REAL TIME DATA ACQUISITION AND PROCESSING FOR GENERATOR MONITORING

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Abstract - 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

I. 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. Fig. 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 trackball.

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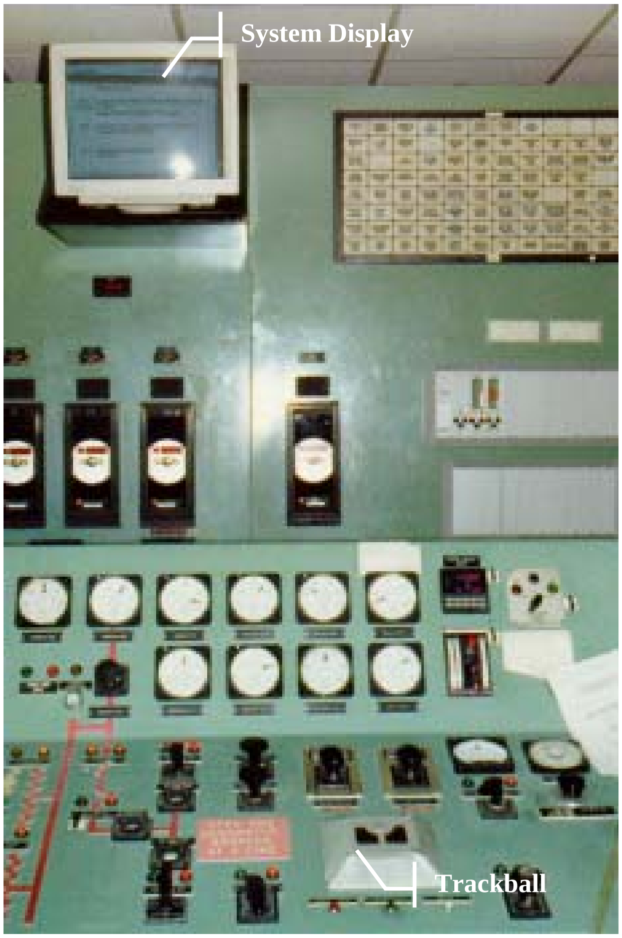

Fig. 1. Power plant control room

II. SYSTEM REQUIREMENTS

A. 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.

B. 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 on-going

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

Fig. 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.

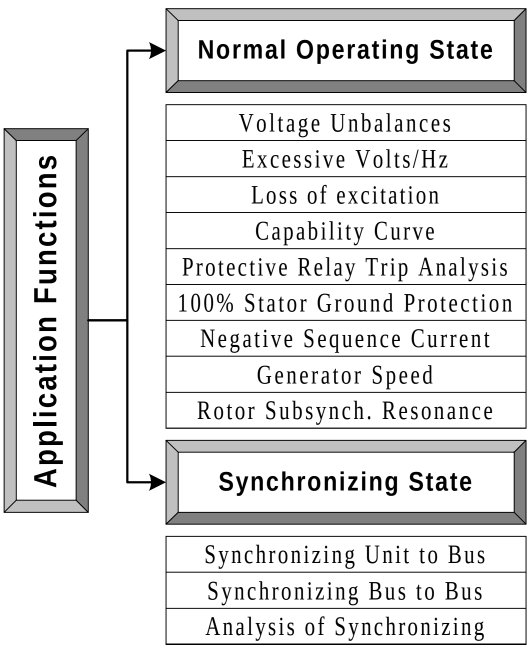

Fig. 2. List of application functions

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.

III. SYSTEM IMPLEMENTATION

Fig. 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.

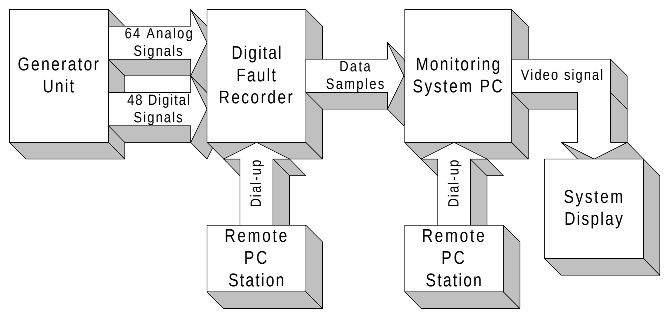

Fig. 3. System's block diagram

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 Kb 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. Additional adapter card for the master unit is 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 Kb of data prior to interrupting the host processor. Fig. 4 shows links between these two units and the external PC.

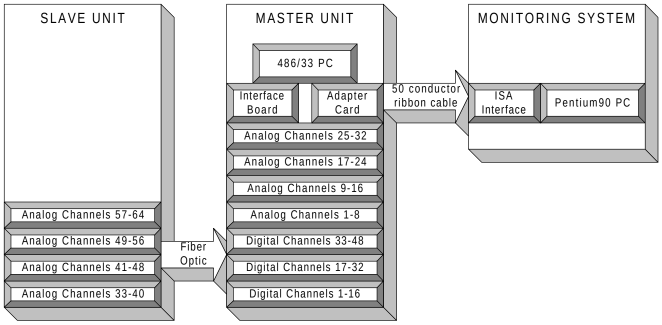

Fig. 4. Communication interfaces for the DFR and external PC

Main software modules are given in Fig. 5. The Data Transfer module is "terminate and stay resident" 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 3.1® 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.

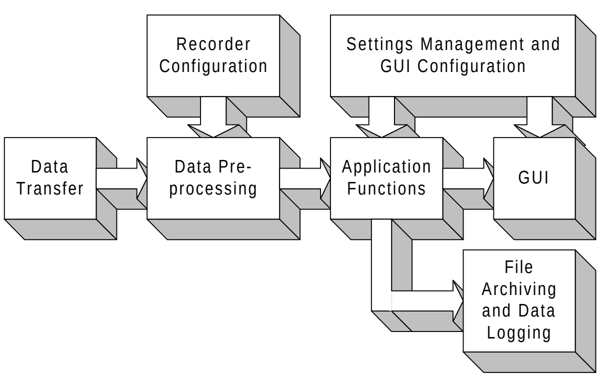

Fig. 5. System's software organization

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.

IV. 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 1. APPLICATION FUNCTIONS RELATED TO THE GENERATOR NORMAL OPERATING STATE

Function Name	*Instrument Monitored*	*Brief Description*
Voltage Unbalances	Relay 60	Detects unbalances between phases on the same instrument transformer Detects unbalances, monitors operation of Relay 60, and detects failure (e.g., blown fuse) of connected instrument transformers Detects under voltage condition
Excessive V/Hz	V/Hz Limiter Relay 59/81	Detects excessive Volts/Hz condition and monitors operation of the limiter and relay
Loss of Excitation	Relay 40G6	Detects loss of excitation condition and monitors relay 40G6
Negative Sequence Current	Relay 46	Detect negative sequence current under small and full load conditions and monitors relay 46.
Trip Monitoring	Relay 86	Provides analysis of a trip sequence after the Relay 86 operates
Generator Speed	Tachometer	Detects if the generator rotor speed is out of prespecified limits
Rotor Subsynchr. Resonance	Tachometer	Detects the rotor's sub-synchronous resonance
Generator Capability	New virtual instrument	Displays generator operating point on the capability curve, and monitors if it goes out of prespecified limits for a given generator
100% Stator Ground Prot	New virtual instrument	Provides 100% Stator Ground Protection

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.

Sixty-four analog signals and forty-eight contacts are being monitored by the DFR. Presently, application functions embedded in the GMS logic require monitoring of twenty-two analog signals and forty-four contacts.

TABLE 2. SUMMARY OF INPUT SIGNALS

Analog Inputs		
	DFR	***GMS***
No. of current inputs	37	3
No. of voltage inputs	24	16
No. of DC inputs	3	3
Total number of analog inputs	***64***	***22***
Digital Inputs		
No. of relay contacts	23	20
No. of switch contacts	13	13
No. of breaker contacts	11	11
Spare	1	-
Total number of digital inputs	***48***	***44***

The one line diagram of the power plant given in Fig. 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.

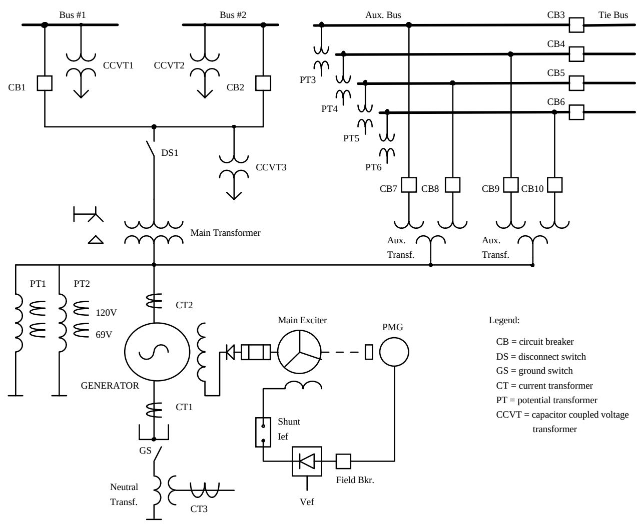

Fig. 6. One line diagram of the power plant

TABLE 3. TYPES OF INPUT SIGNALS

Analog quantities	Signal Location
generator output currents	CT2
generator exciter field current and voltage	I_{ef} , V_{ef}
voltages from the main transformer secondary	CCVT3
generator neutral current and voltage	CT3, Neut. Transf.
generator terminal voltages	PT1, PT2
voltages from the auxiliary buses	PT3 - PT6
voltages from the system buses	CCVT1 - CCVT2
turbine speed	Tachometer
Digital quantities	
relay contacts (e.g., generator lockout relay, differential relay, loss of excitation relay, etc.)	various
control switches (e.g., synchronizing switch, control switch, etc.)	various
circuit breakers (e.g., generator breaker, auxiliary transformer breaker, etc.)	CB1-CB10
main transformer disconnect switch	DS1

V. EXAMPLES OF DATA PROCESSING

A. Generator Synchronizing

Fig. 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.

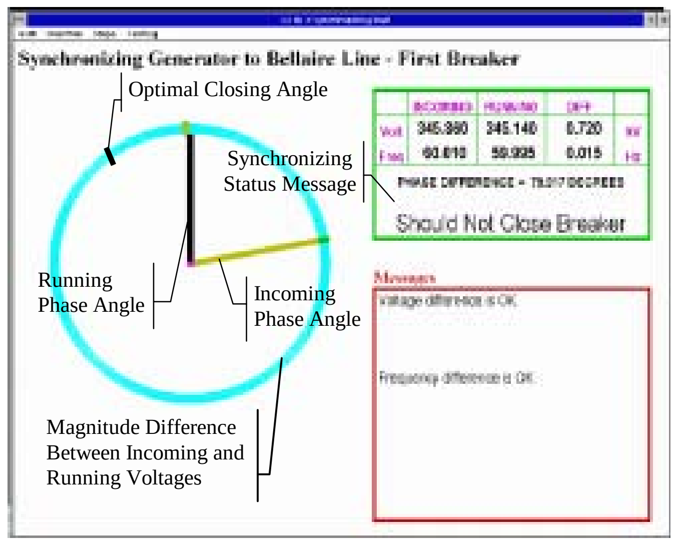

Fig. 7. Digital synchroscope

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.

B. 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 gives the summary of different events that are detected for these three conditions, respectively. The information displayed to the user and stored in the analysis report file is also indicated.

TABLE 4. MONITORING OF THE VOLTAGE UNBALANCES

Voltage Unbalance Between Phases on the Same PT	
Event type	*Voltage unbalance - short* *Voltage unbalance - lasting* *Voltage balance - returned*
Phases involved	*Phase A to B Unbalance* *Phase B to C Unbalance* *Phase C to A Unbalance* *Phase A to B and Phase B to C Unbalance* *Phase B to C and Phase C to A Unbalance* *Phase C to A and Phase A to B Unbalance* *Ph. A to B and Ph. B* to C and Ph. C to A Unbalance
Voltage Unbalance Between Phases on the Same PT	
Event type	*Voltage unbalance - short; Relay 60 - should not operate* *Voltage unbalance - lasting; Relay 60 - should operate* *Voltage balance - returned*
Phases involved	*Ph. A Failure; Ph. B Failure; Ph. C Failure;* *Ph. A and B Failure; Ph. B and C Failure;* *Ph. C and A Failure; Ph. A and B and C Failure*
Relay operation	*Relay 60 - correct operation* *Relay 60 - failure*
Under Voltage	
Event type	*Under voltage condition - short* *Under voltage condition - lasting* *Under voltage condition - returned to normal*
Phases involved	*Ph. A Under voltage; Ph. B Under voltage;* *Ph. C Under voltage; Ph. A and B Under voltage;* *Ph. B and C Under voltage; Ph. C and A Under voltage* *Ph. A and B and C Under voltage*

Implementation logic for voltage unbalance (same PT) module is shown in Fig. 8. There are three different settings for this function. V_t is threshold for detection of unbalance condition (default value is 95% of generator rated voltage); T1 and T2 are time delay settings for confirmation of unbalance condition and checking if an unbalance is short transient or lasting unbalance.

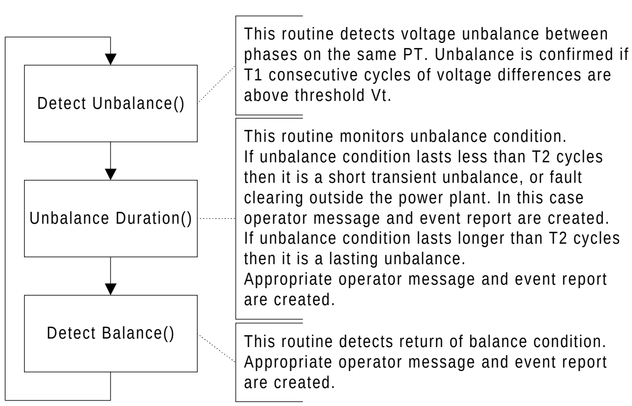

Fig. 8. Logic for voltage unbalance (same PT) function

C. Generator Capability Monitoring

This function monitors the trajectory of the generator operating point. It will alert the operator when the generator unit is in an abnormal operating condition (i.e., when operating point falls outside the normal operating area shown in Fig. 9). Table 5 summarizes types of the events detected by this function. Fig. 9 and Table 6 show generator gross capability graph for this particular unit and definition for each curve, respectively. It is worth mentioning that these curves are configured in the Settings management module and can be modified or adapted for different generator units. Every curve is approximated with a maximum of 12 points. The parts of the curve between two points are treated as linear.

An example of a display for this function is given in Fig. 10. The Capability curve window is automatically displayed when the operating point falls outside the normal operating area, or it can be invoked manually by the operator using menu command. The operating point is displayed in real time (i.e., screen is updated whenever the measurements change for a given increment). The last 20 measurements are also displayed so the operator can observe the trend.

TABLE 5. GENERATOR CAPABILITY MONITORING

Event type	*Generator operating point reaches Alarm Area of operation;* *Generator operating point returns to normal;* *Generator over excitation detected;* *Generator gross MW over limit detected;* *Generator under excitation detected;* *Generator gross MW under limit detected;* *Generator reverse power condition detected;*
20 cycles long snapshot of input quantities	*Generator terminal MWs* *Generator terminal MVARs*

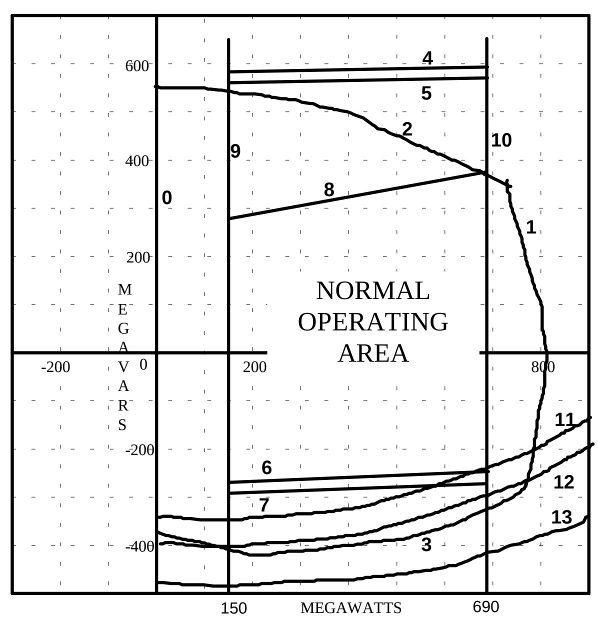

Fig. 9. Generator gross capability settings

VI. 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 module that will be designed to receive status messages from individual application functions and perform further inference action based on the available information.

TABLE 6. GENERATOR CAPABILITY CURVE DEFINITIONS

Curve	*Description*
0	Reverse Power
1	Generator MVA Rating
2	Generator Over excitation
3	Generator Under excitation
4	Maximum Generator Voltage with Aux. Loads
5	Maximum Generator Voltage without Aux. Loads
6	Minimum Generator Voltage with Aux. Loads
7	Minimum Generator Voltage without Aux. Loads
8	Maximum Aux. Voltage
9	Maximum Gross MW Capability
10	Minimum Gross MW Capability
11	Minimum Excitation Limiter
12	Loss of Field Relay
13	Steady State Stability Limit

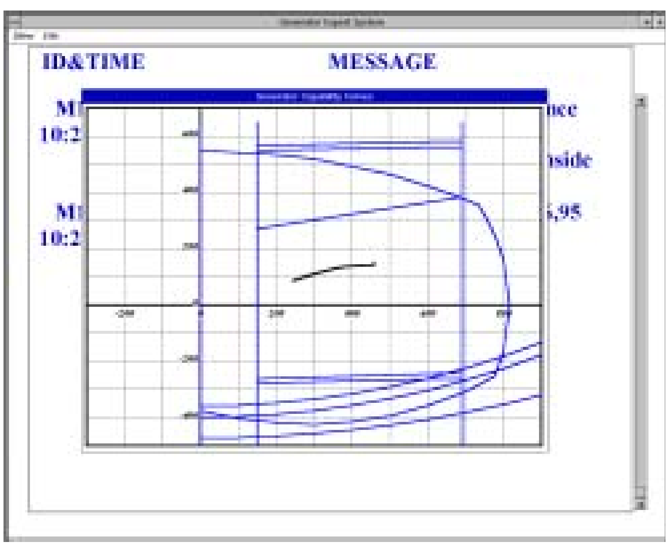

Fig. 10. Generator capability monitoring window

VII. 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.

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APPENDIX

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

- Phasor calculation

$$
\begin{aligned}
X &= X_s - jX_c \\
X_c &= \frac{\sqrt{2}}{N}\sum_{k=0}^{N-1} x_k \cos\frac{2\pi}{N}k \\
X_s &= \frac{\sqrt{2}}{N}\sum_{k=0}^{N-1} x_k \sin\frac{2\pi}{N}k \\
X &= \sqrt{X_c^2 + X_s^2} \\
\theta &= \arctan\left(-\frac{X_s}{X_c}\right)
\end{aligned}
$$

Where N is the number of samples and x_k is the kth sample

- RMS calculation

$$X = \sqrt{X_c^2 + X_s^2}$$

- Positive, negative and zero sequence calculation

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

Where

$$\alpha = e^{-j120^0}$$

- Power flow calculation

$$S = V_a conj\left(I_a\right) + V_b conj\left(I_b\right) + V_c conj\left(I_c\right)$$

- Frequency calculation

$$\Delta f = \frac{1}{2\pi\Delta t}\frac{x_n\omega_0 - x_{n-1}\omega_1}{x_n z_0 - x_{n-1} z_1}$$

Where data window is equal to three quarters of the nominal period. Sampling rate is sixteen samples per cycle. x_k is input signal and Δt is the time step.

$$
\begin{aligned}
\omega_0 &= ax_{n-2} + bx_{n-3} + cx_{n-7} + dx_{n-12} \\
\omega_1 &= ax_{n-1} + bx_{n-2} + cx_{n-6} + dx_{n-11} \\
z_0 &= ex_{n-2} + fx_{n-3} + gx_{n-7} \\
z_1 &= ex_{n-1} + fx_{n-2} + gx_{n-6}
\end{aligned}
$$

$$
\begin{array}{ll}
a = -1.044303503155235 & e = 0.78543321540189 \\
b = 0.52823862829380 & f = -1.05813678372674 \\
c = 0.05 & g = -0.03443924221845 \\
d = 0.01 &
\end{array}
$$