Supervisory Control and Data Acquisition

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Invited Paper

The acquisition of data, the processing of those data for use by the operator, and operator control of remote devices are the fundamental building blocks upon which all modern utility control systems are based. The systems to accomplish these functions are known as Supervisory Control and Data Acquisition (SCADA) systems. This paper provides an overview of the functions of SCADA and the fundamentals of operation of SCADA systems, including a brief description of the key man-machine interface. Several of the key issues and problems in modern SCADA systems, i.e., message standards, system performance testing, and system obsolescence are discussed. The paper concludes with the current trends toward distributed processing, improved man-machine interface, standard systems, smarter RTUs, and standard software. The authors' view of the future, using interchangeable system parts, is provided.

INTRODUCTION

History

Patents for remote control and remote indication were filed as early as the 1890s. These very early systems were intended for either remote control or remote indication but not both. In the 1920s and 1930s various commercial systems evolved employing concepts of check-before-operate and with the capability of conveying status of multiple points. These early systems were based on electromechanical logic which largely evolved from telephone system technology.

The advent of the minicomputer in the 1960s prompted dramatic changes in the design and use of supervisory control systems. Electromechanical systems which preceded the introduction of computer-based systems were largely intended for remote control and simple indication of status. The acquisition of large numbers of status indications and analog values was not practical. The early systems were generally referred to as simply "supervisory control." In the late 1960s, as new minicomputer-based systems began to emerge, the possibilities for vastly increasing data acquisition became apparent, and the expression "Supervisory Control and Data Acquisition" or SCADA came into being as a more appropriate description of the system. It is believed the expression "SCADA" evolved from planning studies which were conducted by and for the Bonneville Power Administration in preparation for construction of BPA's Dittmer Control Center in Vancouver, WA.

Common Usage

Requirements within the electric utility industry for remote control of substations and generation facilities has probably been the driving force for modern SCADA systems. SCADA systems, however, are presently used in many industries and, as a result, are tailored to suit the specific needs of various users.

In addition to electric utility application, other common users include:

- water/wastewater utilities
- oil and gas transmission and distribution
- oil and gas production
- communication networks
- broadcast transmitter remote control
- industrial control.

Design emphasis and manufacturers tend to vary depending on the type of end user. For example, the logic and computational requirements for remote terminal units (RTUs) used in electric utility applications is usually less than that required for gas or industrial process control users. RTU functions common to electric utility applications include:

- reporting by exception—status and analog
- sequence of events recording
- pulse accumulator snapshot.

RTUs intended for industries concerned with the transmission, distribution, or processing of fluids or gases typically contain additional internal logic or programs for:

- local conversion to engineering units;
- individual point calculations including
  - averaging
  - integration
  - minimum and maximum detection

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- — square and square root computation
  - — products
  - — sums
  - — quotients;
- ladder or Boolean logic typical of programmable controllers;
- table lookup;
- local process control loops (proportional-integral-derivative–PID);
- process schedulers (time of day control).

RTU communications for most utility applications is bit-serial, half-duplex (master and RTUs do not communicate simultaneously), using data rates compatible with standard voice-grade unconditioned two- or four-wire circuits. The distance between the RTU and the master station is limited only by the quality of the communication circuit. For industrial and process control applications, where RTUs are located within a few thousand feet of the control room, high-speed data networks operating in the megahertz region are common. Most SCADA systems which are based on a high-speed network architecture for communication also permit communications to occur directly between RTUs and are, therefore, really distributed systems.

In certain industries, such as water/wastewater and gas/oil, the monitoring locations are often characterized by very few points at a large number of locations. Therefore, it is desirable to combine data from several locations at a single RTU. This is often accomplished by using pulse duration transmitters at multiple locations; the RTU uses pulse duration converters to read these signals and transmit them to the master station. Alternately, the multiple locations may have mini-RTUs which send digital messages to the RTU, where the data are received and transmitted to the master station, along with messages from other mini-RTUs (and the main RTU itself).

The balance of this paper describes SCADA systems intended for electric utility application with emphasis on:

- functions
- fundamentals of operation
- design considerations
- issues
- trends and the future.

Functions of SCADA—Electric Utilities

Certain functions are basic to electric utility SCADA systems. The more common functions include:

- Data Acquisition
- Information Display
- Supervisory Control
- Alarm Processing
- Information Storage and Reports
- Sequence of Events Acquisition
- Data Calculations
- Special RTU Processing/Control.

Data Acquisition

The periodic acquisition of data from RTUs is fundamental. Most systems for electric utilities acquire data on a polled basis where data are transmitted from the RTU to the master station only on receipt of a request from the master to the RTU. Two options are available on how the RTU responds. One option is to send the actual value or status of the point or group of points requested. The other option is to send only those points or groups of points where changes of state have occurred or where a value has exceeded a pre-defined delta change which has occurred since the previous poll request. This latter option is referred to as "reporting by exception." The main advantage of report by exception is a reduction in processing overhead at the master station. Average loading on the communication circuits is also reduced over the first option, however, sufficient communication circuit bandwidth capacity should be provided to accommodate the worst case situation when a large percentage of the points are rapidly changing, as when a major electric system disturbance occurs and the dispatcher's need for timely and accurate data is highest. Analog value report by exception is much less in vogue than discrete point report by exception.

The process of data acquisition can be considered as the collective process of several specialized and highly related subprocesses. These subprocesses include:

- internal scanning and rapid update of the RTU internal database;
- periodic RTU polling by the master station;
- transmission of requested data sets by the RTU to the master station;
- checking of the data for transmission induced errors;
- scaling of the data into engineering units;
- write over of the previous status or value in the database.

Information Display

Information display is the process of selectively retrieving both fixed and real-time data from the database, combining, and presenting them to the operator, usually in the form of limited graphics CRT color pages. A typical one-line display is shown in Fig. 1. The fixed data include station one-line schematic information and other displayable information that is nonvarying in time. The variable data include status of two or three state devices, and analog values which vary in magnitude and possibly sign. Unit designations and point identification by name or ID number are usually considered fixed values and are appended to the variables.

Display selection is most often organized in a hierarchical tree structure where index pages permit the operator to select a wide variety of displays using cursor positioning techniques including positioning by keyboard, trackball, lightpen, or touchscreen methods. Many variations of display selection are provided, frequently with the same system. Alternate selection methods include:

- dedicated function keys
- keyboard entry of display ID number or name.

Display selection by a dedicated function key provides very rapid access to frequently used displays but the number of such keys must be limited due to space restrictions. Keyboard selection using display ID numbers requires operator memorization or the use of cross-reference tables.

Display media other than the CRT are occasionally utilized. Common forms include dynamic mapboards where the status of two-state devices, such as circuit breakers, are presented by illumination of lamps. A dynamic mapboard

Fig. 1. Typical one-line CRT display for electric substation.

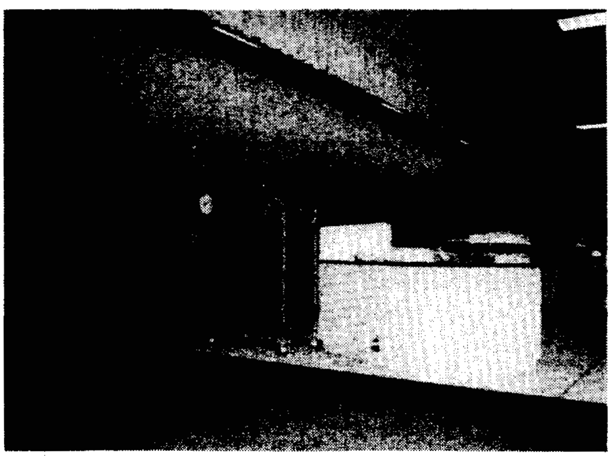

Fig. 2. Dynamic mapboard used in typical control center.

MASTER TO REMOTE CONTROL SELECT MESSAGE

FUNCTION CODE	CONTROL ADDRESS	MODIFIER	STATUS/COMMAND

REMOTE TO MASTER CHECKBACK MESSAGE

FUNCTION CODE	CONTROL ADDRESS	MODIFIER	STATUS/COMMAND

MASTER TO REMOTE EXECUTE MESSAGE

FUNCTION CODE	CONTROL ADDRESS	MODIFIER	STATUS/COMMAND

REMOTE TO MASTER EXECUTE ACKNOWLEDGE MESSAGE

FUNCTION CODE	CONTROL ADDRESS	MODIFIER	STATUS/COMMAND

Fig. 3. Check-before-operate message sequence used for high security.

utilized in a typical control center is shown in Fig. 2. Mapboard display of analog variables is not common with U.S. electric utilities but is occasionally seen in Europe and other areas.

Supervisory Control

Supervisory control is the process of actuating equipment operation at remote locations. The process includes selection of the station, selection of the device to be controlled, and execution of the desired command such as TRIP or CLOSE. Correct selection and operation is critical to the safety of personnel and the security of the electric system. For this reason some form of select-verify selection-operate sequence or for short, "check-before-operate" method is employed, as illustrated in Fig. 3. Operation of a device other than the selected device, or inadvertent operation of a device when no command has been made, must be avoided and is a critical design parameter for SCADA systems.

A variation of discrete supervisory control is "set point control." This form of control provides an operator or computer entered value as an analog output or an internal RTU value for proportional setting of an external device or control loop. Setting the desired MW output from an unmanned hydro turbine generator would be an example. A local control loop at the remote site would then adjust the governor to produce and maintain the desired generator MW.

Alarm Processing

Alerting the operator to unscheduled events and informing him of the time of occurrence, the station location, the device ID, and the nature of the event is generally referred to as alarm processing. Many variations of alarm processing and presentation exist, the specifics being largely a function of the individual SCADA manufacturers. The most common output of the alarm process are chronological CRT alarm lists (see Fig. 4 for typical display), hardcopy printouts, and audible alarms. Some recent systems provide synthesized voice alarms. Some form of alarm acknowledgment by the operator is nearly universal. In larger systems, significant human factor benefits can be realized by prioritizing alarms and by directing alarms only to operating positions concerned with a particular category of alarms.

Information Storage and Reports

Record-keeping has always been an important task in the operation of electric systems. Accurate records are necessary to satisfy legal and governmental requirements, for accounting purposes, for support and forecasting of future system operations, and for engineering planning purposes.

The common practice for record-keeping is to capture preselected data sets at periodic intervals and save them in a rotating file. The periodicity of storage is frequently set at 1-h intervals but specific electric system requirements may require more frequent capture and saves. The common time span for a rotating historical file is on the order of 40 days but spans of up to 12 months are not uncommon. The 40-day file provides one full month's data plus 9–10 days (including weekends and holidays) during which the data can be analyzed and/or archived to a bulk medium such as magnetic tape. Information older than the file time span (40 days in the example) is discarded. File compression schemes are occasionally used where hourly values may be combined to create daily values and daily values may be combined to create monthly values. In actual practice, portions of the rotating file are periodically transferred or "archived" to a tape medium as a precaution against disk failure and possible loss of critical information.

The SCADA historical file provides an excellent source of information for the production of various reports. These reports, their formats and information content, may be customized to satisfy the specific needs of a wide variety of end users.

Sequence of Events Acquisition

Sequence of Events (SOE) is the process of capturing and recording unscheduled events with a time resolution between events of a few milliseconds. Historically, SOE recording has been provided with equipment dedicated to that purpose. Events are generally considered discrete (two-state) occurrences such as occur with protective relaying systems. Oscillographic equipment has also been used for many years for recording transient analog values such as line current or voltage.

In recent years, SOE recording of discrete state changes has migrated into some SCADA systems. It is the process of capturing and recording unscheduled events to a time resolution independent of the periodicity of RTU polling by the central master station. An accurate time base or clock within the RTU is fundamental for SOE recording. Time res-

Fig. 4. Chronological CRT alarm list

olution of events captured by a single RTU is typically ±2 ms. Accurate synchronization of multiple time bases located in a large number of widely separated RTUs presents a technical challenge. The most common approach is to establish RTU clock synchronization via the interrogate message. Time resolution between events captured by separate RTUs may be on the order of ±8 ms. The RTU time clocks are periodically synchronized by transmission of a time code message from the master station using the master-RTU communication channel with adjustments for the propagation time delay. RTU clocks can also be synchronized to a broadcast time code as WWV. The sequence of events at a given RTU may be printed locally at the RTU or may be transmitted to the master station where they are chronologically ordered with events received from other locations and then printed as one combined listing.

Data Calculations

A recurring need in SCADA systems is to perform various calculations utilizing the acquired data. Examples of data calculations with single variables are determination of averages, maximum or minimum values over given intervals, and integration with respect to time. Calculations with multiple variables may include sums, differences, products, quotients, squares, square roots, exponentiation, and others. A good practical application of such calculations is load monitoring of large transformer banks. The maximum capacity of large transformers is determined by their maximum allowable heat rise and transformer heating is closely associated with the MVA load. For various reasons, the most common metering associated with transformers is MW and MVAR but not amperes. MVA is then calculated periodically by the SCADA using the relation $MVA^2 = (MW)^2 + (MVAR)^2$ and placed in the real-time database where it is tested for limit excession.

Boolean calculations may also be applied to discrete status points and the result considered as a new information point. This process has been referred to in some literature as "combinatorial processing." This process can determine a particular state of some part of the electric system not definable by only one status indication. A good example of combinatorial processing is the determination of whether a transmission line is energized or not. In most cases, circuit breakers at both ends of a line must be open for the line to be de-energized. Some lines have multiple circuit breakers at each end of the line (breaker-and-half scheme) all of which must be open to ensure the line is not energized from one end or the other.

Special RTU Processing/Control

Increasingly, more intelligence is being placed in the SCADA RTU. This is more evident in SCADA systems intended for water, gas, and process control than for electric utility applications. Common functions being relegated to the RTU include:

- local PID loop for
  - flow control
  - chemical injection control
  - pressure regulation
  - turbine generator power and reactive power control;
- local scheduling control;
- engineering units conversion;
- programmable control sequencing.

In a few demonstration projects of substation automation, distributed RTUs, usually interconnected by a common high-speed network, form an integral part of system protection as well as potential sources of data for transmission to a central dispatch center.

Fundamentals of Operation

Polling Schemes

SCADA systems intended for electric system operations almost universally use a polling scheme between the central master and individual RTUs. In communications engineering parlance the method is known as "Demand Assignment/Time Division Multiple Access (DA/TDMA)." The master station controls all activity and RTUs respond only to polling requests.

Fig. 5 illustrates the most common communication

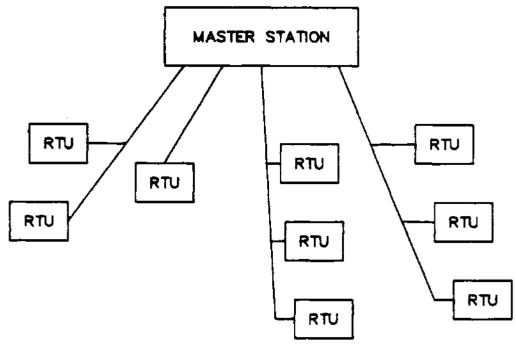

Fig. 5. Typical multi-drop communication system.

arrangement. Multiple two- or four-wire telephone-grade circuits radiate from the master. These communication circuits each operate in half-duplex mode and each operates independently of others. One circuit may be dedicated to a single RTU, but the common and economical approach is to multi-drop or party-line several RTUs from a common communication circuit. The media for these circuits may be leased telephone circuits from a common carrier, private microwave, fiber optic cable systems, two-way cable TV, power line carrier, or even satellite. Polling and command requests and RTU responses are time-multiplexed on each circuit. Each circuit terminating at the master station is independently serviced on an asynchronous basis by the master station. Information rates per channel may range from 300 to 9600 bits/s and are largely influenced by the measurement point count serviced by all RTUs sharing a common circuit. The most commonly used information rate is 1200 bits/s using asynchronous byte-oriented message formats.

The polling periodicity is established by the necessary response of using application functions and by human factor considerations. Where acquired data support closed control loops, such as automatic generation control (AGC), the data sampling rate must be sufficient to maintain desired control loop response. For AGC this periodicity generally ranges between 2 and 6 s. For general operator monitoring of most system variables, an update period of about 10 s is generally acknowledged to be sufficient. Rapidly changing least significant numerals on CRT displays tend to be distracting to operators. Not all variables need to be acquired at the same period and, in fact, usually are not. The factor which usually establishes the basic RTU polling period is the desired response to unscheduled events or alarms. For electric system operations this period is on the order of 2-3 s. Other information may be selectively acquired at each poll period or at multiples of the poll period.

A variation to fixed period polling is the round robin approach used by some European systems. Here, each RTU-to-master message contains an end of message (EOM). When the master station detects the EOM the next RTU sharing the same communication line is then immediately polled. This results in continuous activity on the line with no gaps of time. The individual point sampling rate is then influenced by the number of RTUs sharing the same line and the number of points per RTU and whether or not exception reporting is being used.

Modern RTUs actually scan the connected points at a high rate compared to the master station poll period. When a master station poll request is received by the RTU, the current values or status stored in the RTU memory are fetched on a selective basis and transmitted to the master station.

Polling requests may also contain various command and control requests. The RTU must distinguish these from information requests and respond accordingly. A command sequence for circuit breaker operation is typical. Some form of select-check-operate sequence is almost always used to avoid misoperation.

SCADA systems intended for distributed data acquisition and control within a large substation or power plant may utilize a different polling strategy. Where all RTUs can be physically located within one or two thousand feet of each other, they may be connected to each other, the man-machine interface, and a host processor via a local area network. Such arrangements permit great flexibility in communication between system elements or nodes. Instead of conventional sequential polling under the complete direction of the master station, local area network connected systems generally permit exchange of information directly between any two nodes on a random basis. Carrier Sense Multiple Access (CSMA), Token Ring, or other schemes may be used. Fig. 6 is a simplified block diagram of a distributed system where communications can occur between any nodes on a random basis.

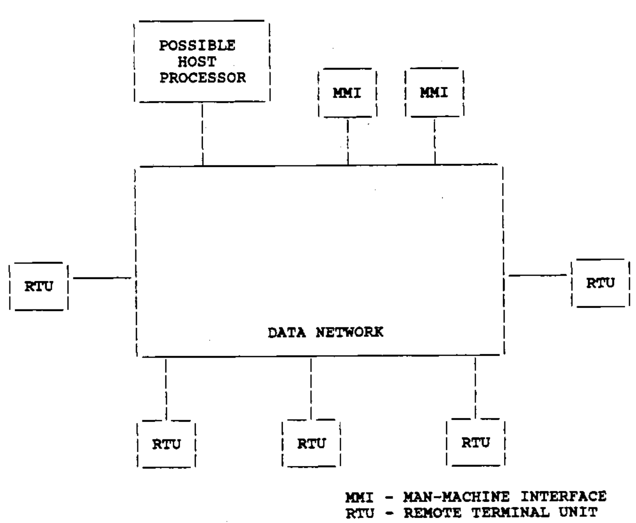

Fig. 6. Network connected local SCADA.

Data Inputs

SCADA systems intended for electric system operations are most frequently called on to monitor the following information from substations and power plants:

Substations
- bus voltages
- line flows (MW, MVAR, A)
- transformer tap positions
- circuit breaker, switch, other device status
- alarms
- MW
- sequence-of-events.

Power Plants
- unit generation MW and MVAR
- auxiliaries MW and MVAR
- unit MWh
- auxiliaries MWh
- station net MW, MVAR
- unit maximum and control limits
- unit performance information
- gate position and limits (hydro)
- forebay and tailwater levels (hydro).

Most magnitude inputs such as bus volts, MW, and MVAR originate in analog form. U.S. electric utilities have a *de facto* standard of 0 ± 1-mA input to the RTU representing the full scale span. The sign indicates the direction of flow since electric flow, in many instances, is bidirectional. Process Control applications, including water and gas utilities, are more likely to standardize on 4–20-mA input ranges. Status inputs are usually represented by a simple binary on–off state. In cases where mechanical devices change state slowly, for example, a motor-operated disconnect switch, three states are necessary: open—in transit—closed. This is accomplished with two limit switches which have four possible states:

1) *A* open, *B* closed—switch open
2) *A* open, *B* open—switch in transit
3) *A* closed, *B* open—switch closed
4) *A* closed, *B* closed—invalid combination.

Certain devices, such as circuit breakers with automatic reclosing activated, may operate and return to the original state in less time than one RTU poll or scan period. Operationally, it is important that such action be detected and reported to the master station. This is accomplished by change detection logic in the RTU which senses high-speed changes in status occurring between scans and conveys this fact by setting a change bit. Some SCADAs actually count and report the number of changes; detection of up to three changes is standard.

Energy quantities, such as MWh, are derived from watt-hour meters in the form of pulses—each pulse representing a specified number of MWh. The RTU counts the pulses in a register and reports the count to the master at designated intervals. In order to minimize overall electric system energy balance errors, a kWh register "freeze" command is often broadcast simultaneously to all RTUs. The register counts are then requested by the master and saved in the master station historical files.

Special RTU inputs or interfaces are occasionally required. These can take on many forms but the more common forms include binary-coded decimal, pulse duration modulation, and serial ASCII character streams via an RS-232 port.

Since RTUs must operate in the high-voltage electric substation/power plant environment, special design features must be included to prevent damage to the RTU, false data reporting, or misoperation. These features may include photooptical isolation, varistors, and switched-capacitor inputs. The various schemes are tested against the IEEE Surge Withstand Capability (SWC) Standard 472-1974 for compliance.

Control Outputs

SCADA systems intended for electric system operations are most frequently called on to provide control outputs to substations and power plants as follows:

Substations
- circuit breaker operation
- motorized switch control
- tap changer transformer control
- protective relay or scheme mode control
- RTU internal register freeze control.

Power Plants
- turbine-generator remote start-stop (hydro, gas turbine)
- gate limit set (hydro)
- turbine-generator MW raise/lower
- turbine-generator MW set-point
- generator voltage/VAR control.

Discrete control outputs generally occur from interposing relays which momentarily close for a specific control action such as Circuit Breaker "trip." The relay contact rating must be carefully sized to carry and interrupt the load which, most often, is another relay in a dc control circuit. If ac control circuits are used, the RTU interpose relay may be replaced with a TRIAC.

Generator MW is remotely set or adjusted in one of two ways: 1) by transmitting raise or lower pulses of variable duration and frequency of occurrence to the turbine governor motor; these pulses adjust the governor speed setting and thus the generator output MW or 2) by transmission of a desired MW setpoint which results in an analog output from the RTU proportional to the desired MW. An external control loop, usually in the governor, then automatically adjusts the speed setting until the desired MW is achieved.

Database

Older SCADA systems tended to have fixed-format databases where user programs required very explicit information about the database and its structure. This philosophy was easier for the database designer but substantially increased the complexity of maintaining the system as points were changed and new application programs added.

With the advent of lower cost memories, it has become easier and more attractive to incorporate various database management features into SCADA systems. These newer SCADA databases permit considerable independence between the data acquisition function which updates the real-time part of the database and the user programs which retrieve data from the database and save computed results back into the database. The newer databases are not rigidly fixed in size but can easily be expanded providing the physical memory is available. Design tradeoffs always exist between the degree of generalization in the database and speed of operation. Highly generalized database concepts, as used in business applications, frequently have excessive compute overhead which makes them unsuitable for time-critical real-time use.

Information contained in SCADA databases may be categorized into several distinct types:

Real-Time: Measurement and status information which is periodically acquired via RTUs or entered by operators. On each update the old values are overwritten. The periodicity of update may vary from a few seconds to hours.

Parametric: Parameter information is semi-fixed data which contain various attributes necessary to interpret real-time data. Included are high, low, and rate limits, scaling and offset information; areas of responsibility codes, scan rates, normal status, and many more.

Calculated: Pseudo-points which are calculated from other points and then treated the same as real-time data. An example of a calculated value would be the summation of two real-time values occurring at specified intervals.

Application: Information which is unique to specific applications. There may be constants, normal status, limits, stored messages, and more. An example would be stored message elements for an alarm processing function.

It is important that system operators be made aware of data in which validity may be suspect. This is frequently accomplished by appending a quality code or flag to each data point in the database. These codes can appear as symbols adjacent to displayed data or color changes to the displayed value which denote the "quality" of the data. Normal data are the default state where no quality code is usually displayed. A point which is out of scan and not being updated, for example, would carry a code indicating that condition.

Man-Machine Interface

One of the greatest challenges in the design of modern SCADA systems is to provide an efficient and somewhat "user-friendly" man-machine interface. The man-machine interface consists not only of the hardware devices such as CRTs, consoles, mapboards, printers, and audible alarms, but also the program functions which make it all work. A typical control room with operator consoles is shown in Fig. 7. The focal point of the man-machine interface is the color

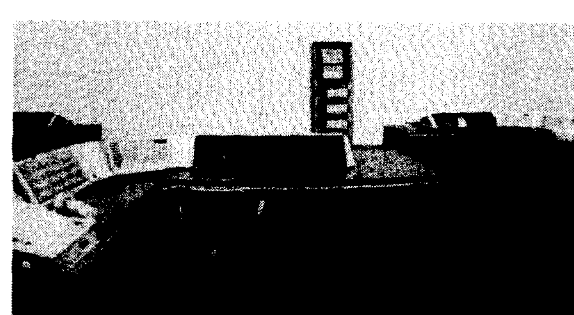

Fig. 7. Typical control room with operator consoles.

CRT. Most CRT units now in use are of the raster-scan limited graphics type where addressing is limited to individual characters. This type of display has been used for construction of utility one-line diagrams and displays containing only alphanumeric information. However, there is an increasing industry demand for displays with resolution beyond the character level. High-resolution trend graphing and other applications require CRT screen addressability to the pixel level. At the moment there is considerable interest and research in the application of extended CRT graphics. Features such as pan and zoom, new graphical presentations and applications which can benefit from three-dimensional presentations are the driving force for extended graphics. Fig. 8 illustrates the capability of a typical full-graphics CRT display.

Historically, there has always been controversy in the role and relationship of mapboards to CRT displays. The industry trend is away from highly detailed mapboards as were common a decade ago. The main reasons are the initial cost and the cost and effort in constantly updating. Mapboards do provide a total overview of a utility network which is often difficult to convey on a single CRT. For this reason they continue to be used but some utilities have done away with them entirely. Where they continue to be used, they most frequently display limited dynamic information.

In some newer SCADA systems, the simple audible alarm has been supplanted with a voice synthesizer which actually verbalizes the alarm message. This feature appears to be most useful when the SCADA consoles are not manned by an operator at all times and an auto-dial feature is provided which may alert an off-duty person, even at home.

Logs and Reports

Log printing generally refers to the chronological printing of events as they occur. These events may be electric system alarms, internal SCADA system alarms, or operator-initiated actions. The format of log printouts is generally identical to alarm and event CRT summaries.

Reports are pre-formatted documents that are produced at periodic intervals or by operator demand. Most often they are produced daily and show the results of system operations on an hourly basis. The information source for reports is usually the stored history file.

External Interfaces

Increasingly the need arises to establish some form of information transfer between SCADA systems and other external systems. Examples of external interfaces include information exchange with:

1) other systems arranged in a hierarchical order within the same utility,
2) adjacent utility SCADA or EMS systems,
3) pool control centers,
4) power brokering arrangements,
5) separate load management systems,
6) local PCs or PC networks,
7) corporate computers,
8) departmental computers such as system planning.

The complexity of such interfaces varies widely. An elementary, but often practical approach, is to have one of the terminals simply emulate a serial printer and unidirectionally transfer information in a standard report format. At the other extreme is a multi-layer packet communication protocol based on well recognized standards. The CCITT X.25 standard, or variations of it, are gaining favor for this application. For those situations where the other interfacing computer is local, the Ethernet standard is useful.

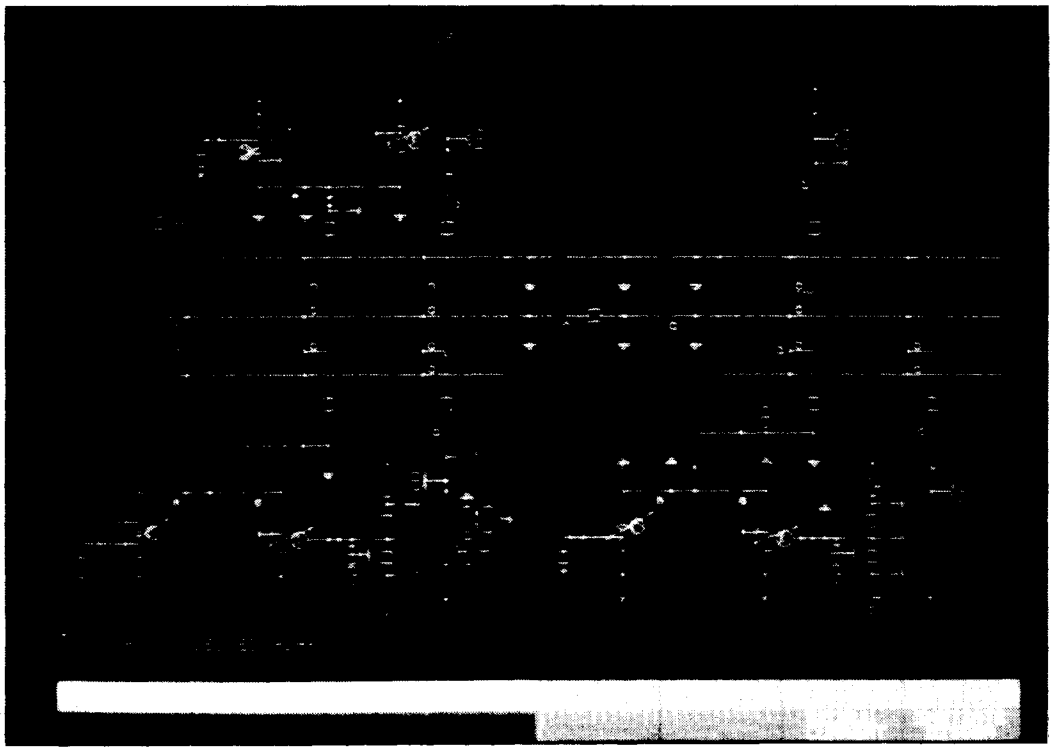

Fig. 8. Typical full graphics CRT display.

Message Protocols and Error Detection

Communications between the SCADA master and RTUs for most conventional systems must be bit-serial using polling methods previously described. All communications, whether master to RTU or RTU to master, occur in the form of messages where each message is composed of three parts: 1) the header, 2) information, and 3) the trailer. The header and trailer are normally fixed in length but the information is usually of variable length with an upper bound before a new message is created.

The outgoing header contains synchronizing bits, the RTU address, and some form of function code. The function code informs the RTU of the type of information which is to follow and is frequently 8 bits in length. The trailer ordinarily contains a security code for the detection of transmission-induced errors and is frequently a Bose–Chaudhuri–Hocquenghem (BCH) code or a Cyclic Redundancy Check (CRC). A security code design objective is to ensure the probability of acceptance of a message received in error is less than 1 in 10^{10} for a maximum received bit-error rate of 1 in 10^4. The information part of the message is often byte-oriented and variable in length.

Design Considerations

Reliability/Availability

Availability is the term most frequently used to define how reliably the SCADA performs its intended function. Availability is defined as:

$$\% \text{ availability} = \frac{\text{uptime}}{\text{uptime} + \text{downtime}} \times 100.$$

The required availability for a given SCADA system can only be determined by the specific use of the system. SCADA systems are generally composed of a master station and multiple RTUs connected via separate communication circuits which are not part of the SCADA. The intervening communication circuits are essential for proper operation of the system but must be separately considered when defining actual SCADA availability. Because of this situation, the SCADA availability requirement is often divided into two parts: master station and RTU.

Most electric utility SCADA systems are designed to operate continuously, i.e., 8760 h/year. Complete unavailability of the system is a serious operational problem and must be minimized by proper design. An acceptable availability figure for the master station is 99.8 or 99.9 percent. A master station with an availability of 99.9 percent can be expected to be unavailable to support operations about 8 h/year. This level of availability can be achieved by incorporating redundancy into the system design such that no single failure will force the system down and by designs which permit the mean-time-to-repair to be of short duration. The latter requires good diagnostics, a high content of easily replaceable elements, adequate spare parts, and good maintenance training.

RTU availability may be separately specified and is typically 99.99 percent. It is uncommon to require redundancy at the RTU but in special situations it does occur. Loss of communications is a more likely event than loss of an RTU and, for this reason, dual communication circuits are occasionally provided for RTUs which serve critical locations.

A common difficulty in specifying and actually measuring availability is the need to precisely define what constitutes downtime. Practical problems and considerations include:

- What are critical functions?
- What are noncritical functions?
- How much travel time should be allowed for maintenance personnel? Maintenance travel time is often excluded from the "contractual" downtime calculation.

The addition of redundancy adds complexity, not only in hardware, but in programming and configuration control. Duplicate main and rotating memories must be maintained. Of special concern are data which are operator-entered or stored historical data. Backup memories must be constantly updated to reflect ongoing operations in the event the backup memories suddenly become the on-line memories. Recovery of actual RTU acquired data after a system failover is usually not a problem since all data can be re-acquired in several scans.

Configuration Management

The collective processes of building and modifying databases, building and changing CRT pictures, and building and modifying report formats is referred to as "Configuration Management." In the earlier days of SCADA systems, accomplishing these processes was very labor-intensive and required considerable programming expertise. Great progress has been made in improving the efficiency and ease of configuration management. Although considerable variation exists between the approaches taken by different suppliers, the end results tend to be similar.

A prerequisite to efficient configuration management is a well-structured database, as previously described. One or two CRT pages of interactive questions and fill-in-the-blanks are often required to define the complete attributes for just one real-time data point. A form of compiler interprets the entries and stores them in the database. Typical point attributes include measurement number, station ID, name, limits, engineering conversion constants, area of responsibility, alarm priority, and many more. Proficiency for entering or changing data point definitions can be acquired with only moderate training.

CRT picture building facilities have also reached a fairly sophisticated level. Some suppliers provide a facility separate from the actual SCADA system which includes a CRT terminal, display generator, and magnetic storage medium such as floppy disk or cassette. Other suppliers may use the master station backup system for the same purpose. The user then creates the static part of the display, including location of fields for display of dynamic information. Once these are created, a data linking process must occur which links specific database variables with the corresponding information field locations on the display.

The format and information content of printed reports is usually established with the aid of a "report builder" function. Interactive CRT displays are provided for the construction of report formats and for the linking of archival information to appropriate locations on the report.

RTU Local Test Features

Facilities must be provided for maintenance personnel to locally exercise and test RTUs independent of the master station. Traditionally, this has been accomplished by utilizing portable test sets which interface to the RTU communication port. The earlier versions of these test sets had a man-machine interface at the bit level requiring interpretation of data in binary form and execution of commands by setting switches corresponding to bit-level encoding.

The introduction of microprocessors into both the RTU design and the test set design is changing the functionality and man-machine interface of local RTU testing. Some RTU designs now provide a separate RS-232 interface for connection of an external test set. In some instances, a small panel may be permanently incorporated in the RTU which permits the selection and visual readout of any measurement or status point or the selection and execution of any control point. Similar panels may be portable and carried by the maintenance technician. Portable CRT terminals or personal computers are also finding application as very powerful and flexible test units.

Issues

Many important issues are currently under consideration in the SCADA industry. Several of these issues address long-standing problems; others are related to keeping up with the rapidly changing technology.

Message Protocol Standards

A long-standing problem with regard to SCADA systems is the capability of communicating between different SCADA system levels within a utility and between different companies/utilities. Message protocol standards are currently receiving considerable attention from such groups as the International Standards Organization (ISO) as well as the IEEE.

The rationale for protocol standards includes the need to avoid customization when interfacing different systems, different RTUs, system upgrades, etc. A continual problem in the industry has been the proliferation of master-to-RTU message formats requiring several different communication interfaces for a typical system and making additions to the system much more difficult and expensive. Additional system software plus custom hardware/firmware are required to provide the required interface. Standard master-to-RTU message formats would greatly simplify the addition of RTUs, thus prolonging system life and significantly reducing expansion costs.

With regard to master-to-master station communication, as well as master-to-submaster levels of the same system, a standard message protocol would promote interchange of information between the various entities. This would provide for a more effective system and allow for many new application functions to be performed by the SCADA systems. For example, a strong need exists for exchange of data describing the real-time state of the electric systems and to improve the accuracy of security software external model functions. In other words, occurrences in electric systems beyond the boundaries of the utility-owned electric system can have a significant impact upon the internal system. Real-time exchange of information would go a long way toward strengthening the accuracy and effectiveness of these security software functions.

Within a utility's SCADA system, exchange of data between submasters, masters, and applications processors is required to provide for proper control of various system elements and to allow applications functions using data from different hierarchical levels to be used. For example, line flow data from SCADA submasters could be passed to the master station for monitoring, and used by applications processors in a state estimator program. The results would be passed back to the submasters. Presently, these internal data exchanges utilize the protocols of the manufacturers of the various system levels. Therefore, if a hierarchical level is replaced, often with the equipment of a different supplier, then custom interfaces are required.

To expedite the development of communication standards, the ISO has developed a common basis for protocols and standards; the Open Systems Interconnection (OSI) Reference Model, as shown in Fig. 9. This model describes

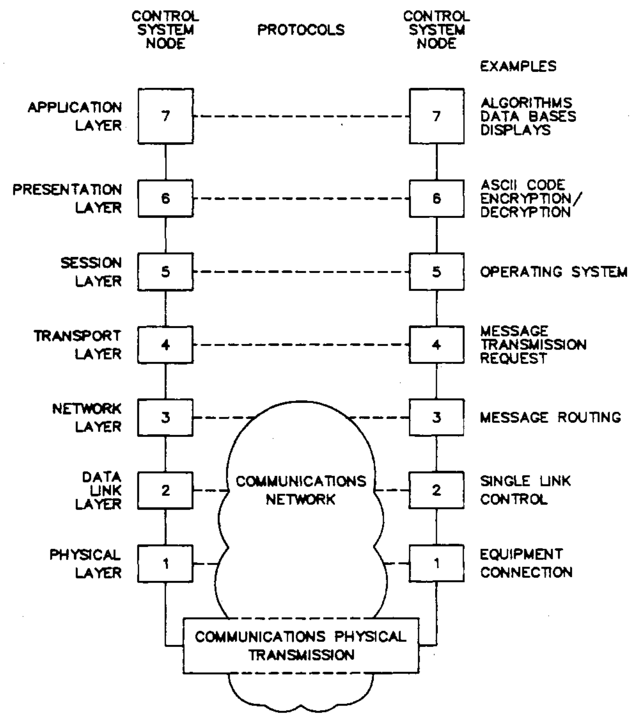

Fig. 9. OSI seven-layer reference model.

the functions involved in communications between systems, and the terms used to define those functions. The OSI model breaks the overall process into a seven-layer structure; each layer defines a set of message protocol functions which may be performed using hardware, software, or firmware. The bottom three layers; Physical, Data Link, and Network, define the components of the communication network, while the top three layers; Session, Presentation, and Application, represent the functions of the end system. The middle layer, Transport, links the bottom and top layers. The interfaces between layers are specified to allow different suppliers of the individual layers. In other words, the overall communication process is divided into seven predefined layers to stimulate common development of individual components. Thus not only can we communicate between different systems, we can interface between different components within a system.

Within the last three years, significant progress has been made with regard to message protocol standards, across a broad front. For communication between different utility master stations, the Western Systems Coordinating Council (WSCC) has developed "Energy Management System Inter-Utility Communication Guidelines," using the seven-layer ISO model. The formatting of specific utility data types has been defined, including accounting, interchange scheduling, and economic dispatch. The WSCC concept uses a commercial communication network, which does not allow automatic generation control data to be transmitted. Present plans provide for several operational systems using the WSCC guidelines in 1987.

At the RTU level, a "Recommended Practice for Master/Remote Communication" has been developed by an IEEE working group of the Substation Committee. This document is now undergoing the balloting process by the IEEE Substation Committee and should be published in 1987. This recommended practice provides all of the functions normally associated with an RTU, as well as providing standard terms and definitions. Should this recommended practice be utilized by the manufacturers, then interchangeability of RTUs would be greatly expedited.

Another important area of message protocol standards is for local area networks (LANs), which interconnect different systems and/or components of a system within a distance of approximately 5 km. These types of protocols are designed for high-speed networks in excess of 1 Mbit/s, using coax cable or fiber-optic cable. The most prominent example of a LAN for this application is the Ethernet standard, which has already been applied in various applications. The Ethernet standard, which is based upon a particular technique known as Carrier Sense Multiple Access with Collision Detection (CSMA/CD), has now been incorporated as part of IEEE Standard 802.3. The token-passing bus is covered by IEEE Standard 802.4. Under consideration by ISO is the IEEE Standard 802.5 for token-passing ring. Also, of interest is that IBM is planning to utilize the token-passing ring standard.

In addition to interconnecting different computer systems, several SCADA suppliers are utilizing these standards to interconnect various components within the system, using a bus or ring structure. This allows expansion to be simplified by adding additional system components, such as communication interfaces, consoles, or computers to the system ring or bus.

In the future, we expect to see these message protocols rapidly embraced by the system users and system suppliers. System users are requiring these types of standards to allow for greatly simplified future growth and expansion, thus minimizing or delaying system obsolescence. Suppliers are proceeding to use these standards in order to improve their competitive position and to minimize the amount of custom hardware and software that goes into each system. Widespread use of these message protocol standards is expected by the end of 1988.

System Performance

Since a SCADA System is a dedicated system designed for ten to fifteen years of usage, the system must be specified and procured for significant growth and expansion in size as well as in computing resources. Therefore, it is necessary to specify the following items:

- database sizing for ultimate system
- system CPU loading to allow for system growth
- man-machine interface response not degraded by growth.

Methods utilized for these specifications include the following:

- *Specification of system expansion.* This is generally accomplished by specification of databases and the number of input/output ports to accommodate the expected future system growth. Also growth in main memory and disk is estimated and allowed for. The expansion criteria can usually be verified by off-line examination of the system configuration and database compilation.
- *Specification of normal CPU loading test.* With this test a scenario of typical loading expected on the system is defined and verified during the system factory test. The purpose of this test is to ensure that significant expansion in CPU resources is available for future growth and expansion without replacement of the CPUs.
- *Specification of stress CPU loading test.* With this approach, a scenario is defined which simulates the expected maximum loading expected on the system due to operator actions, data changes, and alarms. This type of scenario is expected during power system disturbance conditions and must be met, so that the system will perform when it is most needed. Again, we are specifying the stress loading on the CPU to be low enough to allow for system expansion and growth over its lifetime.
- *Specification of man-machine interface response.* With this specification component, the response time of the system for CRT displays and logs, as well as processing of data changes and alarms, is specified under normal and stress loading conditions.

Ideally, all of the above tests would be performed for the fully expanded system with all application functions operating with their ultimate sizes. For example, the system would run with the ultimate number of RTUs and points, generators, network devices, and network buses. With regard to RTUs and points, this can be simulated by a number of methods, including operation of the data acquisition system at increased scan rates, an RTU communication channel simulator, or by extrapolation of results from the existing system. For additional consoles, the additional loading from operator actions can be simulated by increasing the rate of actions at the consoles.

However, there are several functions for which it is difficult to perform any simulations. These include larger application program sizing for automatic generation control, economic dispatch, unit commitment, and system security programs. (Refer to other papers in this issue for an explanation of these terms.) With these functions, CPU loading is not a linear function of the number of generators or buses. Also, CPU loading for system security programs is dependent upon the connectivity and parameters of the actual network. Factory test methods which are utilized in lieu of simulations include:

a) Calculations of program run time from benchmark tests or from comparison with similar-sized systems.
b) Extrapolation of results from the initial system, using a previously agreed upon formula.
c) Estimating the additional CPU loading and reducing the CPU loading specified for the initial system.

With respect to the network security programs, all of these techniques are approximations since the program run time for the ultimate system is a function of the actual electric network, which can only be approximated for the future. Thus substantial overestimations or underestimations could occur.

The fundamental problem of system performance testing arises because of the need to purchase a computer system now to meet the expansion needs of the ultimate system. This approach is caused by the inability to increase the throughput of the system computers or to find upward compatible replacement computers. However, new computer architectures may provide a solution, as discussed later in this paper.

System Obsolescence

SCADA systems in the last fifteen years have been plagued with the problem of obsolescence. In other words, the system is operating satisfactorily, but new technology has passed it by. Since the computer was probably introduced at least two years before the system was sold to the utility (to allow time for software and system development) and the system takes four years to procure, build, and install, the computers are at least six-year old technology by the time operation commences. Therefore, obsolescence is manifested in several ways:

- First of all, there may be difficulty obtaining repair service or spare parts because the equipment is no longer supported by the manufacturer's repair service. Also, the component chips or special integrated circuits may have been discontinued.
- The advance of computing technology has made many new application functions possible at a reasonable cost, thus making for more efficient and productive electric system operations. Therefore many existing systems should be replaced simply to take advantage of these new functions.
- The utility environment has changed faster than originally anticipated, thus requiring control and monitoring of more locations, such as distribution substations. Alternately, the utility may be assuming a major new role, such as a control area or scheduling energy. Again, the system should be replaced to meet the utility's needs.
- Regulatory requirements. In many instances, regulatory requirements unforeseen when the system was originally purchased make new demands on the system capabilities. These requirements may include safety, economics, or just plain paperwork requirements.

What are the solutions to the above problems? Recently, due to the advance of technology in concept as well as just speed and power, several solutions are available to extend system life, as follows:

- *Upward Compatible Computers:* As more different CPUs become available for the same computer family, upgrade of the CPU is possible by replacement of CPU cards or at worst by a new mainframe. This will allow the existing proven application software to be retained; thus great savings will be obtained. Most of this software is perfectly adequate and can be reused; also, the present programming staff is quite well trained.
- *Coprocessors:* These effectively add more CPUs on the same I/O bus and allow independent problem solving by executing different tasks in parallel. Therefore, expansion occurs by simple plug-in addition of processors and reconfiguration of system software.
- *Local Area Networks:* With this approach the computers, man–machine interface, and communication processors all access a redundant high-speed bus or ring. As new consoles, communications processors, and application functions are added to the system, these can be in the form of additional devices connected to the redundant bus. This allows any device to be replaced or upgraded virtually independently of other devices. In addition, a mainframe host computer can be provided for "number-crunching" applications programs. With this approach, the system is continually evolving and may have a much longer overall lifetime, as long as the bus/ring concept will support the necessary configuration.
- *Standard Communication Interface:* These will allow the system to easily communicate to various other computer systems, and therefore to participate in a wider variety of application functions. As an example, data can be obtained from other systems and used in application programs directly, as opposed to complex estimation schemes to calculate or estimate the missing data.
- *Structured Programming Languages and Documentation:* With these languages, the programs are simpler to understand, debug, and document. The amount of custom software, written in hard-to-understand program languages has always been a major problem with SCADA systems. Because there are new programmers on the system every few years, interpreting the documentation, often incomplete, from the previous programmers may be difficult. Very complex programs fall into disuse because the program source cannot be easily changed or expanded. Therefore, structured programming languages, implemented as part of sound software design techniques and documentation standards, will reduce this problem and provide for greater use of the existing software over a longer period of time.

Trends and the Future

Distributed Processing

In the next five to ten years, we will see an acceleration of the trend toward distributed processing. More computers will be used in the systems than ever before, as well as much more memory, as the costs continue to decline. There will be more data communications between systems and within systems than ever before. The addition of new functions will often occur by the use of dedicated computers, firmware, and software. For example, man–machine interface, RTU communications, external communications, and database manager each will be provided with their own computers and software. In addition to the use of distributed processing within a SCADA system located within a single room of the control center, we will see processing distributed throughout the utility's facilities.

The simpler expandability of distributed systems, plus the many methods of minimizing obsolescence to extend system life will cause the design and implementation of a new generation of utility control centers, based upon distributed approaches. Already, several new utility energy scheduling centers in the Midwest and West are using multiple distributed microcomputers. The trend in the past 20 years has been to centralize more and more functions in the utility control centers; this approach requires large dedicated computer rooms, air conditioning, and backup power supplies, at considerable cost. As the availability of private communication networks increases, the consoles will be placed at their desired work places within the various utility facilities. As the size and heat load of the computers drops, the computer rooms, air conditioning, and backup power supplies will decrease in size and cost. Therefore, the computers can be distributed into different facilities, close to the communication hubs and operations needs.

Better Man–Machine Interface

The SCADA systems of the late 1980s and early 1990s will be based on the use of full graphics, to obtain more realistic geographic detail; for pan, zoom, and declutter; for graphic two- and three-dimensional picture representation of complex functions; and for the use of icons to simplify the dispatcher's recognition and manipulation of complex functions.

We will see the use of an increasing number of remote consoles, as the data rates of links to these consoles are increased to the point where system performance is equal to that of local consoles. This will free many operational functions from the confines of the control room. Also, many new organizations in the utility will have access to the database of the system. For example, system planning can use the periodic line flows for obtaining maxima and minima of transmission lines and feeders.

The interfaces to the operator will also be improved, such as cursor control by touchscreens or mouse. Also, voice recognition for alarm acknowledgment will be used, as well as synthesized voice for messages from the system. Again, this will have the effect of freeing the operator from his chair in front of the CRT console and thus permit more flexibility and productivity.

Standard Systems

In the past five years, microprocessor-based SCADA systems have taken a larger and larger percentage of the energy control systems market. These systems are very powerful in computing power despite their small size and provide for user configuration of database and displays. These systems are virtually off-the-shelf and can be configured, installed, and maintained by the utility. Almost no custom software is required, since only standard SCADA functions are performed. We will see these microprocessor-based systems gradually add system functions, such as automatic generation control and economic dispatch, and additional computing capability.

The mid-sized systems which typically have functions associated with automatic generation control, economic dispatch, interchange scheduling, and energy accounting, have improved by the use of more powerful computers, more memory, and front-end microprocessors. Also, security functions are now becoming feasible for these types of systems. These mid-sized systems have improved software for development of displays and database, thus allowing more work to be done by the utility staff. Standard mid-sized systems do not appear feasible in the near term, due to unique utility application function requirements.

Meanwhile, the large mainframes for Energy Management Systems have become lower in price and in size to thus take an increasing share of the smaller systems. Additional applications requiring large compute power, such as optimal power flow and transient analysis, are now feasible. Standardized large systems are even less likely, because the potential cost savings in utility operations usually justify custom application functions.

Smarter RTUs

As the power of microprocessors increases and the cost of memory decreases, it is cost efficient to put more functions in the RTUs. Already, we have seen the acceptance by the industry of Sequence of Events (SOE) as nearly a standard function. In addition, we have capabilities now for dual-port RTUs, to allow access of the RTUs from two utilities, each with a different message protocol. This is especially useful at interchange tie points. Also, many RTUs are now being provided with report-by-exception processing, in which only those analog and status points which have changed significantly since the scan are reported to the master station. This decreases the processing load on the master station under most conditions. Other functions provided by the new generation of RTUs include self-configuration, which allows the RTU to determine which cards of each type are installed and connected and modify its reporting messages accordingly. Also, self-diagnostics should be included in the near future; this will provide diagnostic information to the master station to allow more rapid repair of failed RTU components. Other functions which can be included in the RTU are protective relaying, closed-loop control, and fault recording. In the future, we will see digital fault recorders included within the RTUs to replace the current generation of analog electrostatic type recorders. The digital recorder will have the great advantage of transmitting the fault information to a central location for printout and instant analysis.

In summary, as RTUs assume more and more functions, they must be specified to include typical software functions, such as database, automatic backup, fail-safe, local man–machine interface, and programming.

Standard Software

In addition to all of the advances in hardware and firmware, significant advances are also being made in software. One of the most significant could be the use of UNIX, which holds the promise of a standard operating system. Although not specifically designed for real-time systems, this operating system or derivatives thereof could be utilized. In the area of applications functions, new applications can be developed on their own dedicated processor and added to the system as needed, thus eliminating many problems of multitasking system execution and contention for various system resources. Many other applications are being added to the systems by an unexpected route, i.e., commercial microprocessor-based software packages. These include spread-sheet programs for energy scheduling and accounting, database programs for load forecasting, and graphics display programs (plots, bar charts, pie charts, etc). These microprocessor-based packages not only are very flexible and useful, but they also provide a degree of transportability between different organizations of the utility and with other companies. In addition, we will see the use of

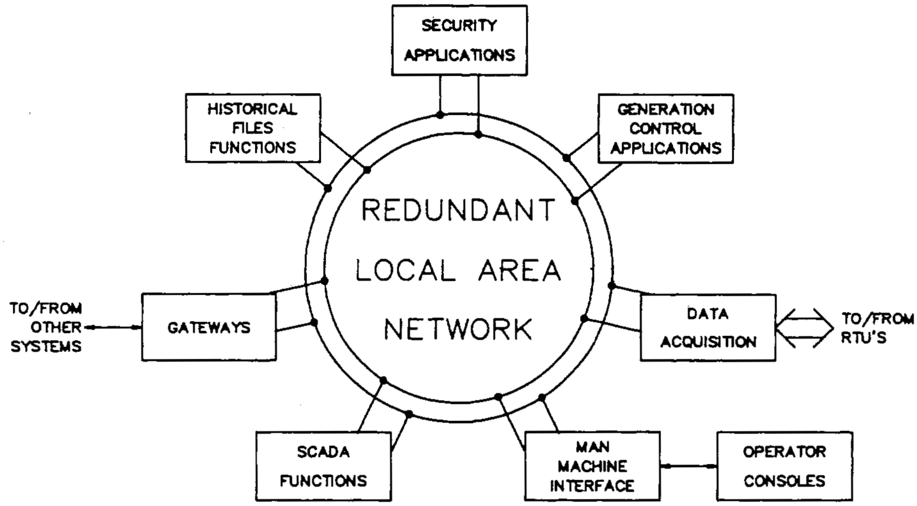

Fig. 10. Distributed modular system concept.

Computer Aided Design (CAD) and Facilities Management incorporated into the SCADA systems, so that the operators have one reference for maps and data.

Interchangable Parts

The SCADA systems of the future will have interchangeable parts, each of which will have access to a redundant data highway (LAN). A typical architecture of this concept is shown in Fig. 10; a key requirement is standard database management techniques. Once this is selected, each part will perform its own function using the data gained from the highway and then making its own results available to other users of the highway. In this manner a variety of suppliers can be used for the application functions. Each system function can then be replaced as necessary and new functions added as necessary. Thus the system will be continually evolving, rather than periodically replaced.

In conclusion, the future of SCADA systems is brighter than ever, paced by the rapid development of technology that allows their use for many new functions at an increasing number of utilities.

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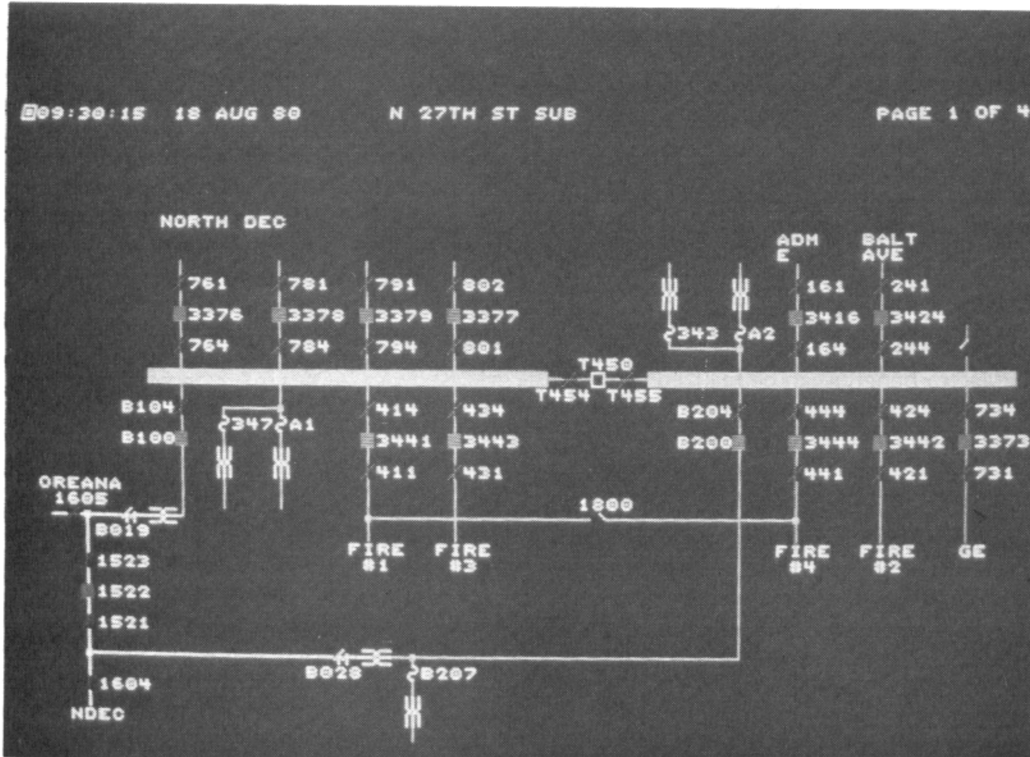

Fig. 1. Typical one-line CRT display for electric substation.

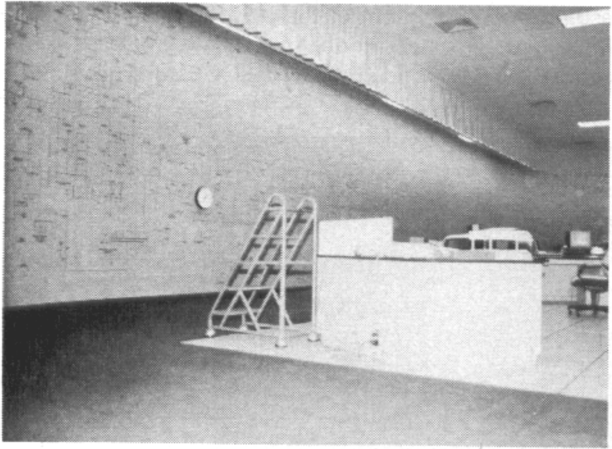

Fig. 2. Dynamic mapboard used in typical control center.

Fig. 7. Typical control room with operator consoles.

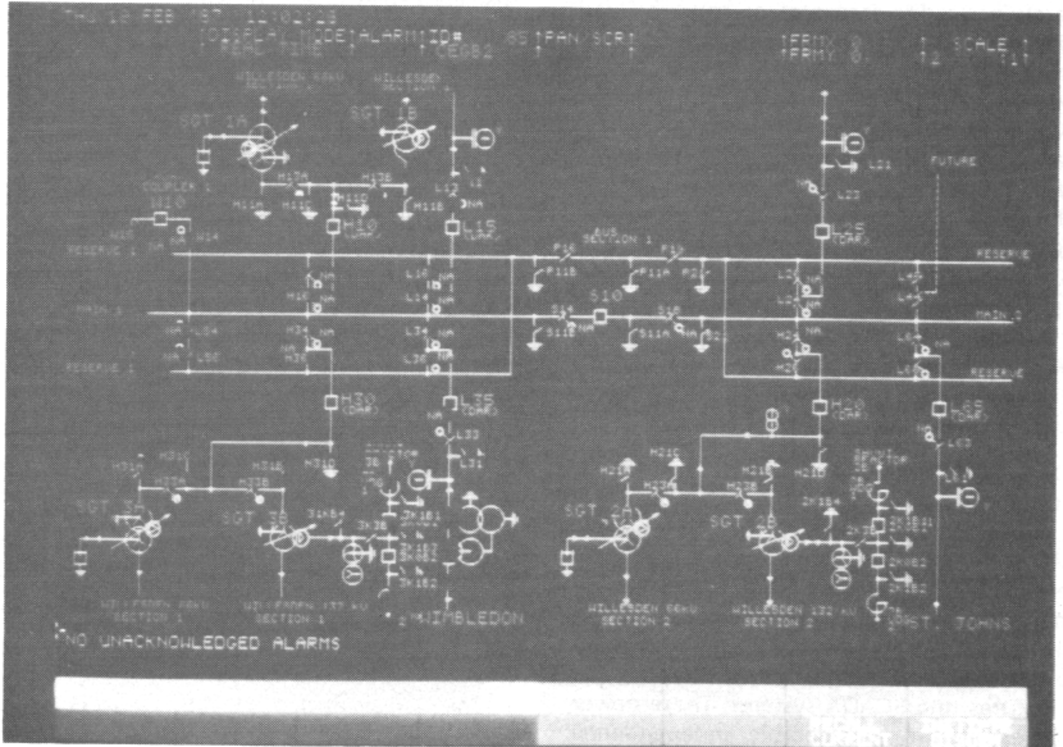

Fig. 8. Typical full graphics CRT display.

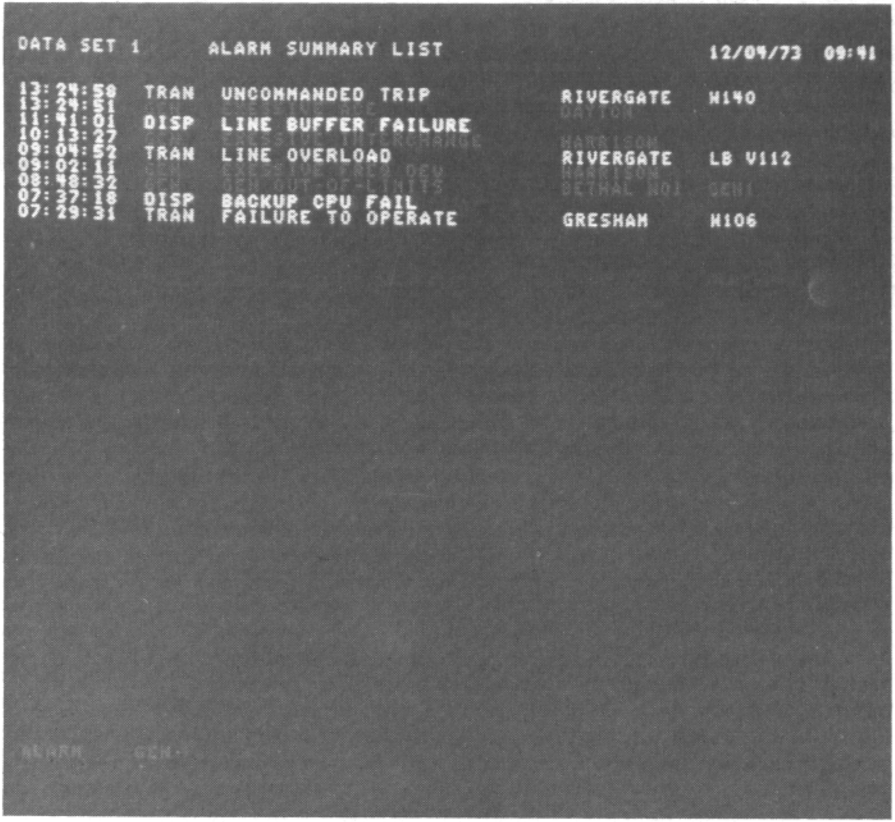

Fig. 4. Chronological CRT alarm list