X. Wu, both former graduate students at Texas A & M University.

APPENDIX

The following are some of the digital signal algorithms used by the data preprocessing module:

- Phasor calculation

\[
X = X_0 \pm jX_1
\]

\[
X_0 = \frac{1}{N} \sum_{k=0}^{N-1} x_k \cos \frac{2\pi k}{N}
\]

\[
X_1 = \frac{1}{N} \sum_{k=0}^{N-1} x_k \sin \frac{2\pi k}{N}
\]

\[
X = \sqrt{X_0^2 + X_1^2}
\]

\[
\theta = \arctan \left( \frac{X_1}{X_0} \right)
\]

where \( N \) is the number of samples and \( x_i \) is the \( i \)th sample.

- RMS calculation

\[
X = \sqrt{\frac{1}{N} \sum_{k=0}^{N-1} x_k^2}
\]

- Positive, negative and zero sequence calculation

\[
\begin{bmatrix}
X_0 \\
X_1 \\
X_2
\end{bmatrix} =
\begin{bmatrix}
1 & 1 & 1 \\
1 & \alpha & \alpha^2 \\
1 & \alpha^2 & \alpha
\end{bmatrix} \begin{bmatrix}
X_a \\
X_b \\
X_c
\end{bmatrix}
\]

where \( \alpha = e^{\frac{2\pi}{3}} \).

- Power flow calculation

\[
S = V_a \cos(\theta_a) + V_b \cos(\theta_b) + V_c \cos(\theta_c)
\]

- Frequency calculation

\[
\Delta f = \frac{1}{2\pi f_0} \frac{s_0 - s}{s_0 - s_{10}}
\]

where the data window is equal to three quarters of the nominal period. The sampling rate is 16 samples per cycle. \( s_0 \) is the input signal and \( \Delta s \) is the time step.

\[
a_0 = a x_{a-1} + b x_{b-2} + c x_{c-3} + d_1 x_{a-2} + d_2 x_{b-1} + d_3 x_{c-0} + d_4 x_{a-3} + d_5 x_{b-2} + d_6 x_{c-1}
\]

where \( a, b, c, d_1, d_2, d_3, d_4, d_5, d_6 \) are constants.

\[
a = -1.044303503155235, \quad b = 0.52823862829380, \quad c = 0.05, \quad d = 0.01
\]

REFERENCES